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Evaluating the Relevance of NRAP Tools to Support Stakeholder Decision Making Related to UIC Class VI Injection Permit Application Process

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1.0 Introduction

The United States Department of Energy Office of Fossil Energy and Carbon Management (DOE FECM) has sponsored the National Risk Assessment Partnership (NRAP) to develop computational methods and tools to evaluate risks and support stakeholder decision making for several aspects of carbon capture storage (CCS). The existing NRAP tools are focused on three key areas of CCS projects: (1) assessing potential leakage risk and assuring containment effectiveness, (2) probabilistic assessment of induced seismicity hazard and subsurface stress state, (3) supporting risk-based design of monitoring. **The NRAP tools were not developed to satisfy the requirements of the U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) Class VI program (https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-carbon-dioxide) or the state equivalent in states with Class VI primacy.However, analyses supported by the NRAP tools may be useful to stakeholders in developing these permit applications.**

While this report is not intended to provide a timeline for the development of the NRAP tools, a general timeline of the NRAP program helps frame the analysis of the current study. The initial phase of NRAP focused on developing tools and methods to quantify the risk first delineated by Dr. Sally Benson in 2007 and reduce uncertainties (Dilmore et al., 2024; Pawar et al., 2016; Pawar et al., 2013). The second phase involved developing tools and guidance to manage risk and reduce uncertainties. Because the CCS industry is quickly evolving and becoming commercially viable, the current phase, which runs through 2027, is to support CCS deployment. Specifically, the goal of the current phase is shown below:

> NRAP is focused on applied research that will directly support the DOE Office of Fossil Energy and Carbon Management's (FECM's) goal of ensuring carbon capture and storage (CCS) readiness for commercial deployment. NRAP is applying its methods and integrated assessment framework to directly address deployment-critical stakeholder questions related to long-term risk and liability, promote the incorporation of quantitative risk assessment into GCS site development best practices, develop adaptive monitoring design tools for efficient and effective risk management, and address other project life-cycle questions. Finally, the NRAP team will adapt site-scale risk quantification tools and methods to assess risks associated with rapid deployment of multiple commercial-scale GCS operations within a geological basin.

Quoted from the *NRAP Phase III Field Work Proposal,* FWP number: 1025009

The current collection of tools is focused on wellbore leakage, state of stress and induced seismicity, and informing monitoring designs. Throughout this process, improvements to NRAP tools are being made as the project continues to refine the tools. Publicly sponsored commercial-scale projects have helped to demonstrate the tools in several relevant reservoirs (see Section 4.2.2). The five NRAP tools reviewed in this study are the National Risk Assessment Partnership Open-Source Integrated Assessment Model (NRAP-Open-IAM), Operational Forecasting of Induced Seismicity (ORION) toolkit, State of Stress Analysis Tool (SOSAT (v2)), Designs for Risk Evaluation and Management (DREAM (v3)), and Passive Seismic Monitoring Tool (PSMT) - – representing a snapshot of the publicly-available NRAP toolset at the beginning of this study. The NRAP-Open-IAM was developed to estimate leakage risk by determining the effectiveness of containment and potential risk-based leakage from a storage reservoir; (2) SOSAT was developed to estimate geomechanical risks at a geologic carbon storage site by quantify[ing] uncertainties in the stress state and related uncertainties as they evolve over the life of the project (DOE/NETL, 2024a); (3) ORION was developed to forecast site-specific induced seismicity risk; (4) DREAM was developed to help operators in the design of efficient and effective monitoring programs; and (5) PSMT was developed to help operators design microseismic monitoring approaches.

The tools have been developed and demonstrated through both conceptual and developing storage projects, and there has been no systematic review of the studies showing the utility of the NRAP tools to satisfy permitting requirements at carbon storage sites. This study seeks to provide an overview of the NRAP tools and their applicability to contribute to the development of U.S. EPA UIC Class VI permit applications for carbon storage projects. The NRAP project was started to provide tools and methods to ”develop computational tools and workflows to quantitatively assess risks and potential liabilities associated with geologic carbon storage and address critical stakeholder questions in support of commercial CCs deployment. (https://edx.netl.doe.gov/sites/nrap). While these tools were not explicitly built to address the various requirements of the U.S. EPA UIC Class VI well permits, they provide information and analysis that might be useful in a Class VI application and their equivalents in states with Class VI primacy. Because the current research is applying these tools to a problem that, while related, they were not originally intended to answer, this study should not be considered an evaluation of how the tools perform for their stated purpose. Rather, the study is intended to identify where the tools can be used in Class VI applications and evaluate relevant work demonstrating application of the tools to reservoirs, similar to target reservoirs some of the current Class VI applications.

The study was accomplished using a three-pronged approach: (1) a literature review of tool development and tool applications; (2) expert interviews of CCS project implementors, NRAP tool developers and users, and experts from the U.S. EPA UIC Program; and (3) an evaluation of the tool’s use as described in the body of reviewed literature and publicly funded programs with publicly available information from current UIC Class VI permits.

2.0 Literature Review

2.1 Methodology

Two literature databases were used to complete the literature review: Google Scholar and the Energy Data eXchange (EDX) database. The papers reviewed from both sources were those that focus on the Open Integrated Assessment Model (Open-IAM), the State of Stress Analysis Tool (SOSAT), the Operational Forecasting of Induced Seismicity (ORION) tool, and the Designs for Risk Evaluation and Management (DREAM). The Google Scholar search was completed using search terms listed inTable 1. This portion of the literature review focused on articles from project developers and CCS practitioners. Tool development papers from the National Laboratories and the DOE-NETL were the focus of literature from the EDX database. Articles from 2016 onward were reviewed because the NRAP tools of interest were released after 2016. These studies were supplemented by additional government-sponsored studies found during the project, studies that did not meet the stated criteria but were deemed to be relevant, and studies suggested by the interviewees (see Section 3.0) and project advisors.

Table 1. Search Terms used to find the literature included in the literature review.

Search Term	Purpose	Keywords[1]
NRAP Class VI	Determine if any of the NRAP tools has been directly used for Class VI applications	Permit, Area of Review, Monitoring, Class VI, Application
NRAP [NRAP Tool][2] Project Application	Determine if the NRAP tools of interest have been used in project demonstrations	Must contain at least one of the NRAP tools of interest[2], Demonstration, Feasibility, Characterization, Construction, Project Phase
NRAP {Project Type}[3]	Determine if the NRAP tools have been used in advancement of specific DOE-sponsored projects	Must contain at least one of the NRAP tools of interest[2], DOE, Federal funding, {project type}
NRAP Risk Management	Determine if the tools have been used for the determination or management of risks and risk mitigation	Risk Management, Likelihood, Severity, Mitigation

1. Keywords in the title and/or abstract to determine the study's applicability
2. [NRAP Tool] = Open-IAM, DREAM, ORION, or SOSAT
3. {Project Type} = CarbonSAFE, Regional Initiative, Regional Carbon Sequestration Partnership

2.2 Literature Found

A total of 34 studies were found through the literature review (26 studies) and the NRAP EDX site (eight studies) (Table 2). Additional summary details of the studies found are provided below:

- **Search term used:** Just under half of the studies found using search terms (12) were found using the "NRAP Class VI" search term. The "NRAP [NRAP Tool] Project Application, and "NRAP [Project Type]" search terms each yielded seven studies. The NRAP Risk Management search term did not yield any studies meeting the criteria outlined in Section 2.1. The remaining eight studies were found on the NRAP EDX site.
- **Tool used:** Most of the studies covered the NRAP-Open-IAM tool (26). Five of the studies found used the SOSAT tool and another five used the DREAM tool. One of the studies found used the ORION tool.
- **Organization Type:** The National Laboratories were authors on approximately two-thirds of the studies reviewed (23 studies). Industry, commercial, and non-profit organizations participated in more than one-third of the studies (12 studies). This, along with an additional six studies authored by universities, indicates some buy-in from users extending beyond the

core NRAP team. The DOE authored three of the studies reviewed, less than 10% of the studies reviewed.

- **Lithology:** Most of the studies reviewed focused on clastic reservoirs (26 studies) or the reservoir was not indicated or was not applicable for the study (e.g., for tool development papers) (11 studies). The remaining studies focused on carbonate reservoirs (three studies). None of the studies feature coal bed methane reservoirs.
- **Factors Studied:** The factors studied in the papers were variable and some of the studies covered more than one factor. The most common factors studied included the Area of Review (AoR) and/or CO_2 plume (14 studies) or leakage, including within subsurface storage complex (out of the reservoir but not to an underground source of drinking water [USDW]) (15 studies), leakage out of the reservoir to soil or USDW (17 studies), and impacts to near-surface receptors (18 studies). Other studies looked at leakage to the atmosphere (four studies), the monitoring approach for the project (10 studies), and the state of stress or induced seismicity (eight studies).

Table 2. Summary details about the studies found through the literature review, including the search type, search term used, the tool used in the study, the organization type(s) of the study authors, the lithology of the storage formation modeled (if applicable), and the factors studied.

Factor	Count
Search Type	
Found through search terms	26
NRAP EDX	8
Search Term Used	
(1) NRAP Class VI	12
(2) NRAP [NRAP Tool] Project Application	7
(3) NRAP [Project Type]	7
(4) NRAP Risk Management	-
(5) From NRAP EDX (no search term)	8
Tool Used[1]	
(1) NRAP-Open-Integrated Assessment Model (NRAP-Open-IAM)	26
(2) State of Stress Analysis Tool (SOSAT)	5
(3) Operational Forecasting of Induced Seismicity (ORION)	1
(4) Designs for Risk Evaluation and Management (DREAM)	5
Organization Type[2]	
(1) DOE	3
(2) National Laboratory	23
(3) University	6
(4) Industry / Commercial / Non-profit	12
Lithology	
(1) Clastic	26
(2) Carbonate	3
(3) Coal Bed Methane	-
(4) Not indicated or not applicable	11
Factors Studied[2]	
(1) Area of Review / CO_2 plume	14
(2) Subsurface Leakage (i.e., out of reservoir, not to Underground Sources of Drinking Water [USDW] or surface)	15
(3) Near-Surface Leakage (to groundwater or soil)	17
(4) Surface and/or Atmospheric Leakage (includes to surface water)	4
(5) Near-surface receptors	18
(6) Surface receptors	-
(7) Monitoring Approach	10
(8) Induced Seismicity or State of Stress	8

Notes: 1. Two studies used multiple tools – one of these studies used the IAM and DREAM tool and the other used the IAM, DREAM, and SOSAT tool. These studies are included in each of the relevant tool counts.
2. The sum of the count for the category is greater than the number of studies reviewed because a study could have more than one result in the category.

2.3 Summary of the Literature Reviewed

As discussed earlier, the NRAP tools were developed with a broader objective of quantification and management of risks at geologic carbon storage sites, not to directly support of Class VI permits; however, many of the studies that were reviewed frame results in the context of the U.S. EPA UIC Class VI program. For instance, several demonstration studies mention the Class VI program as well as various requirements for permit development such as delineating an AoR, calculating leakage risks, designing monitoring approaches, determining project liability, and performing corrective action (Arbad et al., 2024; Harbert et al., 2016; Xiao et al., 2024; White et al., 2020). Other authors have explicitly stated that their papers are meant to demonstrate how the tools can be used to help develop a Class VI application. Pawar et al. (2022a), for example, stated that their study was “aimed at demonstrating how quantitative leakage risk assessment can be used as part of the permit application process for UIC Class VI injection wells”. This review seeks to develop additional information as to how NRAP tools are perceived by the CCS community and identify how these tools might be used in support of Class VI permit applications, given the conditions of the currently submitted Class VI applications.

AS multi-institutional report (Lackey et al., 2022a) provides a crosswalk between the UIC Class VI regulations and a set of 59 industry, academic, or national laboratory- developed computational modeling tools that will help provide evidence to support the development of permit applications. The authors broke the permitting requirements into 12 different aspects of application development. The authors find that NRAP tools may be used in the context of eight of these aspects: (1) site screening (NRAP-Open-IAM); (2) site characterization (DREAM, NRAP-Open-IAM, and SOSAT); (3) AoR calculation and corrective action planning (NRAP-Open-IAM); (4) injection depth waiver/aquifer exemption (NRAP-Open-IAM); (5) proposed operating conditions (STSF and NRAP-Open-IAM); (6) testing and monitoring (DREAM, NRAP-Open-IAM, ORION, and STFS); (7) emergency and remedial response (ERR) (NRAP-Open-IAM and ORION); and (8) post-injection site care (PISC) and site closure (DREAM and NRAP-Open-IAM).

2.3.1 Wellbore Leakage

The NRAP-Open-IAM is the tool used to simulate CO_2 and brine leakage from a CCS reservoir through potential leakage pathways (natural faults and fractures or artificial penetrations – i.e., wells and wellbores) to overlying receptors of concern. Several studies identified through the literature review demonstrated the use of the NRAP-Open-IAM using realistic commercial-scale project conditions and reservoirs currently being considered for carbon storage. These studies accomplished several goals and contained findings that could be directly or indirectly applicable to several aspects of Class VI projects. These include demonstrating containment or a low risk of leakage, developing an AoR (specifically, a risk-based AoR, in contrast to an AoR that fits the strict definition in the Class VI rule and related guidance document; Thomas et al., 2022), proposing a phased corrective action plan, developing an ERR Plan.

The NRAP-Open-IAM is a computational framework that utilizes reduced order models (ROMs) of various components of the geologic storage system (e.g., storage interval, leakage pathways, receptor responses). These component ROMs are linked together in the framework in a way that approximates behavior of the physical system in response to large-volume CO_2 injection and storage. This approach allows for the fast simulation of many different aspects of CCS (e.g., well leakage, fault leakage, groundwater aquifer response to hypothetical leakage) using a fraction of the computational costs that a full physics model requires. Additionally, several papers covering the development of these ROMs and modules and demonstrating the capabilities of the tool are available:

- Vasylkivska et al. (2021) describe the NRAP-Open-IAM and how to use it.
- Lackey et al. (2022b) describe the Semi-Analytical Leakage Solutions for Aquifers (SALSA) module of the NRAP-Open-IAM to contribute to proposed operating conditions.
- Zhang et al. (2018) discuss the development of the Well Leakage Analysis Tool (WLAT), which is now a component in NRAP-Open-IAM.
- Zhang et al. (2016) discuss a method to estimate dense gas dispersion that can be used in the NRAP-Open-IAM framework.
- Bacon et al (2017) demonstrate the Aquifer Impact Model (AIM), now part of the NRAP-Open-IAM using data from the FutureGen 2.0 Project.
- Bacon (2021) reports on the use of FutureGen 2.0 data to develop lookup tables to simulate CO_2 and brine leakage from the Mt. Simon to USDWs. The author also mentions that the tool has been used to calculate the PISC period and AoR for CCS projects.
- Bacon (2022) reports the development of the generic aquifer component, which the author notes can be used in the NRAP-Open-IAM and converted for use in the DREAM tool.
- Meguerdijian et al. (2023) provide an analysis of machine learning used to develop a fault-leakage ROM.

Bacon et al. (2019) and Bacon et al. (2020) used the data from the FutureGen 2.0 Project to demonstrate the capabilities of the of NRAP-Open-IAM. Bacon et al. (2019) demonstrated that the PISC period for FutureGen Project could have been reduced from the default 50-year period required by the UIC Class VI regulations while the site reached a state where the local USDW was not endangered during the post-injection period. In addition, the authors found that three of the monitoring wells proposed in the original permit applications may not have been required, further reducing the capital costs of installing these wells and the operation and maintenance costs required to monitor, maintain, and eventually plug and abandon them. Bacon et al. (2020) followed up this study and concluded that the NRAP-Open-IAM can help support a detailed characterization of project leakage risks.

White et al. (2018) show the use of the NRAP-Open-IAM in a deep, saline reservoir (St. Peter Sandstone) in the northern Lower Peninsula of Michigan in an area where the storage complex has artificial penetrations within the AoR and CO_2 plume. The authors showed that the hypothetical commercial-scale injection program would be protective of USDWs. The authors also made notes on how the tools could be improved. White et al., (2020) is a follow-up study that compares the results of the two Phase I CarbonSAFE projects described in White et al. (2018), Gupta et al. (2019), and Cumming et al. (2019). This paper focuses on the St. Peter Sandstone in the northern Lower Peninsula of Michigan and the Cambro-Ordovician Storage Complex in eastern Ohio. The authors found minimal leakage risks for both projects despite large AoRs and the existence of multiple legacy wells penetrating the storge complex. The authors noted that differences in risks between the two projects were driven largely by depth and resident water salinity, both of which impact the critical pressure calculation as well as the pressure required to affect brine leakage.

Pawar et al. (2022b) demonstrated the use of the NRAP-Open-IAM with a reservoir model produced by the proprietary software ECLIPSE to calculate the protectiveness of the USDW within the AoR. The modeled project involved injecting 6.2 MMt of CO_2 per year the Entrada Formation in the San Juan Basin of New Mexico using 10 injection wells. The authors noted no significant risks of leakage to the USDW resulting from the project. They also proposed a phased corrective action approach for the project. Other authors have also noted that NRAP-Open-IAM may be used to develop a corrective action plan. Arbad et al. (2024), a team from

Texas Tech University, considered an area with thousands of legacy wells in the AoR of a potential CCS project in the Mt. Simon Sandstone of Illinois. The authors found that 54 of these wells are considered high priority and an additional 10 are considered medium priority for corrective action. They specifically note tools like the NRAP-Open-IAM, which they mentioned by name, could help to define leakage risks and thus inform a corrective action plan or active reservoir management.

The NRAP-Open-IAM has also been demonstrated using hypothetical reservoirs. Mitchell et al. (2023), for example, modeled a hypothetical project to model the impact of a “worst-case scenario” of an unknown legacy well intersecting a CCS storage complex within the AoR. The authors used a relatively simple reservoir model built in ECLIPSE in conjunction with the NRAP-Open-IAM to determine if there would be leakage from the reservoir and test the effectiveness of mitigating approaches. The authors found that under the assumed scenario and parameters there would be potential leakage of brine into the USDW but demonstrated how the NRAP-Open-IAM could be used to reduce the leakage risk through application of pressure management strategies while project operators developed permanent solutions to the leakage, an evaluation they specifically tie to the ERR Plan requirements in a Class VI UIC application.

Brown et al. (2023) showed how the NRAP-Open-IAM can complement other methods to provide a robust risk assessment. The authors showed how the model can be used in conjunction with a Bowtie risk assessment at the Quest CCS site in Edmonton, Alberta. The authors mentioned that the Bowtie method has provided the Quest site with a comprehensive risk assessment but, use the NRAP-Open-IAM model to evaluate the potential impacts to groundwater along potential leakage pathways. The authors mention that coordinating these methods could be a powerful tool for risk assessments at commercial CCS sites.

Other authors have described studies that have demonstrated the NRAP-Open-IAM in several different reservoirs. Nguyen et al. (2017) modeled risks at a fractured saline reservoir in the Duperow Formation in Kevin Dome, Montana. The authors found that several important geologic components control risk, namely “fracture permeability, end-point CO2 relative permeability, capillary pressure, and permeability of confining rocks”. In addition, the authors mention that legacy well integrity is an important component of CO_2 leakage into the USDW, particularly after 10 years following injection. Onishi et al. (2019) ran a sensitivity analysis on the range of parameters that could affect the risk of leakage and used the model to show injectivity limitations in one of the chosen reservoirs and to demonstrate that the risk of leakage is fairly low, except in the case of poorly sealed legacy wellbores. The authors also note that running numerical models could help to overcome the limited information related to injection and monitoring.

Doherty et al. (2017) describe using the cemented wellbore model, the multi-segmented wellbore model, the open wellbore model, and the brine leakage model of the WLAT. The authors provide a comparison study for the four leakage models and a field-based case study of the Salt Creek Oilfields in Wyoming. The authors found that several parameters could control the amount of CO_2 or brine leakage, including: "distance from injection site, well age, leak path length and permeability". The authors provide a workflow to determine the wells that are most at risk for leaks and inform injection site decisions.

Carroll et al. (2014) demonstrate the NRAP-Open-IAM using a site in Texas storing CO_2 in the Vedder Sandstone. The authors model potential CO_2 and brine leakage to the High Plains Aquifer and Edwards Aquifer at varying rates and determine the impacts. The authors note that their approach could help inform monitoring, particularly as bespoke, site-specific methods are needed. The authors also stress that long-term impacts to water are possible despite small plume sizes and emphasize the need for establishing baseline groundwater geochemistry measurements is needed to determine impacts.

Keating et al. (2016) conducted a similar study to Carroll et al. (2014) using the same aquifers with different leakage rates and nine different components that could be impacted: phenol, benzene, polycyclic aromatic hydrocarbon (PAH), As, Ba, Cd, Pb, total dissolved solid (TDS), and pH. The authors found that pH and TDS are the two components that are most readily transferable to other aquifers and provide guidelines for determining aquifer transferability (similarity of aquifer and expected/required ROM accuracy), which includes comparing background water chemistry, and state that the no-impact threshold should be used when applying the ROM in another aquifer. The authors note that trace metals ROMs should only be used if the geochemistry and mineralogy of the aquifer is similar to the Edwards or High Plains Aquifers.

Xiao et al. (2024) provide a review of risk and uncertainty assessments in the context of CCS. The authors used NRAP tools to simulate leakage from the Morrow B CO_2-EOR reservoir at the Farnsworth Unit in northern Texas to the High Plains Aquifer using successive iterations of reservoir models. The authors noted that these updates are critical to reduce the uncertainty for the risk models and concluded that complete and objective datasets, such as those available through EDX, are an important asset to improve the calibration and verification of these risk assessments and methods.

Other studies have demonstrated the NRAP-Open-IAM at CCS sites across the country:

- Wang et al. (2023) used data from the FutureGen 2.0 site as training data to demonstrate the construction of a Bayesian network to determine the probability of containment. The authors state that the approach could be used to demonstrate the effectiveness of containment and the likelihood of leakage.
- Pawar et al. (2016) demonstrated the model using a hypothetical site based on the Kimberlina Formation in California. The authors demonstrated how the model can be used to generate risk profiles for parameter ranges (e.g., reservoir properties, injection scenarios, and groundwater quality) and state that the tool is effective at modeling CCS system performance.
- Lackey et al. (2019) also used a hypothetical project in the Kimberlina Formation, but instead, used it to demonstrate a method to calculate risk-based PISC period in the site, which has more than 1000 legacy wellbores.
- Burton-Kelley et al. (2019) also calculated a risk-based PISC period at a hypothetical project injecting into the Broom Creek Formation in North Dakota.
- Xiao et al. (2019) used the NRAP-Open-IAM to develop an AoR for a project in the Navajo Sandstone in the Buzzard's Bench CCS site in Central Utah.
- Chen et al. (2023) demonstrated the NRAP-Open-IAM at a site in the Lower Madison Limestone storage formation at the Rock Springs Uplift (RSU) in Wyoming. The authors showed how assimilating monitoring data into risk assessments completed using the NRAP-Open-IAM could help improve the quantification of risks and reduce uncertainty associated with the analysis.
- Pawar et al. (2020), also considering a hypothetical project at the RSU but instead injecting into the Lower Madison and the Weber Sandstone, demonstrated how the tool could be used evaluate the risk of plume migration in a heterogeneous storage reservoir during the PISC period.

2.3.2 State of Stress and Induced Seismicity

Only four papers reviewed used the SOSAT tool. Appriou (2019) used the SOSAT tool to study state of stress at the site. The authors found that, for the specific case considered, the uncertainties for maximum horizontal stress mean conservative assumptions would lead an operator to assume that there is a 25% probability that the reservoir is critically stressed prior to injection and that the risk of shear failure increases to 43% when the pore pressure is increased to the maximum allowable injection pressure under the Class VI UIC Program. The operators noted that these results are due to conservative assumptions that maximum horizontal stress measurements should be a priority in geologic characterization activities. The authors do note, however, that unintentional hydraulic fracturing is unlikely as the minimum principal stress is relatively well documented. Camargo et al. (2023) followed this paper with a discussion about the differences in pressures that initiate, propagate, and close fractures, also in the FutureGen 2.0 area. Ochie (2022) used the SOSAT tool to determine the risk of induced seismicity in the Arbuckle Group in Oklahoma. The author found a fairly high risk of induced seismicity but, similar to Appriou et al. (2019), attributed it to a lack of constraint on the state of stress. Finally, Bao and Burghardt (2022) developed a Bayesian process to quantify uncertainty in stress estimates and demonstrated it using data from the In Salah project.

Kroll et al. (2024) describe the use of the ORION tool using information and data from the Illinois Basin Decatur Project (IBDP). The authors used a pressure model to demonstrate the application of the ORION tool for the project, which injected 1.1 MMt of CO_2 over three years. The authors took advantage of the publicly available seismic data collected from December 2011 through July 2018, beginning before injection started and continuing for years after injection. The authors reported the successful application of the tool, but also noted some challenges for the tool, including the need for high quality data and the need for knowledge on fault locations and ambient stress.

One of the core accomplishments of the NRAP program is to provide recommendations and best practices for dealing with risk in CCS projects. Templeton et al. (2021) provides guidance on dealing with induced seismicity for the project. The guidance covers methods for conducting preliminary induced seismicity risk assessments, establishing appropriate thresholds, collecting relevant data, evaluating hazards, making risk-informed decisions, managing operations to control induced seismicity risks, and conducting outreach and communication related to these issues. The NRAP team will follow this document up with a forthcoming guidance document that will present best practices for stress state characterization at storage sites (Dilmore et al., 2024).

2.3.3 Monitoring

The DREAM tool was mentioned in five of the reviewed studies. Bacon et al. (2019), for instance, used publicly available information from the FutureGen 2.0 site to demonstrate the NRAP-Open-IAM and DREAM tools. While the FutureGen 2.0 project was discontinued prior to the authors' work, results like these show utility of the NRAP risk assessment approach. The authors used the DREAM tool to develop a performance-based monitoring approach that monitors the leakage of CO_2.

Yonkofski et al. (2016) simulated a hypothetical leak to the Edwards Aquifer and the High Plains aquifer to demonstrate an approach for designing a monitoring system that would minimize the time to detection. The study was instrumental in developing the approach for the DREAM tool. Yonkofski et al. (2017) followed up the study by demonstrating the DREAM tool to determine the optimal monitoring approach for using a model developed by Carroll et al. (2014). The authors focused on building the monitoring well network by determining the number and location of wells to monitor the total amount of dissolved ions leaking into the High Plains aquifer from a hypothetical brine leak. They determined the optimal location for 14 monitoring wells using this process.

Yonkofski et al. (2019) demonstrated the DREAM tool using a hypothetical project injecting 0.2 MMt/yr over 4.7 years in a single injection well in the Niagaran formation in Michigan. The authors applied the DREAM tool to evaluate monitoring locations and approaches to detect potential leaks from the reservoir. The authors used a wellbore integrity index (WBI) to help prioritize potential monitoring locations. Ultimately, the authors modeled six locations that helped to reduce time to detection from the wells with the lowest integrity rating while 10 locations minimized the time to detection for all legacy wells.

In addition to the development of the DREAM tool, the NRAP team has also commented on monitoring at CCS sites to ensure the safety and efficacy of the technology. Harbert et al. (2016) described various monitoring strategies for regulatory compliance and leakage detection at CCS sites. These include key risk aspects for CCS, risk/monitoring feedback mechanisms, and monitoring strategy updates. Yang et al. (2018) used the scenario modeled by Carroll et al. (2014) to demonstrate an adaptive approach to modeling design. The approach uses a decision tree to model the monitoring design that allows for leakage detection.

3.0 Expert Interviews

The expert interviews were intended to gain an understanding of what is currently known about the NRAP tools and how they have been applied to real-world CCS projects by speaking to representatives in the CCS industry. A series of interviews was conducted from April to July 2024. Seventeen separate interviews were conducted with 25 individuals ranging in length from thirty minutes to one hour. The individuals were split into three broad categories: Tool Developers; Research/Academia, Industry, and Project Developers; and Regulators. A breakdown of interviewees and their professional categories is available in Table 3.

Prepared questions were tailored to the expertise of the individual interviewed to derive specific, relevant information from each individual. Interviews with tool developers focused on the original purpose of the tool, the process for developing and testing the tool, expected tool improvements or iterations, and how users can access help for the tools. Interviews with project research/academia, industry, and project developers as well as regulators were intended to show how the experts viewed the NRAP tools; their current processes for modeling, permit development, and risk assessment; the gaps or inefficiencies in their current process and how NRAP tools might help address them; and the information or incentive needed to amend their current process and incorporate the NRAP tools into their processes.

Table 3. Participants in the Expert Interviews on use of NRAP tools to develop Class VI permit applications.

Category	Number of Interviewees	Companies
Tool Development	9	National Labs
Research/Academia, Industry, and Project Developers	14	University, Non-profit Research, Oil and Gas and CCS Consulting, Energy and Carbon Management, Carbon Transport and Storage, State Geologic Surveys
Regulatory	2	US EPA

To ensure the interviews were as productive and open as possible, interviewees were assured that their remarks would remain anonymous. A list of all interviewees is available in the addendum FINAL Expert Interview Memo, however, the information in that report and shared in this report is unattributed to protect the privacy of the sources.

Interviews were conducted first with research, academia, industry, and project developers; second with developers of the NRAP tools ORION, Open IAM, and SOSAT; and finally with regulatory officials. This order also enabled the ability to share with tool developers some of the concerns and insights gained about the tools from the first set of interviews. The interviews with officials at the EPA were improved by the interviews with the first two sets of experts by incorporating information from both previous groups into the discussions. The result was a well-rounded look at how and why NRAP tools were developed, how they are being used across many stakeholder groups in general and to inform CCS development, and how the NRAP tools could be used to enhance an understanding of CCS project risks. The ways in which results from the NRAP tools could be used in the development of UIC Class VI permit applications is also explored. Finally, these interviews also produced some recommendations for improvements to the existing NRAP tools as well as recommendations for new tools that interviewees would like to see developed.

This information is compiled in sections below that focus on each category of interviews followed by bulleted lists of recommendations and finally summed up in a brief roadmap outlining where the NRAP tools could be used to developed information that could be used in a UIC Class VI well permit application.

3.1 Interviews with Tool Developers

Open IAM (Version 1.2.0)

The Open IAM tool was developed to address leakage risk, to perform risk analysis, and consider some uncertainties associated with a particular storage site. Specific issues it addresses are AoR delineation and time to first detection analyses. As the name, Integrated Assessment Model, indicates, the tool allows the user to perform a risk analysis on any part of the geological system starting with the geological reservoir, traveling through potential leakage pathways, and into receptors of concern such as aquifers and the atmosphere.

While the EPA does not endorse any one tool or suite of tools as a regulatory agency, developers of the Open-IAM tool call the EPA "probably the most important stakeholder for the work [they] are doing," and have been meeting with agency officials since the beginning of the NRAP program. The NRAP tools are included in the Rules and Tools Crosswalk, giving them credibility and indicating that they are somewhat vetted, an interviewee said. While the AoR required by the EPA is "regulatory" as opposed to the "risk-based" AoR calculated by the Open IAM tool (which can also calculate the regulatory AoR), it provides complementary information valued by the EPA. The developers interviewed were currently not aware of permit applications that have used the Open IAM tool; however, one of the experts interviewed from research/academia indicated they had used the tools in a Class VI application.

The developers discussed the current functionality of the tool, including its ability to complete a standardized plume stability analysis for the PISC period. Specifically, to site permit development, the tool has specific workflows made to facilitate AoR or Time to First Detection calculations. This could be a powerful tool when the public or regulators assess the risk of a project and protectiveness of its mitigation approaches.

Future developments of the Open-IAM tool could specifically assist with Class VI permit applications. The model has incorporated a Bowtie plat visualization tool that is analogous with the Bowtie plot used in industry but with a slightly different approach. The Open IAM Bowtie plot allows for the representation of summary quantitative risk assessment results (e.g., leakage risk quantification) together with semi-quantitative estimates for other system components (developed outside of NRAP-Open-IAM). There will also be new functionalities that expand the Semi-Analytical Leakage Solutions for Aquifers (SALSA) modeling component, including relating to actual pressure outputs as well as creating an AoR through the tool exclusively. Developers are also considering linking Open IAM with the forthcoming Risk Adaptive Monitoring Plan (RAMP) tool as well to a forthcoming cost and liability model, referred to as the Technoeconomic and Liability Evaluation (TALES) tool. They are also considering implementing a different approach for the graphic user interface (GUI) that will make the overall tool as user-friendly as possible.

The developers added that moving forward they are working to add improved component models to the Open IAM tool, including an update to a new machine learning wellbore model and a hydrocarbon leakage model that will help address questions about transitioning from a Class II to a Class VI well.

The NRAP team is also developing a new tool forthcoming RAMP, that addresses the monitoring aspect of the geological carbon storage project. This new tool, expected to be released in spring 2025, is based on the same framework for uncertainty quantification for risk analysis as Open IAM. This similar structure allows for the two tools to be linked together, extending the range of possible workflows and facilitating more nuanced assessment.

Interviews with Research, Academia, Industry, and Project Developers revealed a concern about how the NRAP tools had been tested or validated. The Open IAM team explained that they have implemented many standard practices in quality assurance to ensure the data produced by their different component models is sound. Two companies presented papers relating their use of the Open IAM model at a carbon storage site and on leakage risk of an AoR plume, which they believe is a good test of the utility of the tool. While they say that they do not have "real gold standard validation" on a site scale, as these are impossible due to the lack of a known large CCS project failure, the NRAP developers believe they have reasonable proxies. One interviewee added that the best way to validate data is to have the tools used in real-world applications. Many of the specific components are trained using data from commercial or national laboratory simulation tools.

Interviewees in the aforementioned category also indicated that when they have tried to use the tools in the past, they encountered difficulties contacting developers or people who could help answer questions about the tools. The Open IAM team can be reached by:

Emailing NRAP@NETL.gov
Via the email listed in the Open IAM User Guide

Additionally, they are investigating establishing a user forum and how to make it accessible but protected against spammers. They are also working to brief more people on their team about frequently asked questions and encountered issues to provide more coverage for interested users.

ORION (version 5)

The ORION tool was jointly developed jointly under NRAP and the DOE FECM Science-informed Machine Learning to Accelerate Real-Time (**SMART**) Decisions in Subsurface Applications initiative to provide a seismic forecast for a variety of end-users; the goal of the forecast is to manage an operation proactively versus reactively, one of the developers explained. They wanted to be able to produce a probabilistic forecast that would implement certain operational management strategies, in advance enabling a proactive response and the reduction of the likelihood of earthquakes. Per one of the developers interviewed, the tool was built to expand on the only commercially available tool that existed in the space, which has since been discontinued, leaving a gap in coverage.

ORION is intended to help reduce the uncertainty and estimate seismic hazards in the pre-operating period. A seismic catalog is required to produce a forecast using the tool in its current iteration. In fact, the longer the catalog of a site's seismic history and the more sensitive the array of smaller events captured, the more useful the tool will be.

Like the developers of Open-IAM, the ORION team has also been in contact with the EPA and other regulators, specifically discussing the use of the tool in the context of wastewater disposal. However, they have not discussed using the tool for the development of a UIC Class VI permit application.

Currently, the developers are pursuing other methods to estimate seismicity rates in areas with sparse and incomplete or sparse data collection networks and where catalogs are incomplete to try to accommodate predictions in the pre-operational period. While still in the research stage, they are working with other researchers largely using GPS and INSAR measurements of the deformation of active plate boundaries. They plan to add the new method to the current tool once they are confident in the results.

In addition, the developers are working on incorporating operational management suggestions into the tool. Currently, they are down-selecting to a few options to modify injection rates or allow users to upload their preferred operational management strategies. They are also working to implement a warning system that builds off their forecast of an exceedance of a certain magnitude currently produced and establishing some decision criteria for NETL and the DOE through some community workshops on the topic. Finally, they are assessing the possibility of "real-time" or near real-time analyses or analyses triggered by an event or change in seismicity rate. In addition, they are ensuring that ORION can be incorporated into service company workflows.

The NRAP team is studying the decision criteria because there are currently no guidelines on seismicity limits set forth by the EPA and different states have different guidelines. They recently met with regulators in Oklahoma and Texas to understand the current state of induced seismicity from a carbon storage project that is allowed to occur. The developer shares that after attending a workshop on induced seismicity, they believe that it is vital to set appropriate expectations about seismic events with the public. They also believe that the additions to ORION that the NRAP team is working on to ORION will help mitigate larger events.

No commercial tools are currently available to validate their results; however, academic tools are under development. Additionally, developers are also working on a joint probability distribution that describes the uncertainty in the model or the forecasts with respect to model inputs and epistemic uncertainty surrounding the model input.

Interviewees offered a walk-through of the ORION User Guide page that includes instructions for installation, examples of tabs – including the support one, and more. They also shared that the Frequently Asked Questions section of the tool offers a place for users to send in emails – the page is cached to the "share on-going issues" page shared with all visitors. The developers also encouraged interested users to email them – they have created a list of people who have downloaded the code, and they interact frequently with them.

SOSAT (Version 1)

SOSAT was developed to determine the state of stress at the site accounting for all the uncertainties and, subsequently, the pressure at which CO_2 can be safely injected. The tool also helps estimate the sheer and normal stress on a fault.

Understanding the importance of geomechanical risk and even induced seismicity, the developers have made it a priority to meet with the EPA, introduce the agency to SOSAT and ensure they are familiar with the approach, and impress upon it the importance of assessing risk appropriately, not just for the good of one site, but to ensure CCS remains a viable technology. Given that the developers work at one of the national labs supporting permit application review for the EPA, they have a unique understanding of the real-world issues project developers face as well as the kinds of data provided in UIC Class VI permit applications. Separately, the development team has used SOSAT to help write some permits. One developer states that the tool answers questions related to characterizing the state of stress required by the UIC Class VI permit application and addresses language in the UIC Class VI Regulation requiring the characterization of faults and fractures, including their stability and the state of stress. They further state that they have worked with some industry partners to use advanced outputs in some analyses for UIC Class VI permit applications to create boundary conditions on some geomechanical models.

Developers see a lot of potential in the tool for other uses as well, including using it to understand the risk of activating a fault and to help determine what sort of data would be most informative to reduce uncertainties related to the stress state. SOSAT could also serve as a tool to educate regulators, making sure that they are familiar enough with geomechanics to make an appropriate decision regarding permitting. They also believe there is merit in using the tool to validate data in permit applications generated by other modeling tools, as well as using it as a direct resource for developing an application.

Like the other NRAP tools reviewed for this research, SOSAT also has forthcoming new features and upgrades. Two new features under development address fault orientation uncertainty (should be available in fall 2024) and an analytic solution that allows the user to calculate stress change at any depth for layer cake horizontally bedded systems (should be available in fiscal year 2025). Additionally, the tool is now web-based, enabling users to perform all of the computations on the cloud, save them and even share them with other people. While that may take time, their updated GUI communicates to users that the calculation has started and will even send an email when it is complete, saving users time and frustration.

The SOSAT developers verified the tool using journal papers and textbook data to verify that their equations are being solved correctly every time something is submitted to the repository.

Developers have interacted with many users and potential users via websites and conference participation. They also advise that users can use the Submit Feedback option through the SOSAT tool, or by emailing developers or NRAP directly.

3.2 Interviews with Research Community, Academia, Industry, and Project Developers

The interviewees in this category have a wide range of experiences with the NRAP tools, ranging from no familiarity with the tools to sitting on the committee that evaluated the tools. Many of the interviewees have used the tools as part of DOE-funded studies, such as the Regional Carbon Initiatives (RCIs) or the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) projects. Some highlights of the range of experience and uses of the tools are summarized in

Table 4. In general, most interviewees in this category had at least some familiarity with the tools, with only a few interviewees indicating a lack of knowledge or use. Some of the interviewees that have some familiarity with, or use of, the tools gained their experience through government-funded research. While some assigned the use of the tools to graduate students, others used them directly. The interviewees that were very familiar with the tool had differing opinions on the use of their results. One expert indicated that they used the results in a UIC Class VI permit application. This use was not typical, however, as this was the only interviewee who indicated this. Another interviewee indicated that they have used the tools with varying success. Most interviewees that were very familiar with the tools were supportive of the program, some suggesting where they saw the tools fitting into the development of a UIC Class VI permit application and one, in particular, suggesting the desire to have some of their post doc students to determine how the NRAP tools compare to the commercial tools they currently use.

Table 4. Summary of select experiences that interviewees had with tools based on their familiarity with the tool.

Little to no Familiarity	Some Familiarity/Use	Very Familiar
-No familiarity at all with the tools -Has worked on project where they were used but has not used them themselves	-Assigned graduate students to use the tools to focus on potential leakage and risk assessment options through the NRAP tools -Used in the past (wellbore leakage model in Open IAM) to test them out -Have run them for actual project but haven't been comfortable enough in the results to use them for Class VI permit applications -Proposed using a specific module for a project in the southern US	-Helped to train regulators in a state that was granted primacy who were looking for toolsets to help evaluate things like well-leakage -Have been working with NRAP since it was formed and have tried using the tools to varying degrees of success -Served as part of the NRAP committee that evaluated the tools -Have used Open IAM the most, for leakage assessment, but have also explored SOSAT and ORION -Used the multi-segmented wellbore app the most, and the open wellbore one for specific internal studies, coupled with shallow aquifer component more with brine leakage contamination -Used the tools on industry project where the EPA requires leakage modeling -In terms of the Class VI permit application, the tools help with corrective action and mitigation plans -Wants to have post-Doctoral students run the whole suite of tools and incorporate them into a project to use as a comparison against the package of commercial tools they currently use

Utility of the NRAP Tools

Interviewees commented on the utility of the NRAP tools. Some found promise in the prospect of the tools supporting the activities of the regulators of CCS. One interviewee thought the best utility of the tools is for a regulator to use to obtain generalized results for a quick check of the elaborate reservoir simulation tools used in the industry. Another suggested encouraging states with primacy to adapt the use of these tools as part of their permit review and evaluation to expedite the compilation and the review of permits. Another stated that the Open IAM was very useful to satisfy California Air Resource Board requirements. The interviewee had legacy wellbores within the CO_2 plume path and used the tool for the risk-based component with wells in the pressure plume.

In addition to the tool users, the interviewees commented on where they thought the tools might fit into the project development and UIC Class VI applications. Comments related to this include the following:

- The tools would be best used as a screening mechanism to determine whether wells should be drilled in a location.
- One interviewee stated that they would review the tool to supplement a qualitative assessment of risk tool that is lacking, especially if it relies on more than just historic seismicity and detailed modeling.
- An interviewee used the cemented wellbore model to try to determine the AoR on a CarbonSAFE project in the Midwest.
- The tools were useful in terms of defining the AoR, even though it doesn't use the EPA defined approach for finding AoR.

- The interviewee used the tool to calculate leakage along the wellbore and impacts to drinking water aquifer and liked that it provided concentrations of brine in the USDW, which allows users to compare that to regulations and water standards.

Considerations when Using the Tools

Some users expressed concerns for using the NRAP tools, specifically to help develop a UIC Class VI permit application. Questions raised by the interviewees include if the EPA would accept the outputs and the track record of the tools compared to industry-accepted tools. In addition, some interviewees found that the learning curve to use the tool was steeper than originally anticipated.

Interviewees were reluctant to introduce additional tools into the tools and processes that they have already established, particularly if they may not be answering the specific questions being asked by the regulator. One interviewee thought that there was a mismatch between the "elegance of the thinking of the NRAP tool developer" and the regulatory mindset, which is very much focused on "what's really conservative and simple and justified and expected." Because the NRAP-Open-IAM works on the probability of leakage, some interviewees were reluctant to use it. Given the scrutiny the Class VI permit applications are getting, the interviewee expressed reluctance to introduce that level of uncertainty to their projects.

Some experts found that early iterations of the tools produced unrealistic results, making them reluctant to invest time into using the current iteration of tools. For instance, one interviewee found that, early in its inception, the DREAM tool consistently indicated the need for seismic monitoring on all projects. This interviewee was concerned that if the solution is not site specific, the monitoring approach to all projects would not be tailored to the specific needs of the site.

Finally, there was a reluctance to trust a reduced order model over the opinions of industry experts. One interviewee indicated that if the public began looking through these tools, they pull them apart and be concerned about the number of ROMs in them.

Tool Suggestions:

Many participants interviewed had ideas about the types of tools that would make their jobs easier, help make Class VI permit application development easier or more streamlined, or even provide missing pieces of information that could shed more light on the subsurface. The ideas for tool needs included the following:

- A screening level numerical model that identifies areas with the best potential for CCS on a regional or subregional level using key parameters as inputs.
- A tool on induced seismicity.
- A tool that provides context for the probabilistic findings related to legacy wellbores, such as historical benchmarking and guidance on what an increase in probability of leakage means.
- A tool that increases the efficiency of monitoring approaches.
- A modeling tool to help understand how to address risk at legacy wellbores.
- A tool that models, using history and onsite monitoring network, to ensure the system can meet regulatory seismic requirements of +2.8.
- A tool to be used to help with the transparency of the UIC Class VI risk assessment process.
- A tool to help understand what the actual flow unit thickness is before year five when the first five-year plume and five-year AoR review takes place.

- A surveillance tool that monitors legacy wells for leakage of CO_2.
- Software that collates all the inputs from various programs (PETREL, GEM) and modules within them used in monitoring in one place, freeing up subject matter experts from running each report separately.

3.3 Interviews with Regulatory Agencies

Both regulatory officials interviewed had knowledge of the NRAP tools. One interviewee remarked that they see a lot of applicability within the tools to support application development. They also felt that there was potential benefit to the regulator in having something standardized that they could use to ensure the application was providing reasonable data. While neither was able to provide information as to whether applicants had used NRAP tools to complete the Class VI permit application, they believed most applications received thus far used familiar commercial tools.

The interviewees provided some clarity regarding the Class VI permit application review process. Importantly, they stressed that it is up to the applicant to demonstrate that their project is safe. The role of the permit reviewer is to go through the evidence and use their professional judgement using other data sources and their knowledge to determine if the application is sufficient. EPA regions are not responsible for additional analyses. They can, however, request that the applicant provide additional analyses. How much the permit reviewer considers outside of the application varies from section to section; however, they do not create models to mirror what has been submitted. “It’s more like a peer review of what’s there,” one interviewee said. “A very detailed peer review, but of what’s there on the paper and in the application.” For some sections, they will rely on information from other sources. For example, when verifying the geologic conditions written in the permit, the reviewer may rely on regional geological experts and other verified sources. The interviewees also shared that all of the permits that have been granted thus far have been issued Requests for Additional Information, meaning permit reviewers required additional information to properly evaluate all permits issued thus far.

The regulatory officials did not indicate concern for projects that show leakage as one of the academia/research/industry/project developer interviewees fear they might. One of the regulatory officials said that there is an understanding that there will always be the potential for leakage, and indicated that this is the reason the permit application requires an ERR Plan.

The officials also had ideas for tools that might help their reviews:

- A tool that is used to perform the ERR Plan and determine the degree of planning needed.
- A tool that worked on a predictive basis to evaluate some of the monitoring information coming in from the well to verify the AoR ahead of the five-year review timeframe. This would help project managers and regulators to determine if there was a need to review the AoR earlier or change the current plans.
- A tool to determine risk of legacy wellbores in the AoR, particularly in the Gulf Coast with its numerous artificial penetrations.
- A tool to determine the expected integrity of the materials used in a well (e.g., casing, cement, etc.) after it is exposed to CO_2, brine, and other fluids in the subsurface environment.
- A tool to help estimate the financial responsibilities of the wells post injection.

Both interviewees stressed the importance of engagement with the U.S. EPA by Class VI permit applicants. They also expressed a desire to learn more about the NRAP tools, and to share that information with reviewers and EPA regions.

3.4 Key Findings

Similar themes were found in interviewees' suggestions to make the NRAP tools more applicable to the development of UIC Class VI permit applications or more user friendly for evaluating CCS projects. The two most popular recommendations included better promotion of the tools and enhancing usability.

Interviewees had ideas for more effective promotion of the tools. One interviewee suggested that for applicants to start using these tools and for EPA to start understanding them, more information that is easily digestible needs to be shared in spaces occupied by the intended audiences. In addition, one interviewee thought it might be beneficial to explain to possible users how to access the tools and indicate that they are open source and free to use.

Interviewees also suggested ways for two-way communication to help users troubleshoot issues when using the tools. One interviewee suggested making it easier to offer feedback by implementing a message forum online so that people using the tools can talk to each other and to the developers. This may help alleviate the concern raised by another interviewee who suggested that it is hard to get training on these tools and it's hard to find the time to tinker around with them to figure it out without guidance from the developers.

Another interviewee found that there is a tendency to promote specific tools, which can lead researchers/project developers to believe there is only one tool available. This person thought that the entire suite of NRAP tools dedicated to risk management should be promoted as a package.

Suggestions to enhance the usability of the tools are related to the format of the outputs and other standardization processes. One interviewee would find it useful if the tools followed a specific workflow that adheres closer to what is currently used in industry. Another interviewee suggested that if the tools were to be used as part of the UIC Class VI application process, that the tools could be refined to be aligned with the UIC Class VI regulations, which are all about protecting the USDW and not as focused on overall risk assessment. Another interviewee went further and suggested that improving the applicability of the tools to the UIC Class VI process can be accomplished by strictly looking from a regulatory perspective, what they are allowed to do in their review process and generally making sure that the tools that they use support them. Another interviewee considered a use beyond that of the regulator. This interviewee conceived of using the tools as part of the verification process for third-party certifying organizations that may apply standardized metrics for CCS projects nationwide.

Finally, some interviewees with more familiarity with the tools had specific suggestions for tool applicability and other issues. These are discussed for each tool below:

NRAP-Open-IAM

- The aquifer component doesn't offer users much control over the outputs or have a direction of flow for the aquifer, which results in users receiving only dimensions and not having the ability to see the plume spreading impact among other things;
- The multi-segmented wellbore model has some bugs that need to be resolved;

- The boundary conditions need to be fixed. Currently, they call for users to keep building bigger and bigger models because the farther you are from your boundary, the less impact is realized from the CO_2 plume and pressure injection. This creates unrealistic conditions and could trigger questions about the simulation model;
- Focus on the cement wellbore models as they get at the heart of the UIC regulation, which is protecting USDWs.

SOSAT:

- If the component calculating probabilistic output fault slip potential on SOSAT is meant to be a public-facing risk document, there should be some guidance on what those probabilities mean to enable users/end users to digest the change from 1% to 2% pre-project to post-project risk;
- Make the GUI more intuitive to the user; and
- Constrain some of the parameters to decrease the potential options.

DREAM

- It would be great to update DREAM to make it more compatible with a wider range of simulation outputs.

ORION:

- Setup for the ORION tool needs to be made easier and its purpose and use needs to be more defined.

All Tools:

- It would be helpful for the tool developers to check the current trend of technology and improve the data input side so that those who want to use the tools do not have to go through multiple data conversions to do so;
- Improve usability, especially for a non-modeler and/or someone not familiar with coding;
- Is there a way to get out from behind EDX? That makes accessibility a challenge.

4.0 Developing Typical Parameters of the Current Inventory of UIC Class VI Permits

4.1 Methodology

Battelle has developed a database of publicly available information from UIC Class VI permit applications that includes information related to the injection program, geophysics, geology and depositional environment, depth, and AoR Calculations (Table 5). Three conceptual models have been developed for typical CCS reservoirs (one for a carbonate, one for a sandstone, and one for data from all permit applications in order to incorporate the projects without a defined lithology) to determine the average and range of parameters that are included in the current inventory of UIC Class VI permit applications. The UIC Class VI database developed by Battelle (2024a) was used to generate information for select parameters listed in Table 5. These conceptual models show the minimum, maximum, and of the available data. In addition, the models show where the data are unavailable. This will help determine if currently publicly available data are sufficient to use the NRAP-Open-IAM and SOSAT tools in meaningful ways.

Table 5. List of relevant parameters included in the UIC Class VI database compiled by Battelle.

Category	Parameter
CO_2 and Injection Program	Project Injection Rate (MMt/yr)
	Number of Injection Wells
	Injection Rate Per Well (MMT/yr)
	Injection Duration (yr)
	Total Injection Mass (MMt)
	Maximum CO_2 Area (mi^2)
	CO2 Per Area (MMt/mi^2)
	Injection Pressure (psi)
Geophysical	Fracture Gradient (psi/ft)
	Max. Allowable Injection Pressure (psi)
Depositional Environment & Formation Names	Depositional Environment
	Geologic Basin
	Reservoir(s) Formation Names
	Caprock Formation Names
Depths Information (ft)	Caprock top (ft bgs)
	Caprock bottom (ft bgs)
	Reservoir top (ft bgs)
	Reservoir bottom (ft)
	Depth of the bottom lowermost USDW (ft)
Area of Review and Number of Injection Wells	Approximate Area of CO_2 Plume (mi^2)
	Approximate Area of Pressure Plume (mi^2)
	Number of Existing Wells in AoR that penetrate caprock
	Number of Existing Wells in CO2 Plume that penetrate the caprock
	Depth between USDW and Injection Zone (ft)

The purpose of this work was to determine if the NRAP tools can be used to evaluate the projects currently under review by following a logical sequence based on typical project conditions of the . In addition, the ability of public users to use publicly available permit information to determine risks of projects currently in the UIC Class VI permit queue was determined.

4.2 Results

4.2.1 Demonstrations with Government-Sponsored Projects

Because there is no accident data to validate the models, demonstrating the models is an effective way to show their capabilities. The NRAP team has been able to take advantage of publicly available permitting information in permits that were being developed as part of government-sponsored projects. The DOE Office of Fossil Energy and Carbon Management (FECM) encourages the use of NRAP tools in many of its funding opportunity announcements (FOAs). For instance, in DOE FECM FOA 2711 (Mod. 7) for the Bipartisan Infrastructure Law funding of the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Phase II, III, III.5, and IV, the FOA requests that applicants support NRAP by "(1) [sharing] relevant datasets, information, and technical insights from field efforts; and (2) [comparing] results from other modeling and simulation tools or methods." As a result of these requests, several DOE-sponsored studies have demonstrated the tools. These are summarized Table 6 6.

Geologic Conditions

Geologic Basin: Because many of the tools have been developed and demonstrated using the FutureGen 2.0 data and CarbonSAFE projects, the tools have been well-demonstrated in the Illinois Basin (five studies) and Gulf Coast (three studies). The tool used in most of these studies is the NRAP-Open-IAM. However, the DREAM tool is used in one of the studies in the Illinois Basin and SOSAT is used in one of the studies in the Gulf Coast. Other basins where the NRAP-Open-IAM was demonstrated include single studies in the following basins: the Central Kansas Basin (SOSAT was also demonstrated), the Patterson Oilfield (near the Central Kansas Basin), the Appalachian Basin, the Michigan Basin, the Denver-Julesburg Basin, the Williston Basin, the Powder River Basin, the Uinta Basin, the Forest City Basin, and the San Joaquin Basin.

These studies compare well to the current inventory of UIC Class VI dataset compiled by Battelle (2024a). The government-sponsored studies have demonstrated the tools in the Illinois Basin and Gulf Coast. Around 42% of the studies found were completed in these two basins. This matches well with the current inventory of permits, more than half of which are in these two basins (44 permits). Additional studies have also occurred in the Central Kansas Basin, the Patterson Oilfield, the Appalachian Basin, the Michigan Basin, the Denver-Julesburg Basin, the Williston Basin, the Powder River Basin, the Uinta Basin, the Forest City Basin, and the San Joaquin Basin. These basins have 19 permits in the current inventory compiled by Battelle (2024a), meaning that the tools have been tested in a geologic basin relevant to more than three-quarters of the permits in the queue. While the tools do not need to have been tested in the same basin or reservoir formation to be applied to a specific project, their use demonstrates that the tools are capable of modeling similar geologic.

Reservoir Formation: The tools have been demonstrated in multiple studies in both the Illinois Basin and the Gulf Coast, which are the locations of the majority of the current UIC Class VI permits. Four of the studies reviewed relied on the Mt. Simon in the Illinois Basin to store CO_2. This appears to be due to the availability of the FutureGen 2.0 data and the willingness of the leaders of CarbonSAFE projects in Illinois to work with the NRAP team. The Potosi Dolomite was the reservoir for the remaining Illinois Basin study. This is the location of the Wabash CO_2 storage project, although it is not clear if the permit applicants used results from the study to support their application. The three projects demonstrated in the Gulf Coast all had different reservoirs (one study used the Massive/Dantzler, Washita-Frederisksburg, and Paluxy; one study used the Paradis and Bayou Sorrel; and one study used the MFS9-10). Additional reservoir formations in the demonstration studies include the following:

- The Lansing and Shawnee Formations of the Central Kansas Basin;
- The Osage-Arbuckle of the Patterson Oilfield in Kansas;
- The Cambro-Ordovician Storage Complex (Rose Run, Copper Ridge, and Nolichucky sandy facies) of the Appalachian Basin;
- The St. Peter/Bass Island of the Michigan Basin;
- The Cloverly, Cedar Hills, and Cherokee of the Denver-Julesburg Basin;
- The Broom Creek of the Williston Basin;
- The Entrada and Nugget formations of the Green River Basin;
- The Minnelusa, Hulett-Canyon, Lakota, Dakota, and Mudd Formations of the Power River Basin;
- The Navajo, White Rim, Kaibab, and Redwal Formations of the Uinta Basin;
- The Osage, Viola, and Arbuckle of the Forest City Basin; and
- The Vedder, Stevens, Carneros Formations of the San Joaquin Basin.

The tools have been demonstrated in several different reservoirs, including in single reservoir scenarios and stacked scenarios. Like the current inventory of UIC Class VI permit applications compiled by Battelle (2024a), clastic reservoirs are the predominate reservoir lithology used to demonstrate the tools in the government-sponsored projects; CO_2 from 16 of the 19 studies was stored in whole or in part in sandstone reservoirs. Six of these studies feature two or more sandstone reservoirs, indicating demonstration in stacked clastic reservoirs. Three of the studies reviewed stored CO_2 exclusively in carbonate reservoirs, including one study that relied on a dolomite reservoir and two studies that relied on limestone/dolomite reservoirs. Four of the studies relied on stacked reservoirs employing both sandstone and carbonate reservoirs. Two of these studies stored CO_2 in a sandstone/dolomite stacked storage complex and the other two stored CO_2 in a sandstone/limestone stacked storage complex. The capability of the NRAP tools to model stacked storage scenarios is important because stacked storage scenarios are proposed in some of the projects currently in the UIC Class VI inventory, according to the data compiled by Battelle (2024a). This is shown in Table 8 for the five projects that reported multiple storage reservoirs.

Stratigraphic Properties: Two stratigraphic properties were also tracked for the projects reviewed: depth to top of the reservoir and depth to the bottom of the USDW. The reservoir depth ranges from 2928 ft to 10,362 ft for the 18 projects that report the depth of the reservoir. The depth to the bottom of the USDW ranges from 350 ft to 3500 for the 14 projects that report USDW depth. The separation between the bottom of the USDW and the top of the reservoir ranges from 1962 ft to 8364 ft.

Project Parameters

Project conditions were tracked for the projects reviewed, including the number of injection wells, total CO_2 injected, injection duration, and PISC duration:

- *Number of Injection Wells:* The number of injection wells ranges from one to 21 injection wells for the 17 projects that have reported the number of injection wells.

- *Total CO_2 injected:* The total CO_2 injected ranges from 50 to 540 MMt for the project duration for the 17 projects that have reported injection totals.
- *Injection Duration:* The injection duration ranges from 12 to 40 years for the 19 projects with injection duration reported.
- *PISC Duration:* The PISC duration ranges from 10 to 200 years for the 14 projects with PISC duration reported.

Table 6. Summary of the use of NRAP tools in DOE-sponsored studies.

Citation	Search Term	Project Title	Organizations	State	Tool(s) Used	Summary	Depth to top of Res. (ft)	Depth to Bottom of USDW (ft)	Geologic Basin	Reservoir	Caprock	Reservoir Lithology	No. Inj. Wells	Inj. Total (MMt)	Inj. Duration (years)	PISC Duration (years)
Bacon, 2021	2	FutureGen2	PNNL	IL	IAM	The authors describe the development of three components of the NRAP-Open-IAM using FutureGen2.0 data.	3904	1942	Illinois	Mt Simon	Eau Claire	Sandstone	4	Not Reported	20	Not Reported
Huerta et al., 2020	2, 4	CarbonSAFE Illinois	ISGS & PNNL	IL	IAM, DREAM	The authors describe screening the NRAP-Open-IAM and DREAM models for use in the Phase II CarbonSAFE Illinois (Macon County) project.	5135	3121	Illinois	Mt Simon	"Shale"[2]	Sandstone	1	50	30	30
Sarathi et al., 2021	3 (CS)	Wabash CarbonSAFE	PNNL	IN	IAM	The authors describe the use of the NRAP-Open-IAM for use in the Wabash CarbonSAFE	4363	1965	Illinois	Potosi	Maquoketa	Dolomite	2	50	30	50
Carman et al., 2018	3 (CS), 4	CarbonSAFE East Sub-Basin	Prairie Research Institute (PRI), ISGS, Uni. of Illinois	IL	IAM	The authors describe running the NRAP-Open-IAM tool on verified geologic data for the CarbonSAFE East Sub-Basin project.	7260	2746	Illinois	Mt Simon	Not Reported[2]	Sandstone	1	Not Reported	15	25
Manzoor et al., 2021	3 (CS)	CarbonSAFE Illinois	Projeo Corporation, PRI, UofI	IL	IAM	The authors describe a risk assessment, in part utilizing the NRAP-Open-IAM tool for the CarbonSAFE Illinois (Macon Co.) Phase II project.	Not Reported	Not Reported	Illinois	Mt Simon	Not Reported[2]	Sandstone	Not Reported	50	30	Not Reported
Appriou et al., 2020	3 (CS)	IMSCS-HUB CarbonSAFE	PNNL	NE, KS	IAM, SOSAT	The authors describe the application of NRAP-Open-IAM and NRAP SOSAT to two sites in the Integrated Midcontinent Stacked Carbon Storage Hub.	2928	400	Central Kansas Basin	Lansing, Shawnee	Sumner	Limestone, Sandstone	6&6	50&50	30&25	10&25
Ansari et al., 2019	3 (RCSP)		Kansas Geo Survey	KS	IAM	The authors describe the use of an early version of the NRAP-Open-IAM tool to quantify the leakage risk of CO_2 injected into the Patterson Field.	5310	Not Reported	Patterson Field	Osage-Arbuckle	Morrow-Chester Shale	Limestone-Dolomite	1	125.93	30	30
Cumming et al., 2018	NA	CAB-CS	Battelle	OH	IAM	The authors describe risk management of legacy wells in the area of review for the Central Appalachian Basin CarbonSAFE with an early version of the NRAP-Open-IAM tool.	8468, 6463	1100	Appal-achian	Rose Run, Copper Ridge, Nolichucky	Wells Creek	Sandstone/ Dolomite	1, 2 (scenarios)	50	30	80
Kelley et al., 2018	NA	CS-Michigan	Battelle	MI	IAM	The authors describe a review of leakage impacts on a saline storage site in the Northern Michigan Basin CarbonSAFE project with an early version of NRAP-Open-IAM.	10,362	1998	Michigan	St Peter/Bass Island	Black River/ Bois Blanc	Sandstone/ Dolomite	3-5	50	20-30	50
Walsh, 2020	NA	ECO2S	Uni. Of Alabama	MS	IAM	The authors focus on the developer of the NSealR tool (an early version/component of NRAP-Open-IAM), Dr. Ernest Lindner, and discuss its application to a storage complex beneath Kemper County, MS.	3396 – 5200* top of complex	Not reported	Gulf Coast	Massive/Dantzler, Washita-Frederisksburg, Paluxy	Marine and Lower Tuscaloosa Shales	Sandstone	Unknown	120-540	40	Not Reported
Wildgust et al., 2018	NA	CS Nebraska (EERC)	Uni. Of North Dakota	NE	IAM	The authors describe the NRAP-Open-IAM tool finding results that suggest no leakage risks for a Nebraska pre-feasibility study.	3254	426	Denver-Julesburg	Cloverly, Cedar Hills, Cherokee	Skull Creek Shale, Blaine & Flowerpot,	Sandstone	4	50	25	100
Peck et al., 2020	NA	CarbonSAFE North Dakota	Uni. Of North Dakota	ND	IAM	The authors, as part of a risk assessment for the North Dakota CarbonSAFE, describe the use of NRAP-Open-IAM on data derived from the candidate sites.	5014	1320	Williston	Broom Creek	Jurassic	Sandstone	2	50	25	100
Dismukes et al., 2019	NA	CarbonSAFE Louisiana Chem Corridor	Louisiana State Uni.	LA	IAM	The authors describe well leakage assessment using NRAP-Open-IAM for an industrial CCS prospect in Louisiana.	4300,7300	997	Gulf Coast	Paradis, Bayou Sorrel	Berea	Sandstone	7	130	50	150
McLaughlin et al., 2019	NA	CarbonSAFE Wyoming	Uni. Of Wyoming	WY	IAM	The authors describe open wellbore leakage risk with an early version of the NRAP-Open-IAM tool for their CarbonSAFE Phase I Prefeasibilty study at Rock Springs Uplift.	~9000, 9216	<1000	Green River	Entrada, Nugget	Sundance Fm, Gypsum Spring Fm	Sandstone	Model-Variable: 3-15	50+	25	50
Scott et al., 2021	NA	CarbonSAFE Dry Forks	Uni. Of Wyoming	WY	IAM	The authors describe the use of NRAP-Open-IAM to assist in characterizing the feasibility of the commercial CarbonSAFE Dry Forks project in WY.	8025-9546	3500	Powder River	Minnelusa; Hulett-Canyon; Lakota and Dakota, and Muddy	Goose Egg, Sundance, Mowry Shale	Sandstones	10-21	50+	25	Not Reported
McPherson et al., 2018	NA	CarbonSAFE Rocky Mountains	Uni. Of Utah	UT	IAM	The authors describe the use of NRAP-Open-IAM to assess the Area of Review for the CarbonSAFE Rocky Mountain Phase I project in central Utah.	~7200-~10000	2850	Uinta	Navajo, White Rim, Kaibab, Redwal	Carmel Fm, Moenkopiu Fm, Elephant Canyon	Sand, Sand, Lime, Lime	1-2	50	30	Up to 100
Holubnyak et al., 2018	NA	Integrated CCS for Kansas (ICKan)	Uni. Of Kansas	KS	IAM	The authors describe the use of NRAP-Open-IAM for risk assessment for the Integrated CCS for Kansas project.	5260-5740	350	Forest City	Osage, Viola, Arbuckle	Morrow Shale	Limestone, Dolomite	4	60.7	25-30	50
Meckel et al., 2018	NA	CarbonSAFE Northwest Gulf of Mexico	Uni. Of Texas-Austin	GOM	IAM, SOSAT	The authors describe that the NRAP-Open-IAM tool will be used once a candidate site has been selected for the CarbonSAFE Phase I (Pre-feasibility) Northwest Gulf of Mexico[1]	4800	None	Gulf Coast	MFS9-10	MFS9	Sandstone	9	150	12	Not Reported
Trautz et al., 2018	NA	C2SAFE	Electric Power Research Institute	CA	Unspec-ified	The authors describe that the KPP site in C2SAFE in California's Southern San Joaquin Valley has been used for tool development as by NRAP.	9000, 7000, 10000	Unconfined (Surface)	San Joaquin	Vedder, Stevens, Carneros	Shale	Sandstone	2, 7, 4	50	20-30	200 (plume modeling)

Note: 1. Report states details plans to use the NRAP tools but does not report on their use. 2. Although a specific caprock formation in not reported, it is likely the Eau Claire Formation.

4.2.2 Carbonate, Sandstone, and Combined Conceptual Models

The UIC Class VI Permit Application Database has been created as part of the Midwest Regional Carbon Initiative (MRCI) program (Battelle, 2024a). The dataset was created using publicly available data from UIC Class VI applications submitted to the U.S. EPA. Table 7 shows several factors included in UIC Class VI permit applications that are relevant for NRAP tools. These are summarized by lithology (carbonate, clastic, and all [including unknown lithology]):

Number of permits (by lithology): The permits currently in the queue are largely clastic reservoirs. Only two of the identified reservoirs are carbonates. Information about the reservoir for an additional 14 permits was either unavailable or redacted from the publicly available permit.

Injection Rates: The injection rate is one of the factors that controls the AoR, pressure buildup, and (with project duration) total amount of CO_2 stored. The injection rate is not a measure of injectivity or storativity but a planned project consideration based on the CO_2 availability, economics, or project design.

- *Carbonate:* The annual injection rates for the two carbonate reservoirs vary by more than an order of magnitude (0.15 to 1.7 million metric tonnes per year [MMt/yr]) and average to 935,000 tonnes per year.
- *Clastic:* For clastic reservoirs, the injection rates vary by 230 times (0.063 to 14.5 MMt/yr) and average to 2.94 MMt/yr. Information for five permits for clastic reservoirs was either unavailable or redacted.
- *All reservoirs:* Nine of the reservoirs with unknown lithology had reported injection rates. Considering all reservoirs, the injection rate averages 2.65 MMt/yr.

Number of Injection Wells: The number of injection wells is one of the factors that controls the pressure buildup and AoR. The average number of injection wells was rounded to the nearest whole number.

- *Carbonate:* One project in a carbonate reservoir has one injection well and the other has two injection wells.
- *Clastic:* Projects in clastic reservoirs have between 1 and 9 injection wells (average of 3 injection wells).
- *All Reservoirs:* The statistics for all reservoirs are the same as that in clastic reservoirs.

Injection Rate per well: The per well injection rate is a calculated parameter (injection rate divided by number of wells) intended to show the amount of CO_2 that will be injected in each well.

- *Carbonate:* The injection rate per well for the projects in carbonate reservoirs ranges from 0.15 to 0.8 MMt/year/well (average of 0.475 MMt/year/well).
- *Clastic:* The injection rate per well for the projects in clastic reservoirs ranges from 0.063 to 8 MMt/year/well (average of 1.1 MMt/year/well). Not enough information is available to calculate the per well injection rate for seven of the projects in clastic reservoirs.
- *All Reservoirs:* The injection rate per well for all projects ranges from 0.063 to 8 MMt/year/well (average of 1.03 MMt/year/well). Not enough information is available to calculate the per well injection rate for 14 of the projects in all reservoir types.

Injection Duration: The injection duration is one of the factors (along with injection rate) that controls the total amount of CO_2 injected during the project.

- *Carbonate:* Both projects in carbonate reservoirs will inject for 12 years.
- *Clastic:* The injection duration of the projects in clastic reservoirs ranges from 2 to 40 years (average of 20 years). Injection duration is not reported for 17 of the projects in clastic reservoirs.
- *All Reservoirs:* The statistics for all reservoirs are the same as that in clastic reservoirs. Injection duration is not reported for 27 of the projects in all reservoirs.

Injection Total: The injection total is controlled by the injection rate and duration. This factor controls the AoR and pressure buildup.

- *Carbonate:* One project in a carbonate reservoir will inject a total of 1.8 MMt and the other will inject 20 MMt (average of 10.9 MMt).
- *Clastic:* The total amount of CO_2 injected by the projects in clastic reservoirs ranges from 0.126 to 290 MMt (average of 53.2 MMt). Injection totals are not reported for seven of the projects in clastic reservoirs.
- *All Reservoirs:* The total amount of CO_2 injected by the projects in all reservoirs ranges from 0.126 to 290 MMt (average of 51.3 MMt). Injection totals are not reported for 16 of the projects in all reservoirs.

Maximum CO_2 coverage area: The maximum CO_2 concentration area is a measure of the area of land that the CO_2 underlies. This factor controls the number natural and artificial penetrations the CO_2 intersects with, the selected monitoring approach, and the receptors in case of a CO_2 leak. This value is often not the same as the AoR, which is a measure of the critical pressure (i.e., the buildup of pressure required to lift CO_2 through a column to the lowermost underground source of drinking water [USDW]). However, this is the area most pertinent for CO_2 leaks from the reservoir.

- *Carbonate:* Only one of the two projects in carbonate reservoirs has a reported CO_2 coverage area (22 mi^2).
- *Clastic:* The CO_2 coverage area in the projects in clastic reservoirs ranges from 0.077 to 33 mi^2 (average of 11.3 mi^2). CO_2 coverage areas are not available for 38 of the projects in clastic reservoirs.
- *All Reservoirs:* The CO_2 coverage area in the projects in all reservoirs ranges from 0.077 to 33 mi^2 (average of 11.6 mi^2). CO_2 coverage areas are not available for 53 of the projects in all reservoirs.

Reservoir top depth: The true vertical depth of the top of the reservoir controls the distance between the reservoir and the lowermost USDW. This, in turn, controls the critical pressure. Reservoir depth is also an important factor in determining if the NRAP-Open-IAM is a viable tool for evaluation (see Section 5.1).

- *Carbonate:* One carbonate reservoir has a depth of 3429 feet below ground surface (bgs) while the other has a depth of 4473 ft bgs (average of 3951 ft bgs).
- *Clastic:* The depth of clastic reservoirs ranges from 2325 to 13,719 ft bgs (average of 6413 ft bgs). Reservoir depths are not available for 23 of the projects in clastic reservoirs.

- *All Reservoirs:* The depth of all reservoirs ranges from 2325 to 13,719 ft bgs (average of 6304 ft bgs). Reservoir depths are not available for 37 of the projects in clastic reservoirs.

Base of USDW depth: Like reservoir depth, the true vertical depth of the top of the lowermost USDW controls the distance between the reservoir and the lowermost USDW. This, in turn, controls the critical pressure. Depth of the lowermost USDW is also an important factor in determining if the NRAP-Open-IAM is a viable tool for evaluation (see Section 5.1).

- *Carbonate:* The bottom of the lowermost USDW is known only for one of the projects in carbonate reservoirs (495 ft bgs).
- *Clastic:* The bottom of the lowermost USDW in the projects in clastic reservoirs ranges from 250 to 12,958 ft bgs (average of 2060 ft bgs). The base of the USDW is not known for 28 of the projects in clastic reservoirs.
- *All Reservoirs:* The bottom of the lowermost USDW in the projects in clastic reservoirs ranges from 250 to 12,958 ft bgs (average of 2045 ft bgs). The base of the USDW is not known for 41 of the projects in clastic reservoirs.

Distance between base of USDW and top of reservoir: The distance between the base of the USDW and the top of the reservoir is an important factor in determining the critical pressure and the protectiveness of the proposed project.

- *Carbonate:* The distance between the top of the reservoir and the bottom of the lowermost USDW can be calculated for only one of the projects in carbonate reservoirs (2900 ft).
- *Clastic:* The distance between the top of the reservoir and the bottom of the lowermost USDW ranges from 761 ft to 8380 (average of 3606 ft). The distance between the top of the reservoir and the base of the USDW is not known for 28 of the projects in clastic reservoirs.
- *All Reservoirs:* The distance between the top of the reservoir and the bottom of the lowermost USDW ranges from 761 ft to 8380 (average of 3582 ft). The distance between the top of the reservoir and the base of the USDW is not known for 41 of the projects in clastic reservoirs.

Caprock thickness: The thickness of the caprock is a measure of the protectiveness of the project design. If all other factors are held constant (e.g., caprock permeability, number of penetrations, etc.), a thicker caprock is considered more protective in this study.

- *Carbonate:* Caprock thickness is 163 ft for one project and 314 ft for the other (average of 239 ft).
- *Clastic:* The thickness of the caprock for projects in clastic reservoirs ranges from 103 ft to 3400 (average of 535 ft). The thickness of the caprock is not known for 25 of the projects in clastic reservoirs.
- *All Reservoirs:* The thickness of the caprock for projects in all reservoirs ranges from 103 ft to 3400 (average of 521 ft). The thickness of the caprock is not known for 39 of the projects in all reservoirs.

Injection pressure: The injection pressure is the expected bottomhole pressure required to inject CO_2.

- *Carbonate:* The injection pressure is known for only one of the projects in a carbonate reservoir (1960 psi).

- *Clastic:* The injection pressure for projects in clastic reservoirs ranges from 1903 to 7448 psi (average of 3495 psi). The injection pressure is unknown for 39 projects in clastic reservoirs.
- *All Reservoirs:* The injection pressure for projects in all reservoirs ranges from 1903 to 7448 psi (average of 3440 psi). The injection pressure is unknown for 54 projects in all reservoirs.

Fracture gradient: The fracture gradient is a depth-dependent measure of the pressure required to fracture the formation. It is an important consideration of the maximum allowable injection pressure.

- *Carbonate:* The fracture gradient is known for only one project in a carbonate reservoir (0.71 psi/ft).
- *Clastic:* The facture gradient for projects in clastic reservoirs ranges from 0.53 to 0.82 psi/ft (average of 0.697 psi/ft). The fracture gradient is unknown in 26 projects in clastic reservoirs.
- *All Reservoirs:* The facture gradient for projects in all reservoirs ranges from 0.53 to 0.82 psi/ft (average of 0.698 psi/ft). The fracture gradient is unknown in 41 projects in all reservoirs.

Maximum allowable injection pressure (MAIP): The MAIP cannot be exceeded by the project. When the MAIP was not reported in the application but the fracture gradient and depth of the top of the reservoir were, the MAIP was calculated assuming 90% of the fracture pressure.

- *Carbonate:* The MAIP is known for only one of the projects in carbonate reservoirs (2206 psi).
- *Clastic:* The MAIP for projects in clastic reservoirs ranges from 2343 to 7800 psi (average of 4326 psi). The MAIP is unknown for 27 of the projects in clastic reservoirs.
- *All Reservoirs:* The MAIP for projects in all reservoirs ranges from 2206 to 7800 psi (average of 4272 psi). The MAIP is unknown for 43 projects in all reservoirs.

Porosity: The porosity of the reservoir controls the volume of space for storage within a given area and, thus, maximum CO_2 coverage area.

- *Carbonate:* The porosity is unknown for both carbonate reservoirs.
- *Clastic:* The porosity for clastic reservoirs ranges from 0.06 to 0.33 (average of 0.209). Reservoir porosity is unknown for 20 projects in clastic reservoirs.
- *All Reservoirs:* The statistics for all reservoirs are the same as that in clastic reservoirs. Porosity is unknown for 36 projects in all reservoirs.

Permeability: The permeability of the reservoir controls the ease with which CO_2 can be injected into the reservoir. The permeability controls the pressure buildup in the reservoir and the number of wells required to inject the volume of CO_2.

- *Carbonate:* The reservoir permeability is known for only one of the projects in carbonate reservoirs (2400 mD).
- *Clastic:* The reservoir permeability in clastic reservoirs ranges from 6 to 1800 mD (average of 298 mD). Reservoir permeability is unknown for 21 projects in clastic reservoirs.
- *All Reservoirs:* The reservoir permeability in all reservoirs ranges from 6 to 2400 mD (average of 344 mD). Reservoir permeability is unknown for 36 projects in all reservoirs.

Table 7. Minimum, maximum, and average values for pertinent parameters in the UIC Class VI Permit Application Dataset (Battelle, 2024a).

Factor	Carbonate				Clastic				All (inc. unknown lithology)			
	Avg.	Min.	Max.	ND	Avg.	Min.	Max.	ND	Avg.	Min.	Max.	ND
No. Permits		2		NA		66		NA		82		NA
Injection Rate (MMt/yr)	0.935	0.15	1.7	0	2.94	0.063	14.5	5	2.65	0.063	14.5	10
No. Injection Wells	2	1	2	0	3	1	9	0	3	1	9	0
Injection rate per well (MMt/yr/well)	0.475	0.15	0.8	0	1.1	0.063	8	7	1.03	0.063	8	14
Injection duration (years)	12	12	12	0	20	2	40	17	20	2	40	27
Injection total (MMt)	10.9	1.8	20	0	53.2	0.126	290	7	51.3	0.126	290	16
Max. CO_2 coverage area (mi^2)	22	-	-	1	11.3	0.077	33	38	11.6	0.077	33	53
Reservoir top depth (ft)	3951	3429	4473	0	6413	2325	13,719	23	6304	2325	13,719	37
Base of USDW depth (ft)	495	-	-	1	2060	250	12,958	28	2045	250	12,958	41
Distance between base of USDW and top of reservoir (ft)[1]	2900	-	-	1	3606	761	8380	27	3582	761	8380	41
Caprock thickness (ft)	239	163	314	0	535	103	3400	25	521	103	3400	39
Injection Pressure (psi)	1960	-	-	1	3495	1903	7448	39	3440	1903	7448	54
Fracture Gradient (psi/ft)	0.71	-	-	1	0.697	0.53	0.82	26	0.698	0.53	0.82	41
Max. Allowable Injection Pressure (psi)	2206	-	-	1	4326	2343	7800	27	4272	2206	7800	43
Reservoir Porosity (%)	NA	NA	NA	2	0.209	0.060	0.330	20	0.209	0.060	0.330	36
Reservoir Permeability (mD)[2]	2400	-	-	1	298	6	1800	21	344	6	2400	36
Caprock porosity	NA	NA	NA	2	0.093	0.02	0.293	32	0.093	0.02	0.293	46
Caprock permeability	NA	NA	NA	2								
Caprock depth (ft)	NA	NA	NA	2								
No. Wells in AoR that penetrate the caprock	0	-	-	1	65	0	1219	29	62	0	1219	43

ND: Number of permits without this data due to it not being included in the current documentation or it being redacted from the publicly available documentation.

1. Three values were reported as >1000 ft, >2000 ft, and >3000 ft, which assumed to be 1000 ft, 2000 ft, and 3000 ft, respectively.

2. Two values were reported as >100 mD, which were assumed to be 100 mD.

Number of wells in AoR that penetrate the caprock: This is the measure of the number of wells within the critical pressure area that penetrate the storage complex. This is an important factor in determining the applicability of certain modules of the NRAP-Open-IAM.

- *Carbonate:* The number of existing wells that penetrate the caprock within the AoR is known for only one of the projects in carbonate reservoirs (0 wells).
- *Clastic:* The number of existing wells that penetrate the caprock within the AoR in projects in clastic reservoirs ranges from 0 to 1219 well (average of 65 wells). This factor is unknown for 29 projects in clastic reservoirs.
- *All Reservoirs:* The number of existing wells that penetrate the caprock within the AoR in projects in all reservoirs ranges from 0 to 1219 wells (average of 62 wells). This factor is unknown for 43 projects in all reservoirs.

Additional Context for the Conceptual Models:

Details providing additional context for the conceptual models are shown in Table 8. Just under 40% of all permits have viewable CO_2 coverage maps, including one of the two permits in carbonate reservoirs and 44% of the permits in clastic reservoirs. These maps place the plume in context of the surface features that overlie the storage complex, a particularly important component in putting potential leakage into context.

Table 8. The number of UIC Class VI permit applications with publicly viewable CO_2 coverage maps and number of permits by Basin, Depositional Environment, and Reservoir and Caprock formations.

Factor	Carbonate		Clastic		Unknown	
Application has a publicly viewable CO_2 Coverage Map	Yes	1	Yes	29	Yes	2
	No/Info not found	1	No/Info not found	37	No/Info not found	12
Basin	-		-		Appalachian	1
	-		Black Warrior	1	-	
	Central Kansas	1	-		-	
	-		Denver-Julesburg	1	Denver-Julesburg	2
	-		Fossil Basin	1	-	
	-		Greater Green River	1	-	
	-		Gulf Coast	28	Gulf Coast	7
	Illinois	1	Illinois	8	-	
	-		Midcontinent Arches Province	2	-	
	-		Mississippi Interior Salt	1	-	
	-		Palo Duro	1	-	
	-		-		Permian	2
	-		Sacramento	7	-	
	-		San Joaquin	6	-	
	-		San Juan	1	-	
	-		-		Sarasota Bay-Peace Myakka	1
	-		-		State of Kansas	1
	-		Williston	8	-	
Depositional Environment[1]	Marine	2	Marine	7		
	-		Eolian	3		
	-		Eolian/nearshore marine	8		
	-		Deltaic	6		
	-		Fluvial	6		
	-		Fluvial/deltaic	10		
	-		Fluvial/eolian/marine tidal	10		
	-		Fluvial/shoreline/marine fan	7		
	-		Not indicated/redacted	10	Not indicated/redacted	14
Reservoir Formation	-		64 Zone SS	1	-	
	-		Anderson SS	1	-	
	Arbuckle Fm	1	-		-	
	-		Black Island-Deaswood E mbr	1	-	
	-		Broom Creek Fm	7	-	
	-		Entrada SS	1	-	
	-		Frio Fm	7	-	
	-		Frio, Wilcox, L. Tuscaloosa	1	-	
	-		Granite Wash Fm	1	-	
	-		Hosston Fm, Cotton Valley Gp	2	-	
	-		Lyons Fm	1	-	
	-		Miocene SS	6	-	
	-		Mokelumne River	1	-	
	-		Monterey	2	-	
	-		Mt. Simon SS	10	-	
	-		Nugget Fm	2	-	
	-		Oakville Fm	1	-	
	-		Paluxy Fm	4	-	
	-		Panoche	1	-	
	Potosi Dol	1	-		-	
	-		Sparta Fm	1	-	
	-		Sparta, Wilcox	1	-	
	-		Starkey Fm	1	-	
	-		U. Tuscaloosa, Paluxy	1	-	
	-		Vedder	2	-	
	-		Wilcox	2	-	
	-		Winters	3	-	
	-		Not indicated/redacted	6	Not indicated/redacted	14

Table 8 (continued). The number of Class VI permit applications with publicly viewable CO_2 coverage maps and number of permits by Basin, Depositional Environment, and Reservoir and Caprock formations.

Factor	Carbonate		Clastic		Unknown	
Caprock Formation	-		Amph B Sh	1	-	
	-		Anahuac Sh/L Miocene	1	-	
	-		Anahuac Sh	5	-	
	-		Burkeville	1	-	
	-		Cane River Sh	2	-	
	-		Capay Sh	2	-	
	-		Chugwater/Goose Egg Fm	1	-	
	-		Cook Mountain Fm	1	-	
	-		Eau Claire Fm	10	-	
	-		Freeman-Jewett Fm	2	-	
	-		Icebox Fm	1	-	
	-		Lagarto Fm	1	-	
	Marmaton/Arbucle Gp	1	-		-	
	Maquoketa Gp	1	-		-	
	-		Midway Sh	1	-	
	-		Moreno Sh	1	-	
	-		Nortonville/Capay/Meganos Sh	1	-	
	-		Oakville Fm	1	-	
	-		Opeche Fm	2	-	
	-		Opeche/Spearfish Fms	3	-	
	-		Opeche-Picard Fm	1	-	
	-		Pine Island/Sligo/U. Hosston	1	-	
	-		Piper/Spearfish Fm	1	-	
	-		Reef Ridge Sh	2	-	
	-		Santos Sh	1	-	
	-		Sawtooth Fm	1	-	
	-		Shelf carbonates	1	-	
	-		Sligo/Pine Island/Rodessa	1	-	
	-		Todilto Mbr	1	-	
	-		Tuscaloosa Fm	1	-	
	-		Twin Creek	2	-	
	-		Washita-Fredericksburg	3	-	
	-		Not indicated/redacted	13	Not indicated/redacted	14

Notes: 1. Depositional environment not included in Table 6. Included as part of government sponsored study summarized in Table 6.

Geologic Conditions: Additional factors used to place the conceptual models into context include the geologic basin, depositional environment, reservoir formation, and caprock formation (Table 8). The Gulf Coast has the most applications in the current inventory (35 applications or around 42% of all applications). The Gulf Coast along with the Illinois Basin (nine applications), Williston Basin (eight applications), as well as the Sacramento (seven applications), and San Joaquin Basin (six applications) account for more than three-quarters of all current UIC Class VI permit applications. Government-sponsored projects have demonstrated the NRAP-Open-IAM in these basins, with the exception of the Sacramento Basin. Additional government-sponsored projects have been demonstrated in the Appalachian (one application), Black Warrior (one application), Central Kansas (one application), and Denver-Julesburg (two applications). Only 14 of the current UIC Class VI permit applications are in basins that have no demonstration projects in the reviewed demonstration projects.

Of the 59 UIC Class VI permit applications with known reservoir rock depositional environments, a slight majority of permits report a depositional environment that is fluvial, deltaic, fluvial/deltaic, or fluvial/shoreline/marine fan (29 permits). Eolian or eolian/near-shore marine depositional environments comprise 11 of the remaining permits. Marine environments comprise nine of the remaining permits, including both carbonate depositional environments. The remaining 10 permits report a combination of fluvial, eolian, and marine tidal environments, indicating a complex storage system.

The NRAP-Open-IAM has been demonstrated in several relevant sandstone reservoir formations across the country, including the Mt. Simon Sandstone (10 permits), the Broom

Creek Formation (seven permits), the Miocene Sandstone (six permits), and the Paluxy Formation (4 permits). In addition, the model is also demonstrated in the Nugget Formation (two permits), the Vedder Formation (two permits), the Entrada Formation (one permit), and the Upper Tuscaloosa (one permit). The model has also been demonstrated in both carbonate reservoirs that have current UIC Class IV permits: the Arbuckle Formation and the Potosi Dolomite. To a lesser extent, some caprock formations in the current inventory of UIC Class VI permit applications have also been a part of the NRAP-Open-IAM model demonstrations: the Eau Claire Formation (10 permits), the Washita-Fredericksburg (three permits), the Maquoketa Group (one permit), and the Tuscaloosa Formation (one permit).

Project Conditions: Project conditions, like total mass injected, number of injection wells, injection duration, and reservoir and USDW depths, have also been tracked for government-sponsored projects that have demonstrated the use of the NRAP tools.

- The number of injection wells is within range of the government-sponsored demonstrations for all 82 projects currently in the UIC Class VI permit applications dataset compiled by Battelle (2024a).
- The total mass of CO_2 injected is lower than the government-sponsored demonstrations for 46 of the 66 projects with total mass of CO_2 injected reported in the UIC Class VI permit applications dataset compiled by Battelle (2024a).
- The injection duration is within the government-sponsored demonstrations for 51 of the 55 projects with injection duration reported in the UIC Class VI permit applications dataset compiled by Battelle (2024a).
- The PISC duration is within the government-sponsored demonstrations for 51 of the 55 projects with injection duration reported in the UIC Class VI permit applications dataset compiled by Battelle (2024a).
- The reservoir depth is within the government-sponsored demonstrations for 41 of the 45 projects with reservoir depth reported in the UIC Class VI permit applications dataset compiled by Battelle (2024a).
- The USDW depth is within the government-sponsored demonstration for 38 of the 41 projects with USDW depth reported in the UIC Class VI dataset permit applications compiled by Battelle (2024a).

5.0 Comparing the Inventory of UIC Class VI Projects to the Stated NRAP Tool Descriptions

Two NRAP tools were selected for this analysis: the NRAP-Open-IAM and SOSAT. The project selected the NRAP-Open-IAM for further evaluation because of its ability to meet several components of the UIC Class VI permit applications, including AoR calculation and corrective action, informing testing and monitoring approaches, determining post-injection site care periods and site closure timing, and informing the ERR Plan among other things (Lackey et al., 2022a). The SOSAT was identified as the second tool for evaluation because it addresses a key factor in site safety (induced seismicity) for regions where this may be a concern and does not rely on a historic seismic catalog like the ORION tool. The DREAM tool was also considered but was not selected because it will soon be replaced by the forthcoming Risk-Based Adaptive Monitoring Program (RAMP) tool.

5.1 NRAP Open-source Integrated Assessment Model (NRAP-Open-IAM)

NRAP-Open-IAM is designed to assess the behavior and associated risks of carbon storage projects. The tool is equipped with a variety of components which address containment risks and leakage impacts associated with CO_2 injection. The tool is used by constructing a system model through coupling of various components which describe different elements of the system – stratigraphy, reservoir properties and conditions, leakage pathways and/or impacted system components. The exact model construction depends on the specific risk being assessed. A robust discussion is included in the NRAP-Open-IAM user manual (Vasylkivska, 2022).

Figure 1 shows a schematic of the general coupling process from the user manual. First, a stratigraphic model is initialized, defining the formation depths, thicknesses and relevant geologic parameters within the system. This information would likely be compiled in a regional geologic assessment of the project site. A reservoir component is added to this stratigraphy model which contains reservoir parameters as well as time-dependent pressures and saturations associated with CO_2 injection. Typically, these values would be provided by the associated reservoir model prepared for UIC Class VI permit submission. The leakage components (i.e., legacy wellbores, faults) are then added to the model along with, if relevant, aquifer components to assess leakage impacts. The intercommunication of these various components allows for customization of the system model to project-specific needs.

A total of 24 different components in NRAP-Open-IAM can be initialized for a given problem. Of these, six are stratigraphy or reservoir components, with the rest being focused on leakage pathways or impact models. For the purposes of this analysis, focus has been placed on the components deemed most applicable to a typical UIC Class VI permit applications. Many of the omitted components were constructed for a specific purpose or project (e.g., the FutureGen2 aquifer and above zone monitoring interval components) while others address factors not typically seen in existing UIC Class VI permit applications (e.g., the hydrocarbon leakage component). The components analyzed for this study fit into one of four categories: (1) reservoir components, (2) wellbore components, (3) aquifer components, or (4) other components. Relevant data from stratigraphy components are discussed as part of the other four component types. For a complete list of NRAP-Open-IAM components, see Vasylkivska (2022).

Components were evaluated by analyzing the input parameters, which were identified as ‘necessary’ or ‘preferred’ based on their relative importance (determined using best professional judgment) to obtain reasonable results for a given project. For example, in the cemented wellbore component, the absence of a necessary input such as reservoir pressure or legacy well location(s) would not allow a user to calculate risk associated with a particular injection plan; on the other hand, wellbore cement permeability is typically unknown, but risk assessment could still be done on a plugged legacy wellbore using this tool with some uncertainty.

Reservoir Components: This analysis considers two of the reservoir components of the NRAP-Open-IAM: (1) analytical reservoir component and (2) lookup table reservoir component. An NRAP user that has access to a static earth model (SEM) and full physics dynamic reservoir model (DRM) would use the lookup table reservoir to convert their model outputs into usable input files with the NRAP-Open-IAM. A user without access to these models, however, could use the analytical reservoir component to approximate a CO_2 saturation plume and pressure plume using key site-specific parameters. The reservoir components are not included in the decision tree analysis in Section 6.0, but are briefly described below because of their importance in establishing the required CO_2 saturation and pressure data for the other NRAP-Open-IAM components.

The analytical reservoir component allows for the semi-analytical calculation of CO_2 mass or concentration and reservoir pressure after defining reservoir parameters such as permeability; porosity; radius (i.e., size of reservoir); brine density viscosity, saturation, and compressibility; injection parameters like injection rate and CO_2 density and viscosity (Table 9). This would need to be linked to the stratigraphy component, which requires knowledge of aquifer, shale, and reservoir thickness as well as preferred parameters like the number of shale layers; and the initial pressure at the top of the system.

The lookup table reservoir component functions using ROMs generated from full physics DRMs to input time-dependent CO_2 saturation and reservoir pressure. The model currently has examples from the FutureGen 2.0 project and Kimberlina Reservoir that can be used to format additional full physics reservoir models.

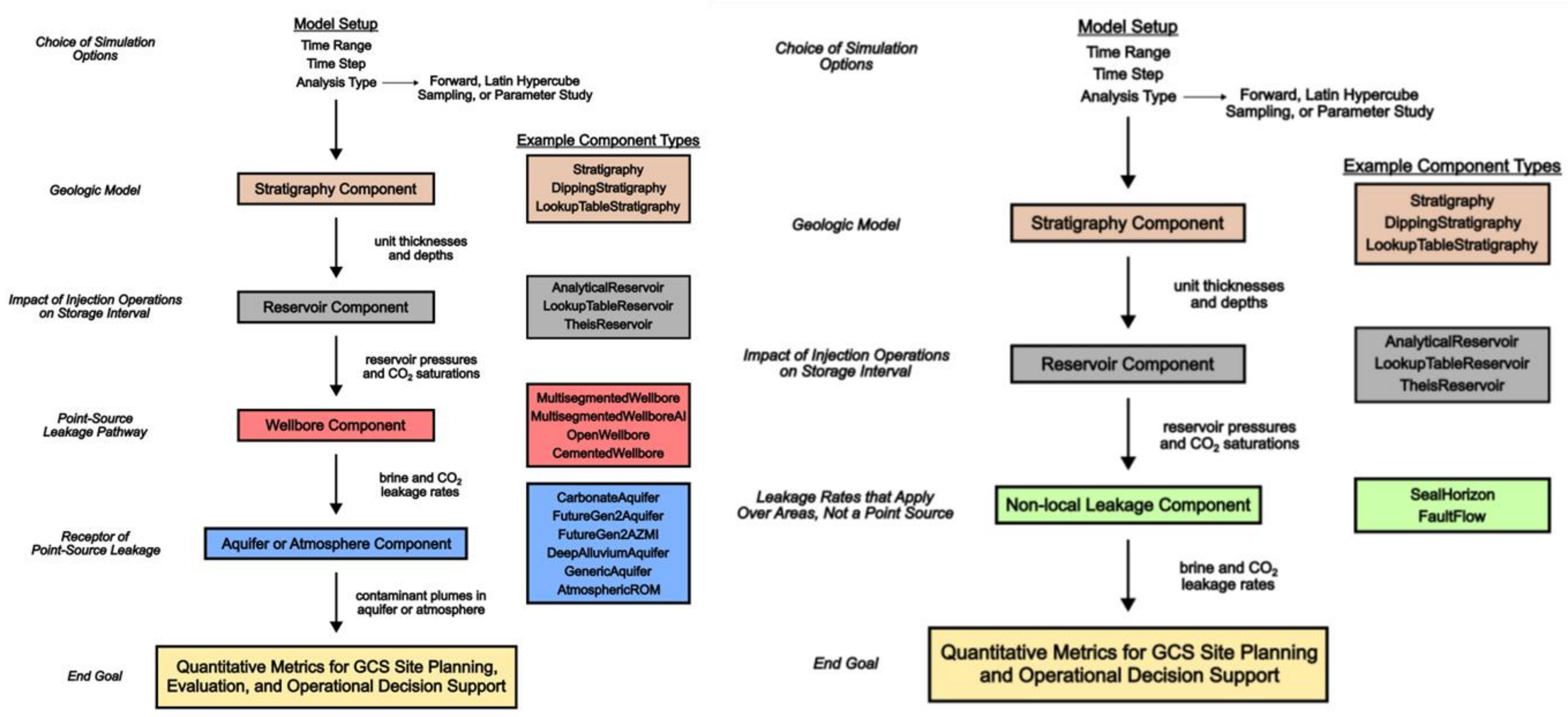


Figure 1. Schematic of the model building process within NRAP-Open-IAM for wellbore leakage and associated impacts (left) and alternative leakage pathways (right). Figures from Vasylkivska (2022).

Table 9. List of input parameters for NRAP-Open-IAM Analytical Reservoir Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Reservoir Permeability	Necessary	Log m^2	-15.3	-12
		mD	0.5	1000
Reservoir Porosity	Necessary	-	0.1	0.3
Injection Rate	Necessary	m^3/s	0.0024	3.776
		MMt/yr[a]	0.06	92.9
Reservoir Thickness	Necessary	m	15	500
		ft	50	1640
Shale Thickness	Necessary	m	1	1600
		ft	3	5250
Aquifer Thickness	Necessary	m	1	1600
		ft	3	5250
Number of Shale Layers	Necessary	-	3	30
Datum Pressure	Preferred	Pa	80,000	300,000
		psi	11.6	43.5
Reservoir Radius	Preferred	m	500	100,000
		mi	0.3	62.1
Brine Density	Preferred	kg/m^3	965	1195
CO_2 Density	Preferred	kg/m^3	450	976
Brine Viscosity	Preferred	Pa*s	2.3e-4	1.59e-3
CO_2 Viscosity	Preferred	Pa*s	4.55e-7	1.043e-4
Brine Reservoir Saturation	Preferred	-	0	0.25
Brine Compressibility	Preferred	Pa^{-1}	3.63e-12	2.31e-11

Notes: a. CO_2 injection rate was converted from m3/s to million metric tonnes per year (MMt/yr), assuming a reservoir density of CO_2 of 778 kg/m^3, which would be expected at a reservoir temperature of 110ºF and a pressure of 2400 psi (equivalent to a reservoir that is 5500 ft deep assuming a temperature gradient of 1ºF/100 ft + 55ºF [ambient] and a pressure gradient of 0.43 psi/ft +14.7 psi [ambient]). Density calculations were found using The National Institute of Standards and Technology Chemistry WebBook, SRD 69 Isothermal Properties (nist.gov).

Wellbore Components: This study assessed the cemented wellbore, multisegmented wellbore, and open wellbore components. The cemented wellbore component analyzes risk at a legacy wellbore that has been cemented from its intersection point with the storage formation all the way to the surface. The multisegmented wellbore component allows for different sections of the wellbore to have differing cement presence and quality while also allowing for leakage into multiple overlying aquifers. The open wellbore assumes complete absence of cement and/or casing within the borehole. More details can be found in Vasylkivska (2022).

Each of these components has specific input parameters shown in Table 10 (cemented wellbore),

Table 11 (multisegmented wellbore), and Table 12 (open wellbore). The ranges of values these input parameters can accept are also included in the tables.

Table 10. List of input parameters for NRAP-Open-IAM Cemented Wellbore Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Wellbore Radius	Necessary	m	0.025	0.25
		in	1	10
Pressure (time-dependent)	Necessary	Pa	1.00E+05	5.00E+07
CO_2 Saturation (time-dependent)	Necessary	-	1.00E-03	1
Well Depth	Necessary	m	960	3196.8
		ft	3150	10,488
Cement Permeability	Preferred	m^2	1.12E-14	7.94E-11
		mD	11.3	80,500
Thief Zone Permeability	Preferred	m^2	1.00E-14	1.00E-12
		mD	10.1	1010
Thief Zone Depth Fraction	Preferred	-	0.3	0.7

Table 11. List of input parameters for NRAP-Open-IAM Multisegmented Wellbore Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Aquifer Permeability	Necessary	m^2	1.00E-17	1.00E-09
		mD	0.0101	1,013,000
Brine Density	Necessary	kg/m^3	900	1500
Wellbore Radius	Necessary	m	0.01	0.5
		in	0.4	20
Number of Shale Layers	Necessary	-	3	30
Shale Thickness	Necessary	m	1	3000
		ft	3	9800
Aquifer Thickness	Necessary	m	1	1600
		ft	3	5250
Reservoir Thickness	Necessary	m	1	1600
		ft	3	5250
Reservoir Pressure (time-dependent)	Necessary	Pa	-	-
CO_2 Saturation (time-dependent)	Necessary	-	0	1
Cement Permeability	Preferred	m^2	1.00E-101	1.00E-09
Brine Viscosity	Preferred	Pa*s	1.00E-04	5.00E-03
CO2 Density	Preferred	kg/m^3	100	1000
CO2 Viscosity	Preferred	Pa*s	1.00E-06	1.00E-04
Aquifer Residual Water Saturation	Preferred	-	0	0.99
Fluid Compressibility	Preferred	Pa^{-1}	1.00E-13	1.00E-08

Table 12. List of input parameters for NRAP-Open-IAM Open Wellbore Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Reservoir Transmissivity	Necessary	m^3	5.37E-12	3.98E-09
Aquifer Transmissivity	Necessary	m^3	5.37E-12	3.98E-09
Brine Density	Necessary	kg/m^3	900	1200
Wellbore Radius	Necessary	m	0.025	0.25
		in	1	10
Top of Open Section	Necessary	m	0	500
		ft	0	1600
Reservoir Depth	Necessary	m	1000	4000
		ft	3300	13,100
Brine Salinity	Preferred	mass fraction	0	0.2
Critical Reservoir Pressure	Preferred	Pa	1.00E+05	9.00E+07

Aquifer Components: This study assessed the carbonate aquifer, deep alluvium aquifer and generic aquifer components. The carbonate aquifer component is intended to assess TDS and pH impacts in a shallow, heterogeneous carbonate aquifer (e.g., Last et al., 2016). The deep alluvium aquifer model is based off of the aquifer present at the Kimberlina storage project, but it can be adapted to other projects with alluvium aquifers. The generic aquifer component makes no assumptions on the properties of the aquifer in question, modeling a homogeneous cylindrical system with properties provided by the user. More details can be found in Vasylkivska (2022).

The input parameters for these components are listed in

Table 13 (carbonate aquifer), Table 14 (deep alluvium aquifer), and Table 15 (generic aquifer). Parameters are identified as ‘necessary’ or ‘preferred’ based on their relative importance to obtaining reasonable results for a given project. The ranges of values these input parameters can accept are also included in the tables.

Table 13. List of input parameters for NRAP-Open-IAM Carbonate Aquifer Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Mean Permeability	Necessary	m^2	1.58E-14	5.01E-11
		mD	16.0	50,800
Permeability Anisotropy (k_h/k_v)	Necessary	-	1.1	49.1
Brine Salinity	Necessary	molality	1.26	1.06E+06
Aquifer Thickness	Necessary	m	100	500
		ft	330	1600
Brine Leakage Rate[a]	Necessary	kg/s	0	0.075
CO_2 Leakage Rate[a]	Necessary	kg/s	0	0.5
Permeability Variance	Preferred	m^4	1.04	77.6
Horizontal Hydraulic Gradient	Preferred	-	2.88E-04	1.89E-02
Calcite Surface Area	Preferred	m^2/g	0	0.01
Organic Carbon Volume Fraction	Preferred	-	0	0.01
Brine Organic Compound Constituents (Benzene, Naphthalene, Phenol)	Preferred	-	see OpenIAM User Guide	see OpenIAM User Guide

Notes: a. Can be calculated from other OpenIAM components

Table 14. List of input parameters for NRAP-Open-IAM Deep Alluvium Aquifer Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Brine Leakage Rate[a]	Necessary	kg/s	0	0.017
CO_2 Leakage Rate[a]	Necessary	kg/s	0	0.385
Permeability of Sand Units	Necessary	m^2	2.00E-13	2.00E-11
		ft	203	20,300
Caprock Permeability	Necessary	m^2	2.00E-17	2.00E-15
		mD	0.02	2.0
Leak Depth	Necessary	m	424.36	1341.48
		ft	1392.3	4401.2
Sand Fraction	Preferred	-	0.7	0.9
Groundwater Gradient	Preferred	-	1.00E-03	1.67E-03

Notes: a. Can be calculated from other OpenIAM components

Table 15. List of input parameters for NRAP-Open-IAM Generic Aquifer Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Aquifer Thickness	Necessary	m	25	250
		ft	82	820
Aquifer Depth	Necessary	m	100	4100
		ft	330	13,500
Porosity	Necessary	-	0.02	0.25
Horizontal Permeability (k_h)	Necessary	m^2	1.00E-14	1.00E-10
		mD	10.1	101,000
Permeability Anisotropy (k_h/k_v)	Necessary	-	0	3
Leaked Brine Salinity	Necessary	mass fraction	0.015	0.05
Cumulative Brine Leakage[a]	Necessary	kg	0	6.98E+10
Cumulative CO_2 Leakage[a]	Necessary	kg	0	6.98E+10
Aquifer Salinity	Preferred	mass fraction	0	0.015

Notes: a. Can be calculated from other OpenIAM components

Other Components: Several other relevant components were assessed in this work: the fault flow component, atmospheric model component, seal horizon component, and the semi-analytical leakage solutions for aquifers (SALSA) component. Fault flow analyzes CO_2 leakage into an overlying aquifer through a fault with specified geometry and properties. The atmospheric model component models dispersion of a CO_2 plume associated with high leakage rates at a point source. Seal horizon estimates leakage through a confining unit assuming a simplified one-dimensional Darcy flow model with no feedback to the reservoir (i.e., no material balance, no pressure changes). The SALSA component is a unique component that models a connected system, estimating brine leakage at wellbores not intersecting the target formation in the event of integrity loss during storage. More details can be found in Vasylkivska (2022).

The input parameters for these components are listed in Table 16 (fault flow),

Table 17 (atmospheric model), Table 18 (seal horizon), and Table 19 (SALSA). Parameters are identified as 'necessary' or 'preferred' based on their relative importance to obtaining reasonable results for a given project. The ranges of values these input parameters can accept are also included in the tables.

Table 16. List of input parameters for NRAP-Open-IAM Fault Flow Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Fault Strike	Necessary	degree	0	360
Fault Dip	Necessary	degree	10	90
Fault Length	Necessary	m	0	1.00E+04
Fault aperture	Necessary	m	0	0.05
Aquifer Depth	Necessary	m	200	2000
Aquifer Temperature	Necessary	ºC	15	180
Aquifer Pressure	Necessary	Pa	1.00E+06	6.00E+08
Reservoir Depth	Necessary	m	860	20000
Reservoir Temperature	Necessary	ºC	31	180
Reservoir Pressure (time-dependent)	Necessary	Pa	1.00E+05	6.00E+08
Reservoir salinity	Necessary	ppm	0	80000
CO_2 Density (Aquifer and Reservoir)	Necessary	kg/m^3	93	1050
CO_2 Viscosity (Aquifer and Reservoir)	Necessary	Pa*s	1.10E-05	1.40E-04
Brine Density (Aquifer and Reservoir)	Necessary	kg/m^3	880	1080
Brine Viscosity (Aquifer and Reservoir)	Necessary	Pa*s	1.50E-04	1.60E-03
Fault Probability	Preferred	%	0	100
Fault Shale Gouge Ratio	Preferred	-	0	100
CO_2 Solubility	Preferred	mol/kg	0	2
Relative Permeability Parameters	Preferred	-	see OpenIAM User Guide	see OpenIAM User Guide
Capillary Entry Pressure	Preferred	Pa	100	2.00E+06
Maximum Horizontal Principal Stress	Preferred	Pa	0	5.00E+07
Minimum Horizontal Principal Stress	Preferred	Pa	0	5.00E+07
Strike of Maximum Principal Stress	Preferred	degree	0	180

Table 17. List of input parameters for NRAP-Open-IAM Atmospheric Model Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
CO_2 Leakage Rate(s)[a]	Necessary	kg/s	1.00E-05	0.5
Ambient Temperature	Necessary	ºC	5	40
Ambient Pressure	Necessary	atm	0.7	1.08
CO_2 Temperature	Necessary	ºC	5	50
Receptor Location(s)	Necessary	m	-	-
Leakage Well Location(s)	Necessary	m	-	-
Wind Velocity	Preferred	m/s	1.00E-10	20

Notes: a. Can be calculated from other OpenIAM components

Table 18. List of input parameters for NRAP-Open-IAM Seal Horizon Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Caprock Area (cell)	Necessary	m^2	1	2.60E+05
Caprock Thickness (cell)[a]	Necessary	m	5	1000
Base Depth	Necessary	m	800	9500
Caprock Permeability (cell)[a]	Necessary	m^2	1.00E-22	1.00E-15
Reservoir Pressure (time-dependent)	Necessary	Pa	1.00E+06	6.00E+07
CO_2 Saturation (time-dependent)	Necessary	-	1.00E-03	1
Pressure at top of seal	Necessary	Pa	1.00E+06	6.00E+07
Temperature of Seal	Necessary	ºC	31	180
Brine Salinity	Necessary	ppm	0	80000
Brine Density	Necessary	kg/m^3	880	1080
Brine Viscosity	Necessary	Pa*s	1.50E-04	1.60E-03
CO_2 Density	Necessary	kg/m^3	93	1050
CO_2 Viscosity	Necessary	Pa*s	1.80E-05	1.40E-04
Capillary Entry Pressure	Preferred	Pa	100	2.00E+06
Caprock Minerology	Preferred	-	see OpenIAM User Guide	see OpenIAM User Guide
Relative Permeability Parameters	Preferred	-	see OpenIAM User Guide	see OpenIAM User Guide
CO_2 Solubility	Preferred	mol/kg	0	2

Notes: a. Probabilistic distribution of parameters can be generated

Table 19. List of input parameters for NRAP-Open-IAM SALSA Component.

Parameter	Necessary / Preferred	Units	Min Value	Max Value
Well Locations	Necessary	-	see OpenIAM User Guide	see OpenIAM User Guide
System Stratigraphy	Necessary	-	see OpenIAM User Guide	see OpenIAM User Guide
Number of Shale Layers	Necessary	-	3	30
Thickness of Stratigraphic Units	Necessary	m	1	2000
Horizontal Hydraulic Conductivity of Aquifer Units	Necessary	m/s	1.00E-13	1.00E-03
Vertical Hydraulic Conductivity of Shale Units	Necessary	m/s	1.00E-16	1.00E-04
Aquifer Conductivity Anisotropy (k_h/k_v)	Necessary	-	1.00E-03	1.00E+03
Aquifer Fluid Densities	Necessary	kg/m^3	900	1500
Aquifer Hydraulic Heads	Necessary	-	-1000	1000
Status of Wells	Necessary	-	see OpenIAM User Guide	see OpenIAM User Guide
Production/Injection Rate of Active Wells	Necessary	m^3/s	-5	5
Wellbore Radii	Necessary	m	0.01	0.5
Storativity of Stratigraphic Units	Preferred	1/m	1.00E-12	0
Stratigraphic Unit Pressurization Rates	Preferred	1/s	-1.00E-10	1.00E-10
Integrity Status of Wells	Preferred	-	see OpenIAM User Guide	see OpenIAM User Guide
Hydraulic Conductivity of Well Elements	Preferred	m/s	1.00E-13	1.00E-03

5.2 State of Stress Analysis Tool (SOSAT)

SOSAT is used to assess the risk of induced seismicity by estimating “the probability of activating a critically oriented fault at a specified range of pore pressures” (Appriou et al., 2020) . The tool works by calculating a probability distribution for the state of in-situ stress using Bayesian techniques, then uses this distribution to calculate the probability of fault activation. SOSAT assumes that a critically oriented fault is present in the domain of interest. A more robust discussion of the methodology behind SOSAT is provided in Burghardt (2019).

As with the various components of NRAP-Open-IAM, a set of input parameters is required to run SOSAT. These parameters are given in Table 20. Unlike NRAP-Open-IAM, no specified ranges are given for the parameters. Reasonable values must, instead, be chosen based on data availability and in collaboration with a subject matter expert. The user manual suggests that familiarity with reservoir engineering and geomechanics is necessary for effective use of the tool, a statement that is heavily weighted in determining the applicability of SOSAT to proposed UIC Class VI permit applications. This is discussed in more detail in the decision tree analysis presented in Section 6.0.

Table 20. List of input parameters for SOSAT Component.

Parameter	Necessary / Preferred	Units
Reservoir Depth	Necessary	m, ft
Pore Pressure Gradient	Necessary	MPa/km, psi/ft
Average Overburden Density	Necessary	kg/m^3, lb/ft^3
Maximum Injection Pressure	Necessary	MPa, psi
Fault Friction Coefficient Properties	Preferred	-
Stress Regime Parameters	Preferred	-
Mean of Minimal Principal Stress	Preferred	MPa, psi
Standard Deviation of Minimal Principal Stress	Preferred	MPa, psi

5.3 Using the Stated Limits to Determine if the NRAP Tools Can Support Current UIC Class VI Permit Applications

The required and preferred parameters were analyzed to determine if individual components of the NRAP tools would be applicable to the current inventory of UIC Class VI permit applications. Two groups were considered in this analysis: (1) permit applicants or permit reviewers (herein referred to as applicant/reviewer) and (2) the public. The assumptions for the analysis were that applicants/reviewers have or can request access to full SEMs and DRMs. In addition, the applicants/reviewers can access publicly available data from federal, state, local, and private entities to supplement or verify what is in the application. Because permit applicants and reviewers have access to required data to use the NRAP models, the question for applicability is simplified to whether or not the tool or component has been designed to work in the reservoir and project conditions and whether the tools have been tested in a similar setting. The project team assumed that less data would be available for members of the public to evaluate project risks. Specifically, the project team assumed that the public can only view information currently available in the public-facing permit application documents. This information could be supplemented by publicly available data from federal, state, local, and private entities.

Individual modules of the NRAP-Open-IAM were evaluated based on the necessary data to run them. Not all required parameters were included in the UIC Class VI permit applications dataset; therefore, this analysis is limited to the required parameters that were included (shown in bold on Table 21). Additional information that could be obtained from the permits or other publicly available sources or information that could be reasonably estimated to fill in the required parameters are also commented on. Preferred parameters are also considered in this analysis but are largely not included in the Battelle (2024a) database.

Reservoir Components

The time-dependent measurement of CO_2 saturation and pressure is required for many of the components in NRAP-Open-IAM.

Applicant/Reviewer: An SEM and full physics DRM is a pre-requisite to a successful permit application. Therefore, time-dependent reservoir pressure and CO_2 saturation measurements are available to the permit applicant and reviewer. Applicants and reviewers, therefore, would have the opportunity to convert their DRM into a lookup table that can be used for the NRAP-Open-IAM.

Public: Four cases are conceived for the public user: (1) access to full physics DRM and required brine and CO_2 properties, (2) access to reservoir properties in publicly available permit applications, (3) access to reservoir and caprock name or reservoir and caprock lithology and depositional environment information in publicly available permit applications, and (4) access to no data or information.

Access to full physics DRM and required brine and CO_2 properties: Access to a full physics DRM along with brine and CO_2 properties would mean the public user could run the NRAP-Open-IAM in the same way the applicant/reviewer could.

Access to reservoir data in publicly available UIC permits: While a full physics model would be preferable for this analysis, the public user likely will not have access to full physics models that are applicable to the specific, proposed project. Therefore, they would have to rely on the use of the analytical reservoir component. This would require, at a minimum, reservoir and caprock thickness, porosity, permeability, and CO_2 injection rate to provide meaningful, project-specific results. All of these parameters are publicly available for 33 of the 82 permits in the current UIC Class VI permit application queue according to the database from Battelle (2024a). This would need to be paired with assumptions related to aquifer thickness and brine and CO_2 properties to provide a site-specific solution. The base of the lowermost USDW is available for 24 of the 33 permits with the other data, indicating that aquifer (USDW), thickness may be available for some of these permits. Assumptions on brine could be made using publicly available data or estimated from other known brine concentrations. Assumptions on CO_2 could either be made using public data from federal or state resources or simplified assumptions based on well-known physical and chemical properties of CO_2.

The other consideration when using the NRAP-Open-IAM is whether the parameters are within the acceptable ranges listed in the user guide. Twenty-seven of the 33 projects that could be tested using the reservoir analytical model have values for all parameters that are within their acceptable ranges. Therefore, it is possible that at least 27 of the projects in the current queue for a UIC Class VI permit application could be evaluated by the public using the analytical reservoir model. Details about the individual parameters are included in the list below:

- *Reservoir Permeability:* 31 permits fall within the acceptable range for reservoir permeability; however, two permits are above the acceptable range.
- *Reservoir Porosity:* 28 permits fall within the acceptable range for reservoir porosity; however, two permits are below the acceptable range and three permits are above the acceptable range. These five permits are not the same as the two permits that fall outside the acceptable range for permeability.
- *Injection Rate:* All 33 permits fall within the acceptable range, ranging from 0.063 MMt/yr to 6.49 MMt/yr.

- *Reservoir Thickness:* All 33 permits fall within the acceptable range of reservoir thickness, ranging from 68 ft to 2800 ft.
- *Shale Thickness:* The equivalent of shale thickness in the UIC Class VI permit application dataset is caprock thickness. All 33 permits fall within the acceptable range of caprock thickness, ranging from 119 ft to 3400 ft.
- *Aquifer Thickness:* There is not enough information in the dataset to evaluate aquifer thickness; however, the stated range of 3 ft to 5250 ft should be sufficient in all instances.

<u>Access to reservoir and caprock name:</u> If the reservoir and caprock name are known, properties may be obtained from publicly available sources. EDX could be an important tool for uncovering these data. This information is available for 24 permits that do not also have publicly available reservoir data. These data would have to be paired with USDW information from published sources or assumptions and information/assumptions related to CO_2 and brine conditions as in the section above.

<u>Access to reservoir and caprock lithology and depositional environment:</u> Alternatively, if reservoir and caprock lithology and depositional environment are known, a range of reservoir assumptions could be obtained from published sources. This information is available for only one permit without publicly available reservoir data or a named reservoir. The caprock for this project is named in the permit, however. These data would have to be paired with USDW information from published sources or assumptions and information/assumptions related to CO_2 and brine conditions as in the section above.

<u>Access to no data or information:</u> If no reservoir data or other information about the reservoir or caprock are available, then the model can likely not produce meaningful results. Twenty-four of the 82 permits currently in the UIC Class VI permit application queue have access to no data or information needed to produce meaningful results from the analytical reservoir component. Six of these wells all have named reservoirs but do not have a named caprock. If a user is willing to make assumptions about the caprock for these projects or investigate the caprock that is typically associated with the named reservoir, then the public user should be able to use the model to provide meaningful results.

<u>Wellbore Components</u>

The UIC Class VI permitting process also requires the identification of all known wellbores that penetrate the storage complex within the project AoR (40 CFR §146.84). Three components in the NRAP-Open-IAM are capable of simulating leakage through the wellbore: (1) cemented wellbore component, (2) multisegmented wellbore component, and (3) open wellbore component. These components are described in Section 5.1. The following section describes the use of these components from the perspective of the applicant/reviewer and from the perspective of the public.

Cemented Wellbore

Applicant/Reviewer: This identification would feasibly include the well location and depth (or at least the formation intersected), meaning that nearly all required parameters should be readily available in the application. Wellbore radius may or may not be reported. If it is not reported, state or privately maintained databases on well construction should have this parameter. Cement permeability (a preferred parameter) may not be included in these datasets; however, if cement class is known, this can be reasonably estimated with caveats. Thief zone depth fraction can be obtained from a stratigraphic column; however, thief zone permeability may require additional data from federal, state, or privately maintained databases or estimated with caveats based on the lithology of the formations. Applicants and reviewers should have the required data and models to generate meaningful results using the cement wellbore component.

Table 21. Summary of the required and preferred parameters to use NRAP modules.

Component	Required	Preferred
NRAP-Open-IAM Reservoir Components		
Analytical Reservoir	**Reservoir Permeability** **Reservoir Porosity** **Injection Rate** **Reservoir Thickness** **Shale Thickness** Aquifer Thickness Number of Shale Layers	Datum Pressure Reservoir Radius Brine Density Brine Viscosity CO_2 Density CO_2 Viscosity Brine Reservoir Saturation Brine Compressibility
Reservoir Lookup Table	**Reservoir Pressure (time-dependent)** **CO_2 Saturation (time-dependent)**	N/A
NRAP-Open-IAM Wellbore Components		
Cemented Wellbore Component	**Reservoir Pressure (time-dependent)**[a] **CO_2 Saturation (time-dependent)**[a] Wellbore Radius Well Depth	Cement Permeability Thief Zone Permeability Thief Zone Depth Fraction
Multisegmented Wellbore Component	**Shale Thickness** **Reservoir Thickness** **Reservoir Pressure (time-dependent)**[a] **CO_2 Saturation (time-dependent)**[a] Aquifer Thickness Number of Shale Layers Aquifer Permeability Brine Density Wellbore Radius	Cement Permeability Brine Viscosity CO_2 Density CO_2 Viscosity Aquifer Residual Water Saturation Fluid Compressibility
Open Wellbore Component	**Reservoir Depth** Top of Open Section Reservoir Transmissivity Aquifer Transmissivity Brine Density Wellbore Radius	Storativity of Stratigraphic Units Stratigraphic Unit Pressurization Rates Integrity Status of Wells Hydraulic Conductivity of Well Elements
NRAP-Open-IAM Aquifer Components		
Carbonate Aquifer Component	**Brine Leakage Rate**[b] **CO_2 Leakage Rate**[b] Mean Aquifer Permeability Aquifer Permeability Anisotropy (kh/kv) Brine Salinity Aquifer Thickness	Permeability Variance Horizontal Hydraulic Gradient Calcite Surface Area Organic Carbon Volume Fraction Brine Organic Compound Constituents (Benzene, Naphthalene, Phenol)
Deep Alluvium Aquifer Component	**Brine Leakage Rate**[b] **CO_2 Leakage Rate**[b] **Caprock Permeability** Permeability of Sand Units Leak Depth	Sand Fraction Groundwater Gradient
Generic Aquifer Component	**Cumulative Brine Leakage**[b] **Cumulative CO2 Leakage**[b] Aquifer Thickness **Aquifer Depth** **Reservoir Porosity** **Reservoir Horizontal Permeability (kh)** Reservoir Permeability Anisotropy (kh/kv) Leaked Brine Salinity	Aquifer salinity
NRAP-Open-IAM – Other Components		
SOSAT		
SOSAT	**Reservoir Depth** Pore Pressure Gradient Average Overburden Density **Maximum Injection Pressure**	Fault Friction Coefficient Properties Stress Regime Parameters Mean of Minimal Principal Stress Standard Deviation of Minimal Principal Stress

Notes: a. The discussion on the Reservoir Components, above, is applicable when reservoir temperature and pressure are required inputs. b. Can be calculated by NRAP-Open-IAM; c. Probabilistic distribution of parameters can be generated. **If text is bold, the parameter has been compiled as part of the UIC Class VI Permit Application Dataset (See Sections 5.1 and 5.2).**

Public: If wellbore data are not provided in the publicly available application, the public user could obtain this information from the federal and state resources listed above, assuming that the user is able to geolocate the CO_2 and pressure plume. Thief zone permeability measurements would require data from potential thief zones in the application or, at the very least, the identification of these formations so that their properties could be found from federal, state, or private resources. Data for potential thief zones were not included in the Class VI UIC permit application database developed by Battelle (2024a). These data or a stratigraphic column identifying intermediate zones between the caprock and USDW may be available in the application.

Multisegmented Wellbore

Applicant/Reviewer: The applicant/reviewer should have all required data to run the multisegmented wellbore component. If the parameters are in the stated ranges covered in Section 5.1, the component could be used to evaluate the project. Reservoir and caprock thickness for the 42 projects in the UIC Class VI permit application dataset with these data are all within the acceptable ranges of the component (see Sections 4.2.2 and 5.1).

Public: The multisegmented wellbore model requires similar data to the analytical reservoir component. Additional required data include aquifer permeability, brine density, and the wellbore radius. While this information was not part of the data obtained as part of the Class VI permit application dataset compiled by Battelle (2024a), most of it could be found in state and federal datasets maintained by state oil and gas departments, the United States Geological Survey (USGS), and/or other state departments. Some of these data may also be available through EDX. In addition, the preferred parameters may be available or may be estimated using reasonable assumptions or federal, state, or privately maintained datasets. Therefore, it is feasible that the multisegmented wellbore component could be used to evaluate the 27 projects that have sufficient publicly available data and all parameters within an acceptable range for the analytical reservoir components. Additionally, for projects that rely on pressure and CO_2 saturation data from the analytical reservoir component built using data from named reservoirs and caprock or lithology and depositional environments, eight have sufficient data to calculate reservoir and caprock thickness. This means that the multisegmented wellbore component could be used by the public to evaluate 35 of the permits currently in the queue for a UIC Class VI permit.

Open Wellbore Component

Applicant/Reviewer: The applicant/reviewer should have all required data to run the open wellbore component. If the parameters are in the stated ranges covered in Section 5.1, the component could be used to evaluate the project. Reservoir top depth for the 45 projects in the UIC Class VI permit application dataset with these data are mostly within the acceptable ranges (43 projects) of the component (see Sections 4.2.2 and 5.1). Two projects are outside of the acceptable ranges: one is deeper and one is shallower than the acceptable range.

Public: The open wellbore component requires information about the reservoir depth as well as the top of the open wellbore, aquifer and reservoir transmissivity, and wellbore radius. Aquifer and reservoir transmissivity could be calculated using data from the UIC Class VI permit application dataset for 37 of the projects that have both permeability and reservoir thickness data. Of these projects, 30 have sufficient data or information about reservoir and caprock names needed to build a reasonable model in the analytical reservoir component. Therefore, it is feasible that the open wellbore component could be used by the public to evaluate 30 of the permit applications currently in the queue for a UIC Class VI permit. Like the multisegmented wellbore component, the preferred parameters for the open wellbore component may be available or may be estimated using reasonable assumptions or federal, state, or privately maintained datasets.

Aquifer Components

The use of the aquifer components will be dependent on the types of aquifers that exist in the area. This evaluation is beyond the scope of the current project; however, given that the model provides components capable of simulating a carbonate aquifer, a deep alluvium aquifer, or a generic aquifer, the components should be sufficient to model any groundwater scenario, if the conditions are within the stated limits of the individual components. Additional information about the aquifers in a project area could be obtained from data available from the USGS or state departments of natural resources.

Carbonate Aquifer Component

For the carbonate aquifer component, the required parameters that can be evaluated using the UIC Class VI permit application dataset are brine leakage and CO_2 leakage rate. These are outputs from the wellbore components and, therefore, the applicability of the carbonate aquifer component mirrors that of the wellbore components.

Deep Alluvium Aquifer Component

For the deep aquifer component, the required parameters that can be evaluated using the UIC Class VI permit application dataset compiled by Battelle (2024a) are brine leakage and CO_2 leakage rate as well as caprock permeability, permeability of the sand units, and leak depth. Only caprock permeability was tracked in the UIC Class VI permit application dataset compiled by Battelle (2024a). Caprock permeability for the 34 projects in the UIC Class VI permit application dataset with these data are mostly outside the acceptable ranges (only eight projects are within the acceptable range) of the component (see Sections 4.2.2 and 5.1). Most of the permeability values are much lower than the minimum of 0.02 mD while one is higher than the maximum of 2.0 mD.

Generic Aquifer Component

For the generic aquifer component, the required parameters that can be evaluated using the UIC Class VI permit application dataset are cumulative brine leakage and CO_2 leakage as well as aquifer thickness, aquifer depth, reservoir porosity, reservoir horizontal permeability, reservoir permeability anisotropy, and leaked brine salinity. Aquifer depth, reservoir porosity, and reservoir permeability were tracked in the UIC Class VI permit application dataset compiled by Battelle (2024a). For the 31 projects in the UIC Class VI permit application dataset with all these data, all three parameters are within the acceptable range of the component for 21 projects (see Sections 4.2.2 and 5.1).

Other Components

The use of the other components of NRAP provide tools to simulate leakage in wells not connected to the target formation (SALSA component), leakage through the seal horizon (seal horizon component), simulate the impact of leakage to the atmosphere (atmospheric component), and simulate leakage through faults (fault flow component). An assessment of each of these components compared to the current inventory of Class VI permit applications is beyond the scope of this study and the available data would make these assessments like the assessments of the wellbore components.

SOSAT

As noted earlier, SOSAT can help assess the risk of activating a critically oriented fault in a CCS storage complex. While the project could not find ranges of acceptable data like those in the NRAP-Open-IAM components, the project is able to evaluate the applicability of the tools.

Applicant/Reviewer: The applicant/reviewer should have all required and preferred data needed to use SOSAT to evaluate their project because these data are likely pre-requisite to obtaining a UIC Class VI permit.

Public: For SOSAT, the required parameters that can be evaluated using the UIC Class VI permit application dataset compiled by Battelle (2024a) are reservoir depth, pore pressure gradient, average overburden density, and maximum injection pressure. Only reservoir depth and maximum allowable injection pressure are tracked in the UIC Class VI permit application dataset compiled by Battelle (2024a). Both of these parameters are available for 36 projects that are currently in the queue for UIC Class VI permits (see Sections 4.2.2 and 5.2).

6.0 NRAP Tool Decision Trees

The NRAP-Open-IAM and SOSAT tools were each evaluated independently to illustrate an effective, logical method of determining the applicability of each tool for use in UIC Class VI permit applications. A series of decision trees was developed to aid stakeholders in determining the viability of these tools in assessing various risks during the permitting process. The decision trees are divided into the following categories based on the specific risk being assessed: (1) leakage through legacy wellbores, (2) fault-associated risks, (3) shallow aquifer impacts/atmospheric release, and (4) other storage risks. The discussion presents the general construction of these decision trees followed by the logical sequence of the individual trees.

6.1 Methodology

In parallel with the development of CCS models based on available data in the UIC Class VI permit application database, the use of NRAP-Open-IAM and SOSAT was evaluated based on the applicability of results to a generic UIC Class VI permit application. To this end, a series of decision trees was developed to inform potential users of the level of confidence they can expect by using these tools for a stated purpose. A series of decision points was identified that influence the efficacy of these tools on UIC Class VI permit applications. While specific risk scenarios have their own specific considerations, four primary questions were identified as relevant for all scenarios:

- Are necessary inputs available and in range?
- Are preferred inputs available and in range?
- Has the tool been demonstrated in a similar scenario or project setting?
- Is subject matter expertise available?

The first two questions are related to site-specific inputs to feed into the tools. The underlying models can provide an answer for any input parameters, but the only way to get relevant information for a particular project is to have inputs that are representative of that project. The SOSAT tool and each component of the NRAP-Open-IAM tool have both necessary and preferred input parameters. Without the necessary parameters (for instance, reservoir depth), no output that is representative of the project can be achieved. The preferred parameters, on the other hand, serve to narrow the uncertainty based on results, but are not required to obtain a reasonable answer. The lists of necessary and preferred inputs for each tool are provided in tables in Section 5.0.

The third question addresses whether these tools have been used in the past for either a similar scenario (e.g., similar ages of legacy wellbores) or a similar project setting (e.g., same basin). The literature review described in Section 2.0 shows where the tools have been demonstrated in published studies, while the publicly available information disclosed in the UIC Class VI permit applications can help inform whether these tools have been used during the application process. As the tools become more widely adopted, the documentation of their use for specific purposes can serve as a roadmap for future users, alleviating the degree of effort required to determine how best to apply a given tool to the user's scenario.

The fourth question involves the availability of subject matter expertise for either using/modifying the tools (since they are open source) or interpreting the results. The collaboration of a subject matter expert (SME) is critical for conducting a risk assessment, especially when using these tools. Outlining a specific risk scenario or series of scenarios and appropriately identifying the critical risks and parameters that control these risks is essential in obtaining an accurate evaluation. In addition, an SME can more accurately interpret results from these tools and provide guidance on a path forward when data may be lacking. Since the tools are open source, a SME familiar with programming can also tailor the tools and/or risk assessment workflow to project-specific needs. Thus, any decision point of this nature will have a large influence on the qualitative ranking of a branch.

It should be noted that at the time of writing, the NRAP tools are in the relatively early stage of their development and adoption of the tools is still limited (see Section 3.0). In testing several of the tools (particularly within NRAP-Open-IAM), some bugs were encountered that made generating results difficult. Use of the GUI was limiting, and writing and executing Python scripts referencing source code was more reliable. Previous modeling work conducted by Battelle (2024b) took a similar approach, generating Python scripts in collaboration with the tool developers. This, again, highlights the necessity of a SME to make effective use of these tools. If possible, communication with developers or prior users should be established to ensure proper application to a new project.

6.2 Decision Tree Description

The decision trees are constructed to guide a user through a series of binary (yes/no) decisions that increase or decrease the level of confidence in a given aspect of the NRAP-Open-IAM or SOSAT tools. Figure 2 below, which shows the decision tree for leakage through legacy wellbores, illustrates this decision-making process as well as the general features shared across each of the trees. The process diagram flows from left to right, starting with the identification of a specific risk to be analyzed and ending with a qualitative ranking on the applicability of results from the tool in question to the UIC Class VI permitting purposes. Each column within the tree represents a single question which advances the decision-making process. The first three questions are intended to identify the specific risk analysis scenario that is being addressed and the tool that is being used. For example, in the top tree of Figure 2, the risk analysis scenario uses NRAP-Open-IAM wellbore components (specifically the cemented wellbore component) to assess leakage through a fully cemented legacy wellbore.

After the scenario is identified, the user follows a single line through the decision tree to guide the process. The remaining questions present a decision point with two options (yes/no), each of which creates a further branch in the tree. Following a branch to its terminal point gives a qualitative ranking on the degree of applicability of model results for evaluating the specific risk scenario as part of a UIC Class VI permit application. Green implies the tool provides results that would be a good fit for the problem; yellow-green indicates the tool will solve the problem but may require additional assumptions or caveats; yellow implies that an alternative method may be better suited to solving the problem but that the NRAP tool could be used with uncertainty in the absence of other options; and red indicates that use of the tool is not suited to solving the specified problem as part of a UIC Class VI permit application, either due to missing inputs or lack of expertise in using/interpreting the tool.

The color of the lines connecting the various decision points indicates the degree of confidence the user can have in the tool in question at that point in the decision-making process. The colors follow the same general scheme as the terminal points of the tree (green=high confidence, red = low confidence), and the degree of confidence evolves as the user moves down the branch. The order of the questions, as they appear in the tree, follow a general logical progression: identify the risk scenario and ensure it is an intended use of the tool; assess data availability; analyze previous work (literature and/or prior permits); and finally ensure sufficient subject matter expertise is available to effectively use the tools. However, an alternative order could be hypothesized, which would change the structure of the trees as they have been constructed. The qualitative result for a given pathway through either tree, however (i.e., same answers to every question) would be the same, regardless of question ordering.

NRAP-Open-IAM – Leakage through Legacy Wellbores

Figure 2 shows the decision trees for assessing legacy wellbore leakage risk in a CCS project. Each of the cemented and multi-segmented wellbore components begin with high confidence, as these are commonly encountered in UIC Class VI permit applications, and the NRAP-Open-IAM tool can provide quality results for these scenarios given sufficient input data and user expertise. The open wellbore component starts with lower confidence, as the presence of an open wellbore is unlikely in any project site that could feasibly support CCS injection. However, the tool itself will give quality results with sufficient inputs.

The NRAP-Open-IAM wellbore components only work in the presence of an upward pressure gradient, so it is critical that any wellbores being analyzed are within the pressure-affected area of an injection project. Hence, this results in an immediate red line for a “no” response to this question. As with most of the tools, having site-specific inputs (such as reservoir depth and pressure) is crucial to getting a result that is relevant to a specific project. Each of the remaining questions leads to higher or lower degrees of confidence in using the NRAP-Open-IAM wellbore components, but some level of an answer can generally be reached.

NRAP-Open-IAM – Shallow Aquifer Impacts / Atmospheric Release

Figure 3 shows the decision trees for assessing shallow aquifer impacts (both saline and fresh water) and assessing the impact of an atmospheric release of high volume of CO_2 using various aquifer components and the atmospheric model component, respectively, within NRAP-Open-IAM. The aquifer components are designed to assess salinity and pH impacts to deep saline aquifers but have been previously applied in assessing risk to USDW aquifers from leaking wellbores during CO_2 injection (Battelle, 2024b). However, within this prior work, it was found that model outputs are coarse when leakage rates into the aquifer in question are low. As a result, higher leakage rates tend to decrease uncertainty in the results, but a low leakage rate doesn’t necessarily make the tools unusable.

The atmospheric model component, on the other hand, is designed specifically for high leakage rate scenarios and models the dispersion of a high concentration CO_2 plume at the surface. As a result, low leakage rates do invalidate the use of this tool since it is explicitly not tailored to slow emission scenarios. This component also has no preferred inputs, eliminating that decision point within the tree. The four common questions tend to have much the same impact on tool applicability for both aquifer impacts and atmospheric release as is seen with legacy wellbore leakage models.

SOSAT and NRAP-Open-IAM – Fault-Associated Risks

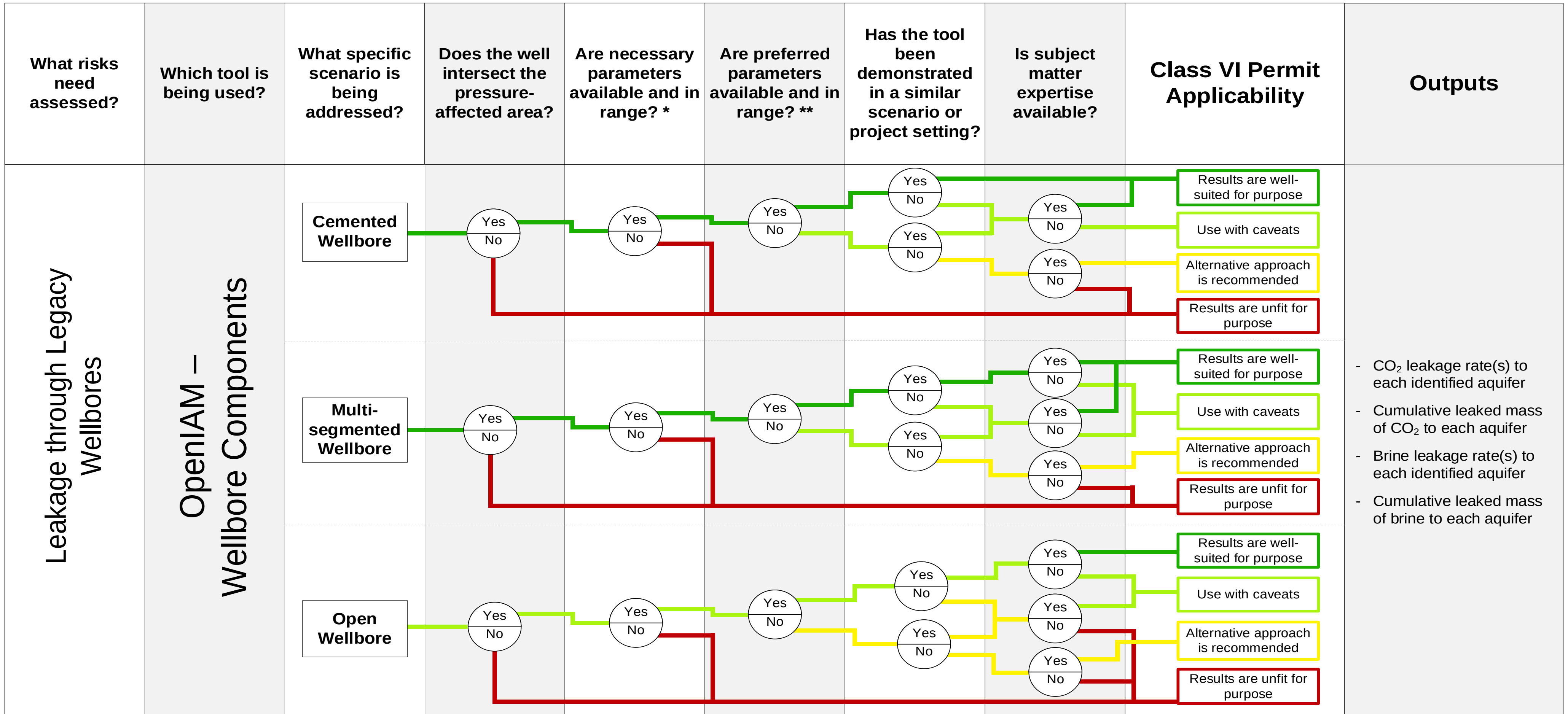
Figure 4 shows the decision trees for risks associated with faults in the storage reservoir and/or overlying formations. The fault activation tree, shown here, is the first and only appearance of the SOSAT tool due to its highly specialized design as compared to the broader spectrum of risks assessed by NRAP-Open-IAM. Both SOSAT and the various NRAP-Open-IAM fault leakage components are more appropriate when there is a known fault present in the storage system and the levels of confidence in branches associated with a known fault reflects this fact. However, confirming the presence of a fault often requires seismic data, which is not always available, and/or drilling a well. Even with necessary data, fault locations and parameters are often highly uncertain. Because of this, the lack of a known fault does not necessarily preclude use of these tools in a risk assessment. Both tools can be used to assess risk in hypothetical faults devised by the user.

Due to the complexity of the modeling methods within the SOSAT tool, there are relatively few high-confidence points within the decision tree without having prior work, on which to base a workflow, or a SME. Even within the user's manual, it is noted that "familiarity with reservoir engineering and geomechanics terminology is a prerequisite to the effective use of [SOSAT]" (Burghardt, 2019). Quantifying the likelihood of fault activation is a very useful assessment in CCS projects; however, in the absence of a SME, the recommendation is typically to use an alternative approach. The fault flow components of NRAP-Open-IAM are much more straightforward to use, but a SME is still typically recommended to properly contextualize the often high leakage rates obtained from estimating leakage through an open fault.

NRAP-Open-IAM – Other CCS Project Risks

Figures 5 and 6 show the decision trees for caprock leakage and connected system leakage, respectively. Among the other models present in the NRAP-Open-IAM software package, the seal horizon (caprock leakage) component and semi-analytical leakage solutions for aquifers, or SALSA (connected system leakage) component are the most applicable to the UIC Class VI permitting process outside of those already discussed. Given the simplicity of the seal horizon model (1D Darcy Flow with no mass balance), this component is only capable of producing an order of magnitude estimate on caprock leakage resulting from CO_2 injection. For this reason, an alternative approach to assessing caprock leakage is typically recommended. If an order of magnitude estimate is necessary, however, the tool is straightforward to use, and results are easily interpreted.

The SALSA tool provides analysis of a unique leakage scenario, where in situ fluid that exits the storage formation (either through a leaking wellbore or through caprock) can continue to migrate upward through additional conductive pathways (e.g., other wellbores). The tool is currently only capable of assessing pressure-driven brine leakage in CO_2 storage scenarios, which somewhat limits its applicability to UIC Class VI permit applications. However, given that brine leakage is a risk inherent to CCS, a SME could make use of this tool in demonstrating project viability.

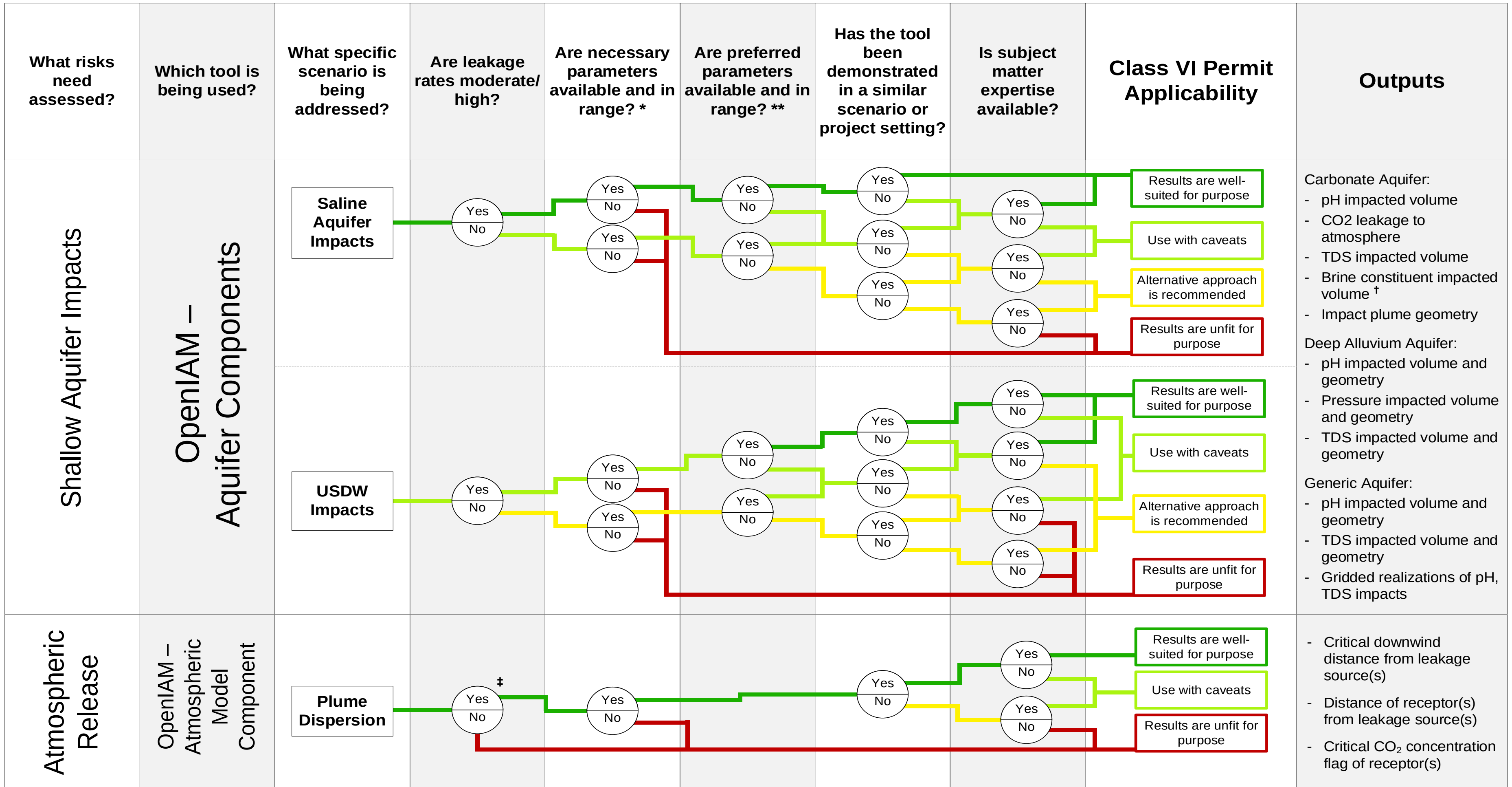


***** *Necessary inputs include: OpenIAM Cemented Wellbore – wellbore radius, reservoir pressure/saturation, well depth; OpenIAM Multisegmented Wellbore – wellbore radius, reservoir pressure/saturation, aquifer permeability, brine density, number of shale layers, shale thickness(es), aquifer thickness(es), reservoir thickness; OpenIAM Open Wellbore – wellbore radius, brine density, reservoir/aquifer transmissivity, reservoir depth, top of open wellbore section*

****** *Preferred inputs include: OpenIAM Cemented Wellbore – cement permeability, thief zone permeability, thief zone depth; OpenIAM Multisegmented Wellbore – cement permeability, fluid properties, aquifer residual water saturation, fluid compressibility; OpenIAM Open Wellbore – brine salinity, critical reservoir pressure*[†]

[†] *Pressure above which the open wellbore begins to leak*

Figure 2. Decision tree for assessment of leakage through legacy wellbores using NRAP-Open-IAM.



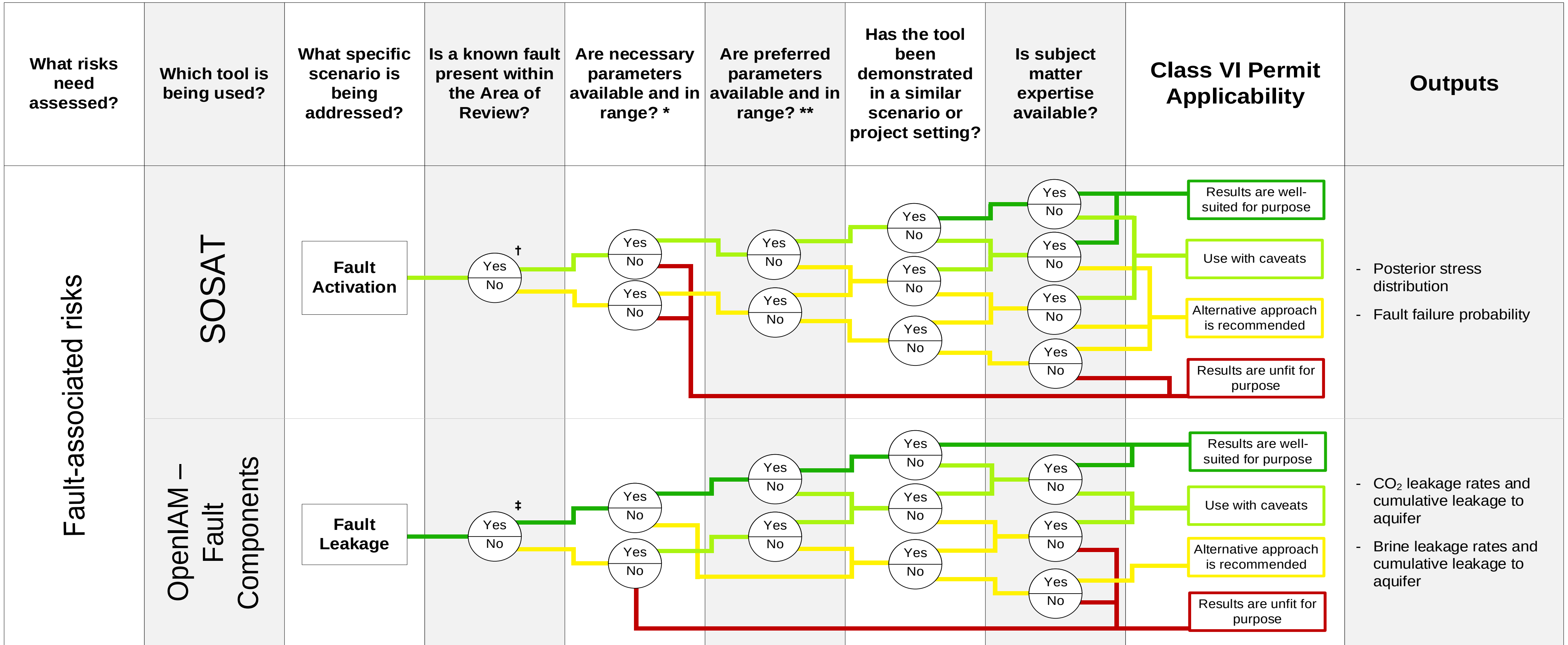
** Necessary inputs include: OpenIAM Carbonate Aquifer – aquifer permeability, aquifer thickness, fluid properties, fluid leakage rate(s); OpenIAM Deep Alluvium Aquifer – aquifer permeability, caprock permeability, leak depth, fluid leakage rate(s); OpenIAM Generic Aquifer – aquifer thickness, aquifer depth, aquifer permeability, aquifer porosity, fluid properties, fluid leakage rate(s); Open IAM Atmospheric Model – CO_2 leakage rate(s), ambient temperature/pressure, CO_2 temperature, leakage locations, receptor locations*

*** Preferred inputs include: OpenIAM Carbonate Aquifer – permeability variance, horizontal hydraulic gradient, calcite surface area, organic carbon volume fraction, brine compound constituents†; OpenIAM Deep Alluvium Aquifer – sand fraction, groundwater gradient; OpenIAM Generic Aquifer – aquifer salinity; Open IAM Atmospheric Model – wind velocity*

† Brine constituents include arsenic, lead, cadmium, barium, benzene, naphthalene, phenol

‡ Leakage rates should be greater than 1.0e-5 kg/s

Figure 3. Decision tree for assessment of aquifer impacts and/or atmospheric release using NRAP-Open-IAM.



*** Necessary inputs include:** *SOSAT – reservoir depth, pore pressure gradient, average overburden density, maximum injection pressure; OpenIAM Fault Flow Component – fault geometry, aquifer/reservoir depth, aquifer/reservoir pressure, aquifer/reservoir temperature, fluid properties*

****** *Preferred inputs include: SOSAT – fault friction coefficient properties, stress regime parameters; OpenIAM Fault Flow Component – stress regime parameters, relative permeability parameters, capillary entry pressure, CO_2 solubility, fault probability, fault shale gouge ratio*

† *SOSAT assumes presence of a fault; this conservative approach can be used to inform project developers of data gaps to lower geomechanical risk (even in absence of a known fault)*

‡ *analysis of leakage through hypothetical faults could be useful in certain scenarios*

Figure 4. Decision tree for assessment of fault-related risks using NRAP-Open-IAM and/or SOSAT.

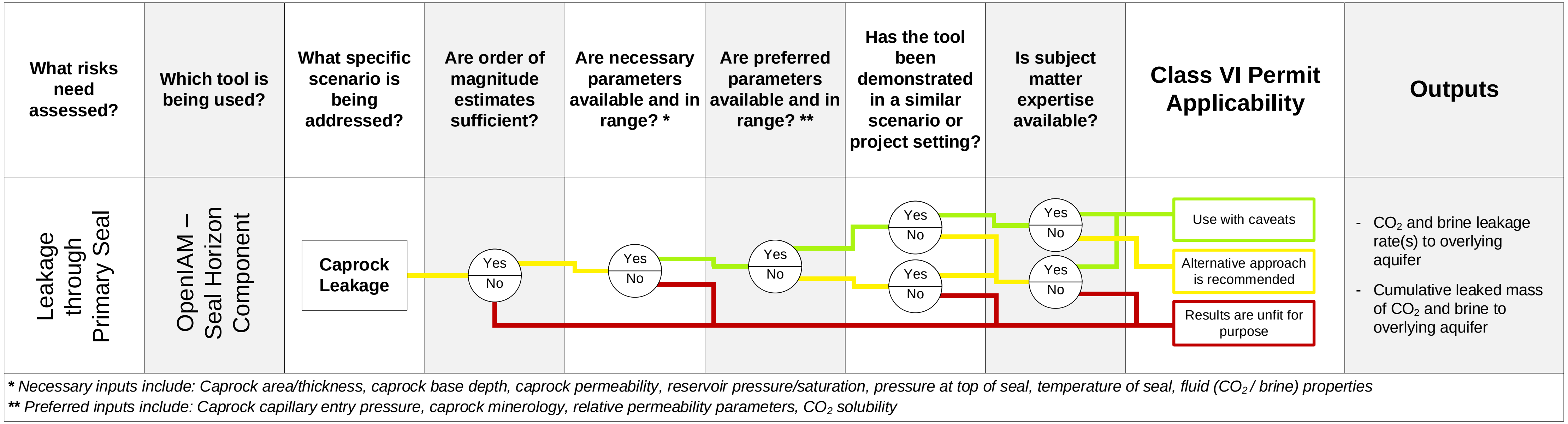
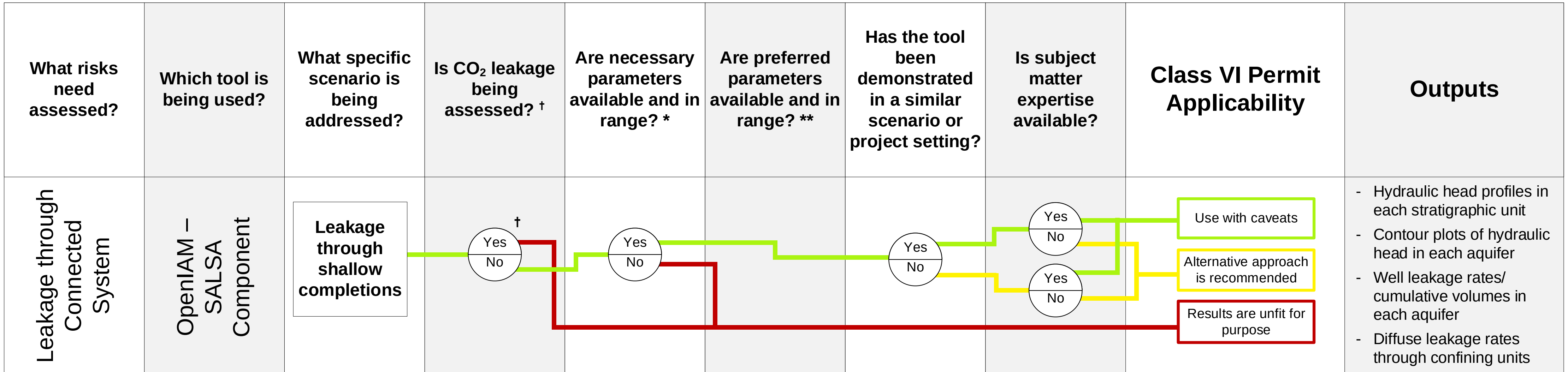


Figure 5. Decision tree for assessment of leakage through caprock using NRAP-Open-IAM.



***** *Necessary inputs include: Well locations, system stratigraphy, number of shale layers, thickness of stratigraphic units, hydraulic conductivity of aquifer/shale units, aquifer fluid densities, aquifer hydraulic head(s), well status, production/injection rate of active wells, wellbore radii*

****** *Preferred inputs include: storativity of stratigraphic units, stratigraphic unit pressurization rates ‡, integrity status of wells, hydraulic conductivity of well elements*

† *Only brine leakage is assessed in the SALSA component*

‡ *Meant to represent pressure conditions (over/under-pressured) of formations, either over geologic time or due to current/past production/injection operations*

Figure 6. Decision tree for assessment of leakage through connected systems (e.g., wellbore to shallow unit to second wellbore to second shallow unit) using NRAP-Open-IAM Semi-Analytical Leakage Solutions for Aquifers (SALSA) component.

7.0 Discussion

One of the main goals of this study was to investigate the applicability of the current suite of NRAP tools to the projects currently being considered by the U.S. EPA for a UIC Class VI permit applications. This was accomplished through the literature review, an evaluation of how the tools had been applied in the past (Most of the UIC Class VI permits with known lithology are in clastic reservoirs with only two in carbonate reservoirs [see Section 4.2.2]. This may change over time as more projects are permitted in areas without clastic reservoir options, particularly as there are previous and ongoing DOE-sponsored CarbonSAFE projects targeting carbonate reservoirs (DOE, 2023; DOE/NETL, 2024b). The NRAP program should be well positioned to support these projects, particularly as the tools have been demonstrated in at least three carbonate reservoirs through DOE-supported projects (Table 6). The tool that has been demonstrated the most is the NRAP-Open-IAM. As discussed in Sections 4.2.1, the tools have been demonstrated in geologic basins and project conditions that are relevant to the current inventory of UIC Class VI permit applications compiled by Battelle (2024a).

The study also compared the stated ranges of required data for multiple components of the NRAP-Open-IAM and SOSAT with the data reported for the current inventory of UIC Class VI permit applications compiled by Battelle (2024a). The analysis showed that the project applicant/reviewer should have sufficient data to run most relevant components and most of the reported data are within the limits of the tools. However, the use by the public may be more limited. The analysis found that there is sufficient public information to use the analytical reservoir to generate pressure and CO_2 saturation data for 52 projects. Of these, at least 27 projects provide enough of the required data that were tracked by Battelle (2024a) needed to use the tool. An additional 23 projects listed the names of the relevant reservoir and caprock formations (or their lithology and depositional), and a user could feasibly research the required parameters to run the tool with some accuracy.

Despite the potential for the NRAP tools to support the development of UIC Class VI permit applications, the expert interviews did not reveal widespread usage by project developers for their permit applications (see Section 3.0). Suggestions for how the tools could be developed to support UIC Class VI activities are presented in Section 8.2.

The remaining UIC Class VI permit applications either have at least one parameter out of the acceptable range for the component (six projects) or do not have information sufficient to generate site-specific results using the analytical reservoir component. The current study highlights this component, in particular, because in the absence of a full-physics DRM, this component is needed to generate the necessary time-dependent pressure and CO_2 saturation results needed for the use the NRAP-Open-IAM. Therefore, a public user would not have sufficient information to use the tool for approximately one third of the permits currently in review.

Because most of the UIC Class VI permit applications are currently being evaluated, many of the permits reviewed had some relevant information that was redacted or, for more recent projects, had not yet been reported. Additional information for all permits will be made available once the permit review is completed and permission to inject is received (McEvoy, personal communication). Many of the permits without basic information like lithology, injection rates, and number of injection wells were entered into the queue recently. As a result, their full permit applications had not yet been uploaded. This, combined with the availability of fuller permit applications once permission to inject is received, means assessing the applicability of the NRAP tools is a moving target. While it would be unfair and, perhaps, unwise to expect the applicant to freely publish all affected land parcels with ownership information, SEMs, full-physics DRMs, and pressure and CO_2 saturation plumes within the pre-application permit, perhaps mechanisms could be developed for the risk assessment by trusted institutions, with results shared with the public. Some of this assessment and peer-review may already be part of the EPA permitting process, as we understand that the National Laboratories have been engaged to support the U.S. EPA in technical reviews.

The NRAP tools, combined with EDX, may provide a powerful solution for ensuring the public is able to evaluate the risk of a nearby project without the need for companies to publish sensitive ownership information, models, or plume areas. This study found 19 in-depth geologic studies from several geologic basins and reservoirs formations that are relevant to the current queue of CCS projects (Section 4.2.1). Because the current effort was only seeking the application of NRAP tools, additional studies covering these and other basins and reservoirs likely exist within EDX and the body of published literature. An effort to draw additional, relevant research from EDX and incorporate the findings into the NRAP tools could help public users to independently evaluate the risk of a nearby proposed project.

The current study also sought to develop a process to easily evaluate the use of the tools and the ability of the tool to provide relevant information for a UIC Class VI permit application. The decision trees presented in Section 6.0 provide a logical stepwise approach to evaluating the tools. While there are additional considerations that could have been included in the decisions trees, they were created in a way to determine the following (in order): (1) if the question being answered by the tool was relevant to the project, (2) if the required and preferred data were available and within the accepted range of the tool, (3) if the tool had been demonstrated in a similar setting, and (4) if the user had access to the proper expertise to interpret the results.

The expert interviews allowed evaluation as to the perception and use of the tools by many different stakeholders in the CCS industry. Through this process, many conclusions became apparent about the possible inclusion of NRAP tools in the Class VI permitting process. While many interviewees were content to continue using the tools that have been through decades of use and refinement in related industries, there is a desire to see some standardized tools reach regulators. There is also a willingness to try NRAP tools or reassess, but many of the experts indicated that they were uncertain if the regulatory agencies would accept them for a UIC Class VI permit application. The knowledge that the regulators are open to applications that use the tools to generate information for permit applications is communicated through this study as well as by Lackey et al. (2022). This information should be more widely promoted.

One of the points raised during the expert interviews was a reticence to use results that indicate a leak is possible in a UIC Class VI permit application. The experts who raised this point preferred to present the case for why their projects were protective. This approach, however, may mean that useful information that might arise from a comprehensive risk assessment is missing from the project application. The solution to this is to put the leakage results into context. Last et al. (2016) provides a framework for placing noted groundwater degradations into context using accepted regulatory thresholds and establishing background concentrations for key analytes. Additional work to ensure that the probability of leakage of CO_2 or brine is placed into context and communicated effectively is needed to allay concerns of overstating or understating risks of leakage.

Finally, the study recognizes that the NRAP group continues to create tools relevant to risk assessments for geologic storage projects. Forthcoming tools include the RAMP and TALES models (Dilmore et al., 2024). The NRAP development team provided an update on the development of these tools, including platform and poster presentations, demonstrations of the tools, and a listening session at the 2024 DOE FECM/NETL Annual Project Meeting in

Pittsburgh, PA. While evaluating these tools is beyond the scope of this study, the ability for TALES to provide liability assessments may help close a gap that was identified through the expert interviews reported in the current study.

8.0 Conclusions and Next Steps

8.1 Summary of Tool Accomplishments Relevant to UIC Class VI Permit Applications

The body of research indicates that NRAP tools can be used for analyses relevant to UIC Class VI permit applications. These analyses include demonstrating containment or a low risk of leakage, calculating AoR and risk-based AoR, proposing a phased corrective action plan, developing an ERR Plan (see Section 2.3.1) as well as determining the potential for induced seismicity (see Section 2.3.2), and developing a responsive monitoring program (see Section 2.3.3). The applicability of tools has also been demonstrated by several government-sponsored projects (see Section 4.2.1).

The NRAP tools are recognized by the research community as valuable tools for completing risk assessments (see Section 3.0). Many of the experts interviewed indicated that they were familiar with the NRAP tools and many saw value in their outputs. One of the experts interviewed indicated that they used the NRAP tools in direct support of a Class VI permit application. Some of the experts interviewed, that were not yet aware of the NRAP tools, expressed interest in looking into their capabilities. Others were reluctant to use the tools because they were already comfortable with the commercially accepted tools they currently use. These experts indicated that they would use the NRAP tools if they answered questions that were currently beyond the capabilities of their existing tools.

The NRAP tools (NRAP-Open-IAM, in particular) have been demonstrated in a large body of research and through several government-sponsored projects. The projects span several geologic basins (e.g., the Gulf Coast, the Illinois Basin, the Williston Basin, and the San Joaquin Basin), lithologies (i.e., clastic and carbon reservoirs), and key reservoirs (e.g., Mt. Simon Sandstone, the Broom Creek Formation, and the Paluxy Formation) (see Section 4.0). The reservoirs for which applicability of NRAP tools has been demonstrated include several key reservoirs where commercial CCS projects are being developed (e.g., the Mt. Simon Sandstone, the Broom Creek Formation, and the Paluxy Formation). The NRAP-Open-IAM and SOSAT tools are capable of modeling risks under geological and reservoir conditions that are relevant to many of the geologic carbon storage projects that are currently under review by EPA's UIC Class VI program (see Section 5.0).

8.2 Recommendations and Next Steps

Several recommendations and next steps were developed as part of the study.

There is a need to demonstrate tools beyond NRAP-Open-IAM. While the NRAP-Open-IAM has been demonstrated by several government sponsored projects, other tools, like SOSAT and ORION, do not have the same body of research. Consider promoting these tools for use in DOE-sponsored studies to develop this body of research.

Promote the tools with write ups discussing how they work and what they address. Some project developers interviewed were reluctant to use a tool that is not a widely used product in industry and/or not developed by them for the purpose of permitting. Some of the operators specifically mentioned that they are unlikely to use a tool, particularly if they do not understand the model development or underlying research and calculations. . User manual and best practice manuals with an easily digestible understanding of how these tools work, including demonstrations, and where they fit into the CCS project development would help address these concerns.

Continue the dialogue with the regulators, project developers, and interested stakeholders. Continued discussions between the U.S. EPA and the tool developers could lead to a product that is usable for sanity checks for permit applications (see Section 3.3). In addition, teaching the regulators and permit reviewers, either in states with primacy or on the federal level, how to use the tools for verification of permit application information could help promote their use.

Launching an information campaign for the suite of NRAP tools most relevant to Class VI well permit applications could help this dialogue. There is a need to share information about NRAP tools and conduct training sessions for the people who could benefit from them during the process of applying for a UIC Class VI permit. The audience for this dialogue includes EPA officials, regulatory agencies in states with primacy, third-party reviewers for UIC Class VI permit applications, project developers, decisions-makers at organizations contemplating or currently doing CCS projects, and individuals working in risk analysis. Methods of outreach should include promotional stories published in inter-agency newsletters, workshops (synchronous Zoom classes, in person at EPA regional meetings, Groundwater Protection Council [GWPC], Global CCS Institute meetings), involving non-governmental organizations (NGOs) interested in CCS as evaluators of the tools and as possible beta testers.

Consider developing new tools or components that address some of the gaps in the current commercial and open-source offerings as outlined in this report. Several gaps were identified during the expert interviews. The members of academia/research, industry, and CCS project development indicated that they would find tools that are capable of assisting with the following activities to be useful: screening CCS sites, evaluating induced seismicity and seismic monitoring, dealing with risks posed by legacy wellbores (including providing historical context, suggesting how and when to address these risks, and monitoring the wellbores for signs of leakage), creating efficient monitoring approaches, increasing the transparency of the risk assessments process of a UIC Class VI permit application, estimating flow unit thickness and AoR size in advance of injection, and collating the inputs from widely used commercial software for analysis in a single platform. The regulators interviewed indicated that they would find tools that are capable of assisting with the following activities to be useful: determining the suitability of ERR and financial responsibility plans, providing real-time or near real-time monitoring of pressure and CO_2 plume development, determining the risk of legacy wellbores in the Gulf Coast offshore, and determining the expected integrity of materials used in wells when exposed to CO_2 and other fluids in the subsurface environment. Some of the issues raised by the interviewees are already addressed by the current NRAP tools (e.g., induced seismicity, monitoring efficiency, and leakage from legacy wellbores), indicating an opportunity for the NRAP team to promote their tools as solutions to known problems. Other issues not addressed by the current set of NRAP tools may be areas of future development.

Consider polling a group of individuals from various stakeholder groups with the CCS industry to determine their needs relative to tools to aid in the development of or evaluation of UIC Class VI permit applications. This could help establish an understanding for what the current gaps are to establish information required for permit applications. The next step would be to determine what NRAP tools meet those requirements. This could help focus the efforts of NRAP to develop tools that address these data gaps.

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