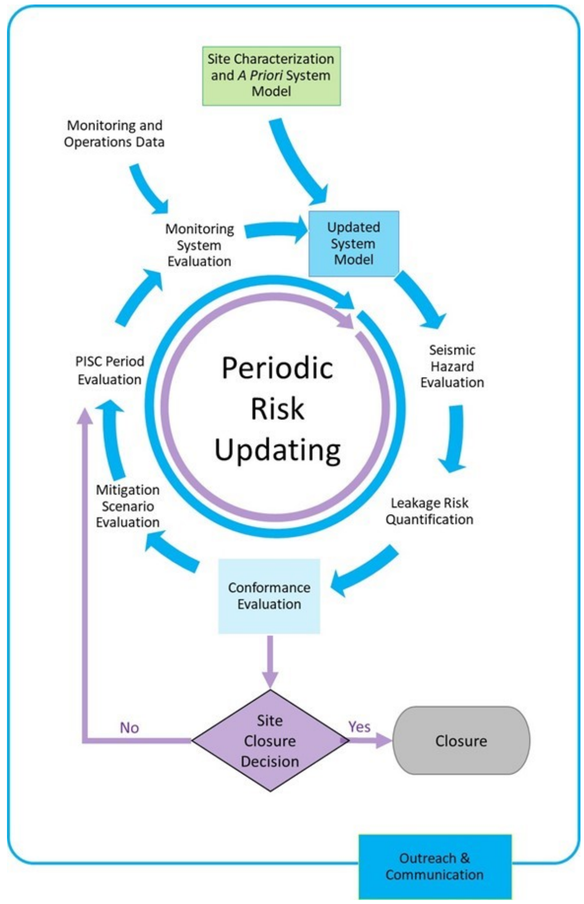

NRAP Recommended Practices for Containment Assurance and Leakage Risk Quantification

21 December 2022

Office of Fossil Energy and Carbon Management

DOE/NETL-2022/3344

NRAP-TRS-I-002-2022

Disclaimer

Cover Illustration: The risk updating cycle operative during the operations and post-injection site care (PISC) project phases. The flow diagram indicates the route to successful closure as well as the recursive nature of periodic risk updates based on operational and monitoring data collection.

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NRAP Recommended Practices for Containment Assurance and Leakage Risk Quantification

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Acronyms, Abbreviations, and Symbols

Term	Description
2D	Two-dimensional
3D	Three-dimensional
ALARP	As low as reasonably possible
AoR	Area of Review
AZMI	Above Zone Monitoring Intervals
CCS	Carbon capture and storage
CCUS	Carbon, capture, utilization and storage
CO_2	Carbon dioxide
DOE	Department of Energy
EnKF	Ensemble Kalman Filter
EPA	Environmental Protection Agency
ERRP	Emergency and remedial response plan
ES-MDA	Ensemble Smoother with Multiple Data Assimilation
FECM	Fossil Energy and Carbon Management
FEP	Features, events, and processes
FMI	Formation micro-imaging
GCS	Geologic carbon storage
HTPF	Hydraulic tests on pre-existing fractures
IAM	Integrated assessment model
IEAGHG	International Energy Agency – Greenhouse Gas Control Programme
IPCC	International Panel of Climate Change
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
LM	Levenberg-Marquardt
MVA	Monitoring, verification, and accounting
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
NRAP-Open-IAM	NRAP Open-Source Integrated Assessment Model
PISC	Post-injection site care
PNNL	Pacific Northwest National Laboratory

Acronyms, Abbreviations, Symbols (cont.)

Term	Description
PRMS	Petroleum Resources Management System
PSO	Particle Swarm Optimization
ROM	Reduced-order model
RPN	Risk priority number
TDS	Total dissolved solids
USDW	Underground Source of Drinking Water
VOI	Value of information
VSP	Vertical seismic profile

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This work was completed as part of the National Risk Assessment Partnership (NRAP) project. Support for this project came from the U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM). The authors wish to acknowledge Mark McKoy (Carbon Storage Technology Manager, NETL Office of Science and Technology Strategic Plans and Programs), Darin Damiani (Program Manager, DOE FECM Carbon Storage), Traci Rodosta (Program Manager, Carbon Storage Testing and Validation), John Litynski (Director, DOE FECM Division of Carbon Transport and Storage), and Mark Ackiewicz (Director, DOE FECM Office of Carbon Management Technologies) for programmatic guidance, direction, and support. The authors acknowledge reviewers from the international carbon capture and storage research, development, and deployment community who took time to provide technical review of this report. We also acknowledge René Frijhoff of PNNL for his thoughtful comments and technical input. Finally, the authors also acknowledge Susan Carroll (Lawrence Livermore National Laboratory), Nicolas Huerta (Pacific Northwest National Laboratory), and Eugene Morgan (Penn State University) who participated in early framing and discussions of these recommended practices.

EXECUTIVE SUMMARY

This report presents recommendations for quantitatively assessing and managing leakage risk and effective containment assurance at geologic carbon storage (GCS) sites, amidst uncertainty in site characteristics and performance. These recommended practices are a product of the U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management's National Risk Assessment Partnership (NRAP)—a multi-year collaborative research effort of Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, National Energy Technology Laboratory, and Pacific Northwest National Laboratory.

These recommended practices are organized as a set of conceptual workflows that correspond with the stages of the GCS project lifecycle. They consider aspects of site characterization, quantification of potential leakage, assessing the spatial extent of potential environmental impacts, optimizing monitoring design for detection of potential leakage, evaluation of concordance between monitored and forecasted reservoir response, assessing conformance with expected/accepted performance, and determination of the timeline over which risk of impactful leakage can be expected to abate. These conceptual workflows are intended to aid stakeholders in making risk management decisions at GCS sites and to support development of sound, risk-based justifications for characterizing the subsurface, defining area of potential leakage impact, designing site monitoring plans, selecting leakage risk management/mitigation alternatives, and estimating site closure timelines.

The recommended practices cover issues related to:

1. Collection and use of site-specific information to support quantitative risk assessment of a GCS site,
2. Use of integrated system performance models that are underpinned by credible representations of critical site features, events, and processes (FEPs) that capture important physical, chemical, and mechanical phenomena influencing site performance and leakage risk,
3. Uncertainty in FEPs at a site (using descriptive and/or inferential statistical techniques),
4. Site monitoring, inspection, and performance observation; parameter and uncertainty estimates; and forecasts of site performance and site monitoring design to account for new information,
5. Decision-making, amidst uncertainty, with respect to potentially impacted area, site monitoring, risk management/mitigation, and site closure, and
6. Risk communication and consensus building between various GCS stakeholders.

Recommendations made herein focus on assessment and management of environmental subsurface risks associated with unwanted fluid migration at GCS sites; a complementary NRAP report makes recommendations for induced seismicity risk management practices at GCS sites (Templeton et al., 2021). To provide the widest utility to GCS project stakeholders, these recommendations are presented in conceptual form and do not directly address any specific subsurface storage or environmental impact regulations or standards. These recommendations will be refined and updated by NRAP researchers as new insights into best practices for risk-based containment assurance and leakage risks are gained.

1. INTRODUCTION

The 2005 Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon Capture and Storage (CCS) (IPCC, 2005) highlighted geological carbon storage (GCS) as a technically feasible technology to sequester substantial quantities of carbon dioxide (CO_2) away from the atmosphere to reduce the greenhouse gas impacts of human activities. That report described the need to develop and implement structured processes to quantify GCS risks, design and implement operations to avoid unacceptable risks, inform monitoring activities and interventions to manage remaining risks, and accommodate and inform various stakeholders. Since then, the international research, development, and deployment community has made substantial progress to develop frameworks and processes to satisfy those needs (IEA GHG, 2009, 2018; Jenkins, 2020; IPCC, 2014; NETL, 2020; Pawar et al., 2015). Going forward, work is needed to ensure that these frameworks and processes can be successfully used to support practical applications of commercial-scale deployment and promote effective risk communication between stakeholders. It is within this context that the U.S. Department of Energy (DOE)'s National Risk Assessment Partnership (NRAP) publishes these recommended practices for containment assurance and leakage risk management at GCS sites.

1.1. NRAP APPROACH FOR QUANTITATIVE RISK ASSESSMENT

NRAP is a multi-year, collaborative research effort that focuses on developing the scientific basis, computational tools, and methods for risk management and uncertainty reduction at GCS sites, undertaken by Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), National Energy Technology Laboratory (NETL), and Pacific Northwest National Laboratory (PNNL).

NRAP's approach to quantifying GCS subsurface environmental risk relies on numerical modeling to forecast full system behavior of GCS sites, while considering site-specific uncertainty and variability. The GCS system, as illustrated in Figure 1, includes the storage reservoir, potential pathways for unintended fluid migration (wells, boreholes, faults, fractures) and receptors of concern (groundwater aquifers and the atmosphere).

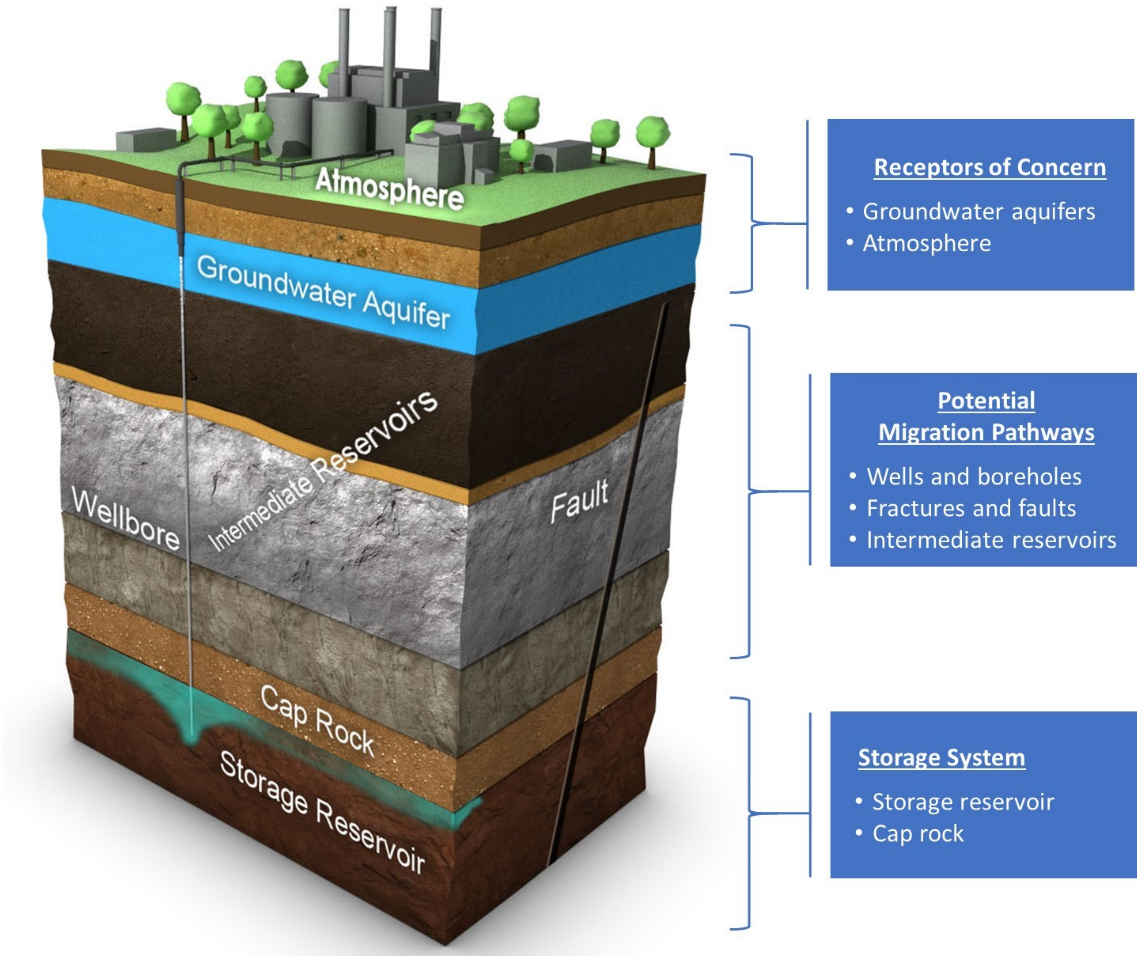

Figure 1: Simplified schematic of GCS site components considered in an integrated systems model for leakage risk assessment.

NRAP uses various computational approaches for rapid characterization of important system behavior in response to CO_2 injection. Physics-based numerical simulations of system component behavior (e.g., Bromhal et al., 2014; Buscheck et al., 2019; Wainwright et al., 2013) are used as the basis for developing reduced order models (ROMS) to enable fast forecasting of component behavior (e.g., Bacon et al., 2013, 2016; Harp et al., 2016; Jordan et al., 2015; Keating et al., 2016;). In select cases, reduced-physics and analytical approaches are also applied to estimate system component model performance (e.g., Huerta and Vasylkivska, 2020; Lindner, 2016; Pan and Oldenburg, 2017). Computationally efficient ROMs are coupled within an integrated assessment model (IAM) to create a tool for fast forecasting of site-scale subsurface system behavior and uncertainty quantification (King et al., 2018; Pawar et al., 2016; Stauffer et al., 2009; Vasylkivska et al., 2021). Focused laboratory, simulation, and field experiments are used to constrain key uncertainties in GCS site performance and to validate IAM forecasts (Huerta et al., 2020; Iyer et al., 2018; Rod et al., 2020; Roy et al., 2018).

Complementary to the systems modeling of site performance evaluation and leakage risk quantification, NRAP is also developing computational approaches for modeling of monitoring—full-physics and data-driven inversion of geophysical data to evaluate the detectability of potential unwanted fluid migration (Appriou et al., 2019; Buscheck et al., 2019; Commer et al., 2022; Feng et al., 2022; Gasperikova et al., 2022; Harbert et al., 2016; Wang et al., 2020; X. Yang et al., 2019; Yang et al., 2022). Models of subsurface system behavior are used together with models of monitoring technologies as the basis for optimization of monitoring design for GCS sites (Chen et al., 2018; Chen and Huang, 2020; Cihan et al., 2015; Yang et al., 2018; Y. Yang et al. 2019; Yonkofski et al., 2016a,b).

These approaches can be applied together to understand important trends in GCS system performance and risk, support GCS project decisions related to site selection, design of injection on operations, and permitting (Bacon et al., 2020; Bacon et al., 2019; Birkholzer et al., 2015; Bromhal et al., 2014; Doughty and Oldenburg, 2020; Harp et al., 2017; Harp et al., 2019a; Harp et al., 2019b; Kroll et al., 2020; Lackey et al., 2019; Pawar et al., 2020; Vasylkivska et al., 2021; White et al., 2020).

Key products of NRAP research include:

- Better understanding of the critical features, events, and processes (FEPs) that control risk and risk uncertainty,
- Computational tools and frameworks that facilitate forecasting of GCS system performance, enable dynamic risk evaluation, uncertainty reduction, and support risk management decisions,
- Recommended practices describing conceptual workflows to quantitatively assess and manage subsurface risks related to potential leakage and induced seismicity at GCS sites, and
- Technical insights related to the acceptability and manageability of subsurface risks at qualified, well-operated GCS sites.

Computational tools developed as products of NRAP Phase II research enable quantitative assessment of subsurface environmental risks and support risk-based decision-making at GCS sites during site evaluation, construction, operational, and post-injection phases (Figure 2). These tools are provided freely to researchers and stakeholders engaged with regulation, development, and deployment of commercial-scale CCS (https://edx.netl.doe.gov/group/nrap-phase-ii-and-iii-tools). A summary of the NRAP tools, relevant background publications, and the NRAP recommended practices is provided in Appendix B. Demonstrations of the various workflows presented in this report are described in detail in several peer-reviewed manuscripts and are summarized in a catalog of use cases described on the NRAP website Huerta et al., 2021).

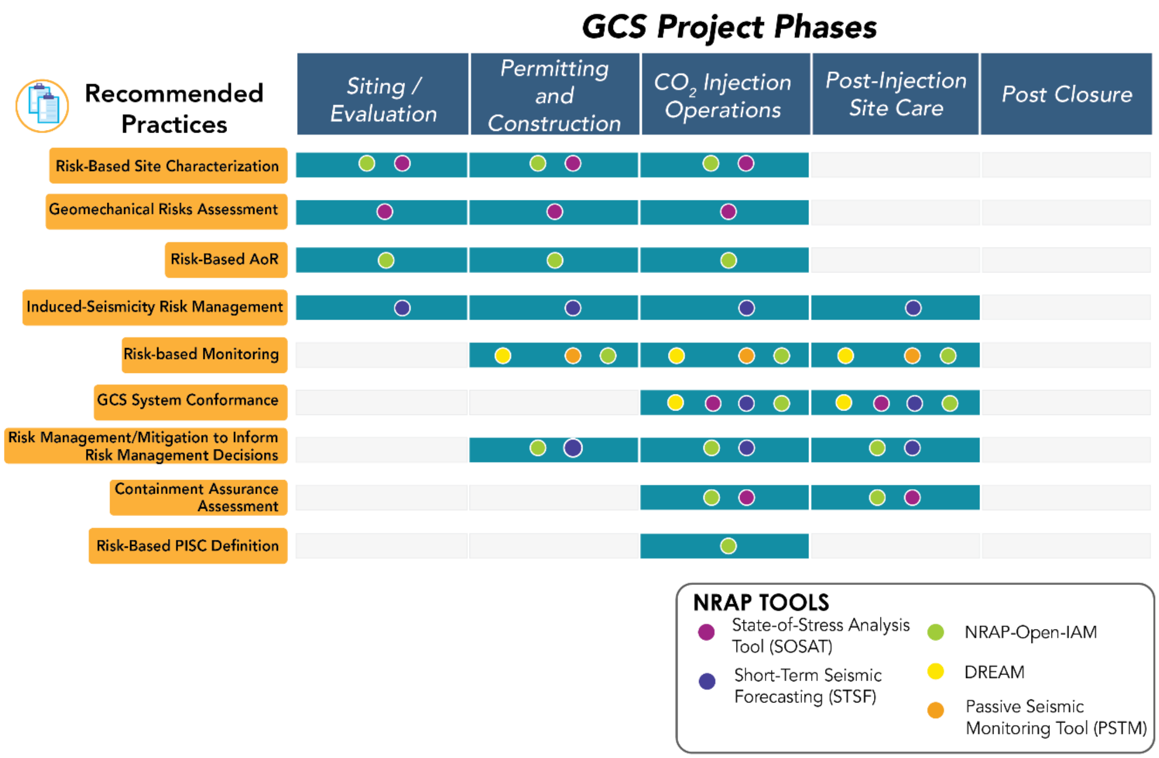

Figure 2: Mapping of NRAP Phase II tools to NRAP recommended practices and GCS project phases.

Ongoing testing, validation, and iterative improvement of these products by the broader carbon capture, utilization and storage (CCUS) research, development, and deployment community will help ensure that they are robust and can contribute meaningfully to DOE's goal of ensuring GCS technology for commercial-scale deployment is secure and environmentally acceptable.

1.2. CONTEXT AND OVERVIEW FOR RECOMMENDED PRACTICES

1.2.1. Concepts of Risk Assessment and Management

Risk management describes a broad set of activities taking place over the entire duration of a GCS project life cycle and includes consideration of all project risks, including financial performance, public acceptance, political viability, technical performance, and liability. These project risks relate to various stakeholder activities, including evaluating project economics, acquiring sufficient pore space rights, gaining public acceptance, assessing and managing subsurface technical risks, and adhering to prevailing legal and regulatory requirements. All GCS project decisions must be made amidst significant uncertainty, while giving stakeholders confidence that the project design is robust and can be successfully constructed, operated, and closed in conformance with various technical and non-technical performance criteria. Those performance criteria are informed by stakeholder perspectives and experience. The performance criteria are also subject to governing economic conditions, legal and regulatory regimes, and perceptions of value over risk.

In risk assessment, criticality is defined as the product of the probability of occurrence of an unwanted condition and the severity of that condition, if it were to occur. Indices of probability and severity are typically evaluated semi-quantitatively by binning severity (e.g., as catastrophic, critical, marginal, negligible) for one or more categories of impact (safety, environmental, operational, non-operational cost), and binning probability of occurrence of unwanted events. Values for each of these are estimated through various means (e.g., expert elicitation, prior system performance, performance of analogous systems, physics-based simulation, or a combination thereof). Results of a semi-quantitative criticality assessment are often illustrated in a risk matrix with traffic light color scheme assigned to acceptable criticality (green), tolerable, if controlled to as low as reasonably possible (ALARP) levels (amber), and unacceptable (red), as illustrated in Figure 3(a).

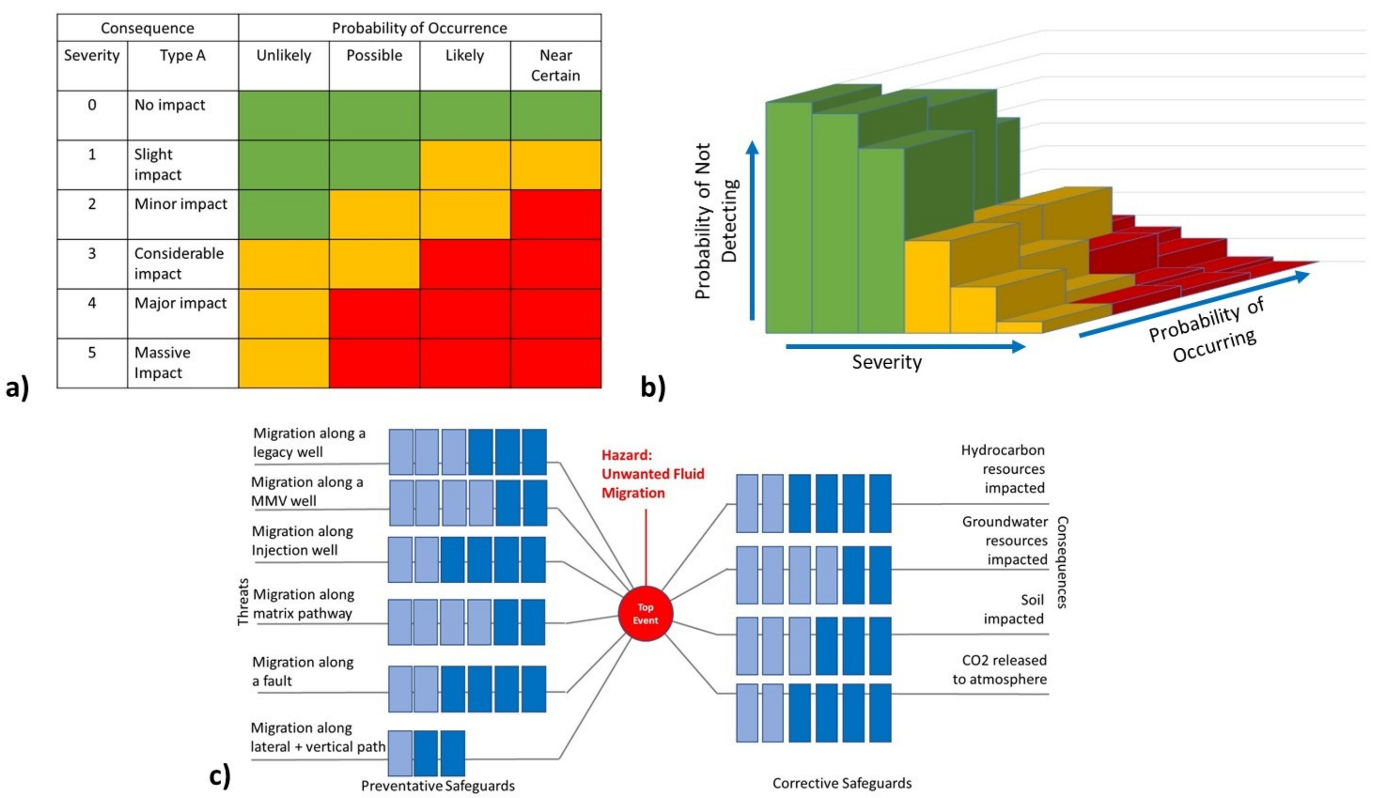

Figure 3: Illustration of select foundational concepts in risk assessment, including: a) a risk matrix, which provides a visually intuitive representation of risk criticality; b) risk priority number, which combines risk criticality and the probability of not detecting a condition of concern; and c) the bowtie diagram, which illustrates how risks can be managed to ALARP levels.

The risk management concept of ALARP categorizes risks as being negligible and broadly considered acceptable, tolerable given that further risk reduction is impractical (i.e., measures have been taken to reduce risks to ALARP levels), and unacceptable and unjustified except in in the most extreme cases. Judgement about what level of risk is acceptable, tolerable, or unacceptable is case specific and subject to prevailing regulation, engineering standards, cost/benefit analysis, and stakeholder perspective. Building toward a common understanding of thresholds of acceptable, tolerable, and unacceptable risk, therefore, is a focus of risk communication between stakeholders.

Site monitoring serves an important element of risk management, and the risk priority number (RPN; a facet of the Failure Modes and Effects Analysis approach) considers the probability of not detecting an unwanted condition at a geologic carbon storages site. RPN is simply the product of the probability of not detecting that condition and the criticality of the condition (illustrated in Figure 3(b)).

The bowtie method is a risk evaluation and management framework that demonstrates causal relationships in engineered systems with inherent operational risk. The bowtie framework (illustrated in Figure 3 (c)) provides a graphical representation of plausible accident scenarios and the passive and active measures in place to control those scenarios—reducing risks to ALARP levels. In a bowtie analysis, practitioners define a “top event” as the event that represents the point at which system control over a hazard is lost and potential for harm is realized (e.g., CO_2 or brine migration above the uppermost geological seal in a geologic carbon storage system; Bourne et al., 2014). This is represented graphically as the central element in a bowtie diagram. The whiskers shown on the left side of the bowtie diagram represent all the potential threats that could lead to the top event—potential migration pathways for fluid migration (e.g., migration along a legacy well). Along each of these whiskers are active and passive controlling safeguards. Whiskers shown on the right side of the bowtie diagram represent distinct potential consequences (e.g., potential impact to groundwater); along these whiskers are active and passive mitigative safeguards. Together, the set of controlling and mitigative safeguards serve to maintain risks to ALARP levels. The qualitative bowtie diagram is underpinned, in assessment of complex engineered systems, by detailed quantitative analysis based on a combination of fault tree and decision tree analysis methods, and detailed, physics-based systems models (Brown, et al., forthcoming; de Ruijter and Guldenmund, 2016).

Quantitative risk assessment, in contrast to semi-quantitative methods, requires substantially more characterization data and numerical systems models to forecast system physical response, but allows for enhanced understanding of risks, factors impacting risks, and benefits of implementing various risk management measures—particularly in the amber criticality region where risks should be managed to ALARP levels. Furthermore, quantitative assessment provides results that can be interpreted relative to thresholds for acceptable engineering performance, regulatory compliance, and detectability as they evolve temporally and spatially and in the context of uncertainty.

Value of information (VOI) refers to a concept and set of complementary methods of decision theory science that seeks to assess the value of new information to ensure robust decision making (Raiffa and Schlaifer, 1961; Eidsvik et al. 2015; Koski et al., 2020). VOI theory holds that the cost of acquiring new data to constrain uncertainty about the condition or performance of a system can be justified only to the extent that the new information helps to inform decisions in the face of uncertainty and relative to defined standards of system performance. VOI methods, generally speaking, must specify the key decision to be made, the uncertain parameters that affect the decision, scenarios that would result from the key decision, and the value (typically monetary, but potentially for another common unit of consequence) assigned to each resulting scenario by the decision maker (Koski et al., 2020). In the context of geologic carbon storage, key decisions relate to site selection, design and permitting of efficient and safe injection operations, design of monitoring to evaluate storage system conformance and ensure regulatory compliance, and post-injection site care and closure timeframes. The recommended practices described herein include reference to collecting new data to better-inform key stakeholder decisions for GCS projects; this concept of VOI is, therefore, embedded in the conceptual workflows.

The risk management process calls for proactive, bi-directional, and ongoing communication between all stakeholders (Aven, 2016)—sharing understandable and actionable information on assessed and perceived risks associated with an enterprise, confidence in assessed risks (uncertainty), definitions of ALARP risk levels, and controls in place to reduce risks to defined ALARP levels (Dean and Tucker, 2017; NETL 2017d). Such dialog and information sharing can build trust between stakeholders and help to establish and maintain "social license to operate."

1.2.2. Managing Risks and Reducing Uncertainties to Build Confidence in GCS Decision-Making

NRAP is primarily focused on forecasting of subsurface performance and assessment of environmental risks at GCS sites—those associated with potential loss of injected CO_2 from geologic containment and leakage into receptors of concern, and with impactful ground motion from CO_2 injection-induced seismicity (Templeton et al., 2021). The subsurface engineered GCS system is subject to both engineering performance constraints and regulatory requirements that must be considered over the project life cycle, and public opinion of real and perceived risks must be proactively considered and addressed.

A principal tenet of the NRAP approach to risk management is that risks should be assessed quantitatively, and important uncertainties treated explicitly and dynamically to better inform stakeholder decision-making over time. There is a series of decisions related to subsurface technical risk that must be made throughout the project life cycle phases (site development, operation, closure, and post-injection site care (PISC)). These decisions are made in the context of uncertainty in the FEPs that govern important subsurface storage-related processes at a GCS site. Many of these uncertainties can be constrained over time as operations and monitoring yield better knowledge of site characteristics and performance; other uncertainties may be recalcitrant or irreducible.

Proceeding with site development and operations requires stakeholders to have confidence that there is sufficient knowledge of site performance at present and that subsequent activity will allow greater understanding of performance over time to support key decisions throughout the GCS project life cycle (current and future decisions). In other words, it requires confidence both that performance will be acceptable over the project's life, and that uncertainties can be sufficiently constrained in the future to make well-informed future decisions. This concept that future decisions should be considered long before those decisions are acute is reflected in GCS regulation and technical guidance that, for example, specifies that Area of Review (AoR), monitoring design, and PISC plans should be established during the site permitting phase and updated periodically over the project life.

In current practice, many site development and operational decisions related to subsurface environmental risks are treated heuristically, based on operator experience. The NRAP approach calls for the integration of various types of site data and information into an assessment framework that enables quantitative, physics-based, and site-specific forecasting of system performance to support more objective decision-making, amidst uncertainty.

In the context of physics-based, quantitative risk assessment being advanced by NRAP, this conceptualization of risk calls for uncertainties in FEPs to be adequately represented directly or indirectly in IAMs of GCS subsurface system performance, with updating of those representations as more information becomes available.

Once developed, an IAM provides a framework to understand the influence of parameter, model, and scenario uncertainty on risk. Conservative estimates of the distribution of uncertainty in independent variables should be established by physical constraints, site characteristics, and credible, defensible expert knowledge. These probability distribution functions are sampled using stochastic Monte Carlo-type sampling or parametric sensitivity analysis techniques. Model uncertainty refers to the uncertainty introduced to system performance models by the uncertainty in the approach that the model uses to represent the behavior of physical systems (e.g., reservoir models that incorporate traditional empirical models of relative permeability vs. those that take into account percolation theory), uncertainty in model boundary condition assumptions (e.g., boundary flow assumptions) and uncertainty introduced by system component integration (e.g., coupling of system component models without accounting for feedback between those components). Finally, it is important that the IAM has flexibility to account for different operational scenarios and choices that might influence system performance and risk at GCS sites, over time. This ability to treat scenario uncertainty is an important feature to enable decision support.

One common critique of quantitative and stochastic modeling of subsurface fluid migration and leakage risk at a GCS site is that these methods are excessively computationally burdensome. NRAP advocates for an integrated assessment modeling approach that relies on coupling of reduced-complexity and/or data-driven proxy models for important system components. By coupling computationally efficient ROMs with the integrated assessment framework, the stochastic forecasting of whole-system behavior is fast, making the IAM a useful and practical tool for probabilistic risk quantification and decision support.

A second critique is that many of the model parameters in subsurface engineered geologic systems are highly uncertain, and propagation of parameter uncertainties can yield unacceptably high uncertainty in forecasts of performance, with limited value for decision-making. This line of thinking suggests that these stochastic models are primarily useful for screening/bounding analyses early in the project life cycle. However, another valuable attribute of the recommended approach is that it is amenable to updating based on observed system performance (operational and monitoring data), which can substantially reduce uncertainties over time and build confidence in forecasts. This iterative approach becomes an important aspect of decision support for risk management at a GCS site.

In practice, model uncertainties are typically accounted for using a variety of approaches including:

1. Verifying predictive models using benchmarking tests.
2. Using ensembles of numerical models to explore the range of uncertainty introduced by model assumptions.

3. Exploring the uncertainty introduced by assumptions in coupling of independently developed component ROMs by developing fit-for-purpose coupled numerical models of physical systems to identify range of parameter space over which coupling is appropriate.
4. Drawing on expert opinion to validate model assumptions and forecasts.

Ultimately the importance of the uncertainty in models should be understood and weighed in the context of the overall uncertainty in system performance.

1.2.3. Overview of Recommended Practices for Leakage Risk Management/Containment Assurance

These NRAP recommendations rely on forecasts of time- and location-dependent risks and uncertainties as the basis for monitoring design, risk management, and informing decisions on project transition between life-cycle stages. The recommendations also call for incorporating observations from site characterization, monitoring, inspection, and performance data to update parameter and uncertainty estimates, and for using quantitative evaluation of concordance between observed and forecasted site performance to evaluate conformance. Revised forecasts based on updated parameters can guide adaptive site monitoring plans and risk management decisions, constrain uncertainty over time, and build confidence in GCS site containment integrity, acceptability of residual risks, and mitigation responses to residual risks. The extent and intensity of additional monitoring should be guided by the value that new information yields for informing risk management/site closure decisions. The authors propose this quantitative approach to better inform stakeholders and foster information sharing and proactive communication on subsurface environmental risks at GCS sites.

The recommended practices described in this document are presented as a series of interrelated workflows, including:

1. Planning and Execution of Risk-Based Site Characterization
2. Assessing the Geomechanical Risks at a GCS Site
3. Delineating a Risk-Based AoR
4. Developing and Using Risk-Based Monitoring
5. Assessing GCS System Conformance
6. Evaluating Risk Management/Mitigation Scenarios
7. Defining a Risk-Based Period PISC and Closure
8. Evaluating CO_2 Containment Effectiveness

While not discussed explicitly in this document, risk communication is also a critical element of risk management at all stages of a project life cycle (NETL, 2017c). Clearly described and defensible workflows can help promote risk communication and build stakeholder confidence.

NRAP recommendations for leakage risk management/containment assurance correspond approximately to the phases of a GCS project as defined by the U.S. EPA (2013a): Siting/Evaluation, Permitting, Construction and Testing, CO_2 Injection Operations, Post-Injection Site Care, and Post Closure – and detailed in Appendix A, Table A1. As compared to the NETL CO_2 Storage Resource Classification (NETL, 2017e), these recommendations apply to qualified sites with contingent storage resources as well as sites with active injection operations (with limited consideration given to site characterization of prospective storage resources that are useful to support initial leakage risk assessment).

This iterative approach for risk assessment, monitoring, risk management, and periodic updating suggests a process of continued improvement in the understanding of the GCS system and an overall reduction in uncertainty with respect to project risks (Figure 4).

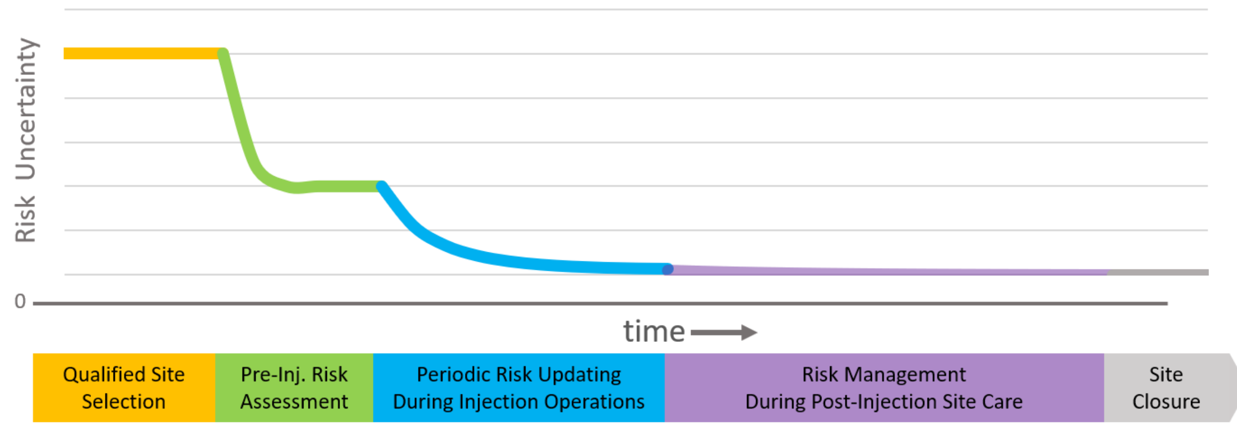

Figure 4: Depiction of the expected reduction in risk uncertainty throughout the lifetime of a GCS project.

The NRAP approach begins with site and risk characterization during the pre-injection phases (Figure 5), with subsequent recursive execution of recommended steps during the operational and PISC phases until risks are adequately managed and site closure is justified, as represented by the looped process flow diagram shown in Figure 6.

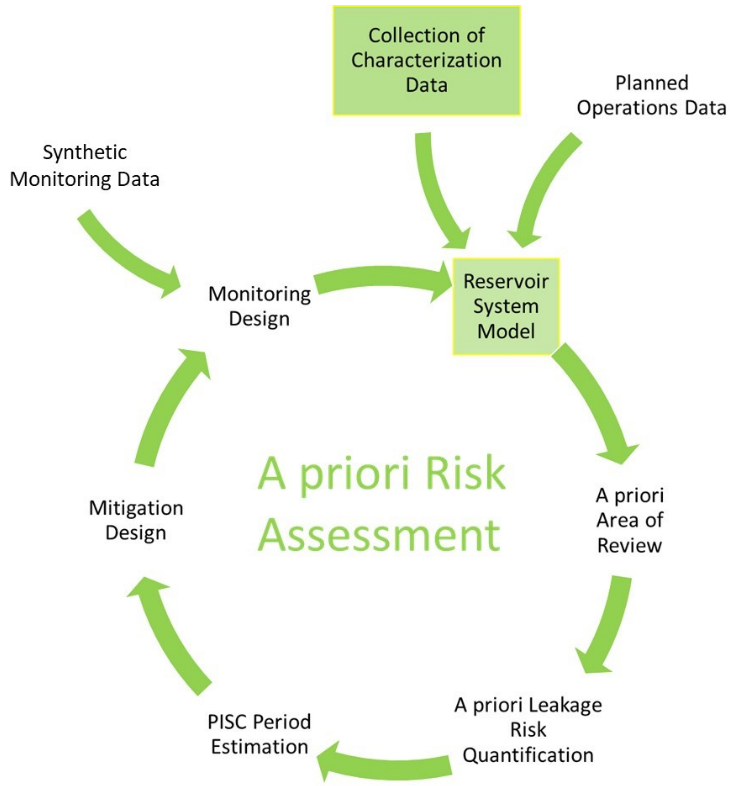

Figure 5: The pre-injection risk assessment updating cycle.

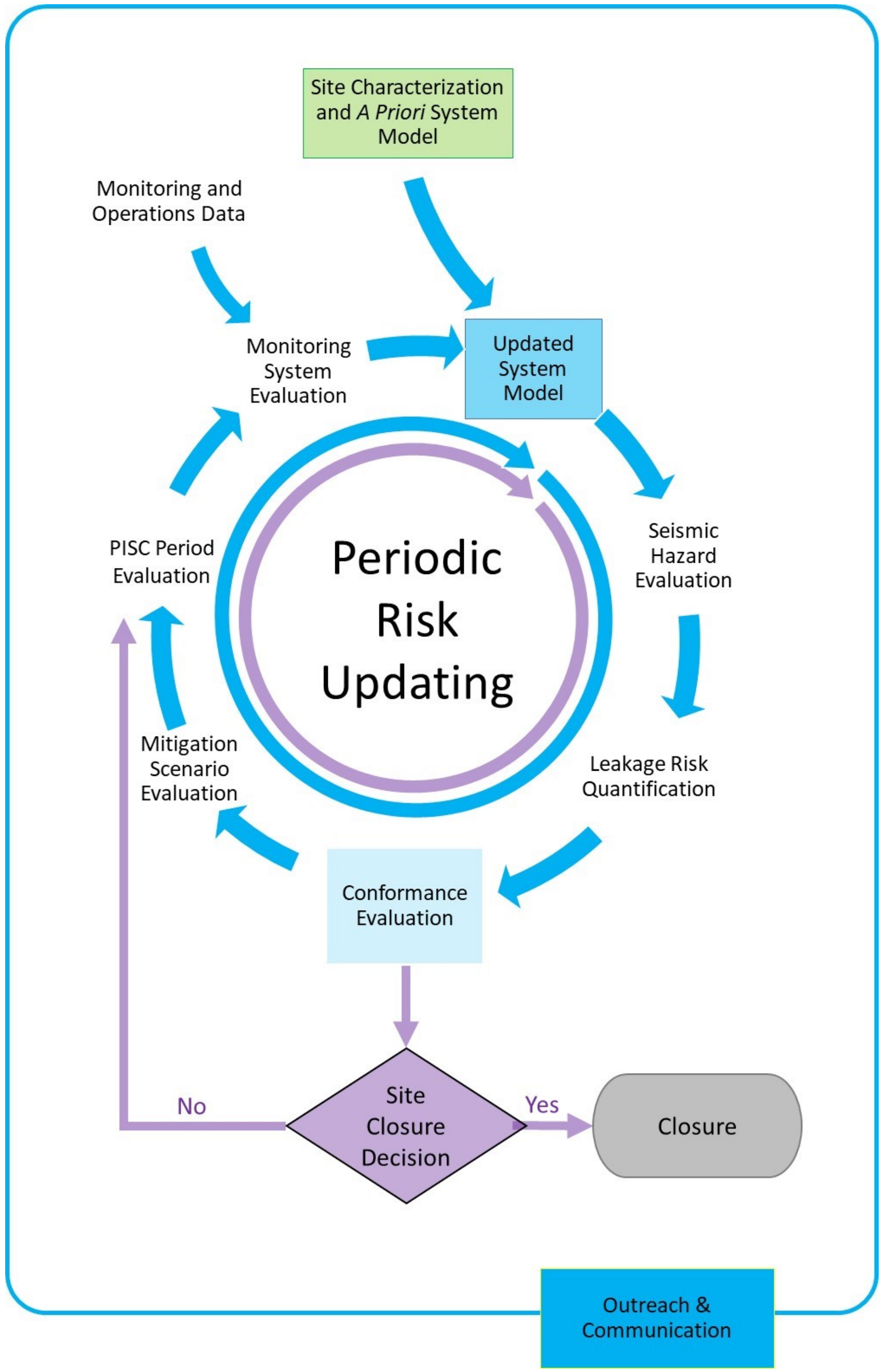

Figure 6: The risk updating cycle operative during the operations and PISC project phases. The flow diagram indicates the route to successful closure as well as the recursive nature of periodic risk updates based on operational and monitoring data collection.

The set of recommended practices is intended for use by GCS project stakeholders to support decision-making over the project life cycle, and relates to questions such as:

1. Site Selection and Evaluation Phase
    - Which subsurface properties control leakage risk?
    - What operational parameters/conditions would minimize geomechanical risks?
2. Qualified Site Injection Design and Permitting Phase
    - How can an appropriate, risk-based AoR be delineated?
    - How might operational choices impact leakage risk?
    - What is an effective design to monitor for leakage?
    - How can containment assurance be probabilistically assessed?
3. Construction and Testing Phase
    - How does improved site characterization affect the AoR delineation?
    - What changes, if any, should be made to initial monitoring design?
4. Operation Phase
    - What site monitoring data should be collected to validate models of GCS system performance?
    - How effective are site monitoring plans at detecting potential leakage?
    - Do monitoring observations agree with model results?
    - Does agreement between performance models and monitoring data give sufficient confidence that injection operations will continue to conform with relevant standards?
    - How can monitoring data be used to update system models, adapt monitoring plans, and inform decisions on appropriate risk mitigation measures?
5. Post-Injection Site Care and Closure
    - How will the risk of leakage and confidence in containment effectiveness evolve after injection stops?
    - How do system model results inform design in the post-injection phase?
    - How long should post-injection site care be maintained, and when is site closure justified?

1.2.4. Caveats and Other Considerations

The recommended practices described herein are general and conceptual in presentation. They were developed from the perspective of onshore geologic storage in saline aquifers at individual greenfield sites, though several of the recommended practices presented may have relevance for injection and storage of CO_2 in onshore brownfield (i.e., depleted oil and gas field utilization and storage) and offshore geologic settings. These recommendations provide value to support stakeholder decision-making faced both by operators and by regulators, but they are deliberately “policy neutral,” making no explicit reference to specific federal, state, or international regulations or standards, but can guide operators and stakeholders in their decision-making. It is hoped that the transparency of the conceptual workflows will facilitate communication among stakeholders and the general public and help to build social acceptance of expanding commercial-scale GCS deployment. Demonstrations of the various workflows presented in this report are described in detail in several published and forthcoming peer-reviewed manuscripts and are summarized in a catalog of use cases described on the NRAP website (Huerta et al., 2021). Future work to engage with operators and regulatory stakeholders to test and demonstrate these recommended practices on more and increasingly complex/realistic cases will drive their improvement and ensure their practical utility.

2. RISK-BASED GCS SITE CHARACTERIZATION

2.1. PURPOSE

Site assessment and characterization are crucial elements of site selection, the most critical component of the permitting process for GCS (Figure 7). Site-screening and site selection efforts include consideration of criteria unrelated to the storage component, such as proximity of the source or CO_2 transport issues. These recommended practices relate specifically to characterization of GCS subsurface performance after preliminary site screening and site selection. Characterization efforts focus on confirming the viability of a site and gathering the information necessary for the permitting process. Risk-based characterization of a candidate GCS site includes activities ranging from data collection and analysis to the demonstration of site suitability through reservoir simulations. All available information is gathered on the critical components (i.e., reservoir, caprock, potential leakage pathways, intermediate formations, and groundwater aquifers) of the GCS system at the sites under consideration. If these sites are greenfields, with no previous development, additional efforts to gather site-specific field data—like drilling an exploratory well—may be necessary to obtain sufficient information about the GCS system. The uncertainty associated with critical components of a GCS site must be constrained using accepted literature values, completing traditional engineering estimations, or gathering site-specific field data. Even after these steps are taken, uncertainties in properties of critical GCS system components will remain, and the implications of these uncertainties should be understood to inform site screening and site selection efforts (Figure 7). This section describes an approach for forecasting leakage risks at a site in a manner that captures the uncertainty associated with site properties. The workflow is intended to be applied early in the site selection process to help identify GCS system properties in need of additional characterization and to finalize the site selection process. The workflow continues through site operation to provide continuous feedback on leakage risks at the site as the uncertainty associated with properties of the GCS system is reduced through monitoring.

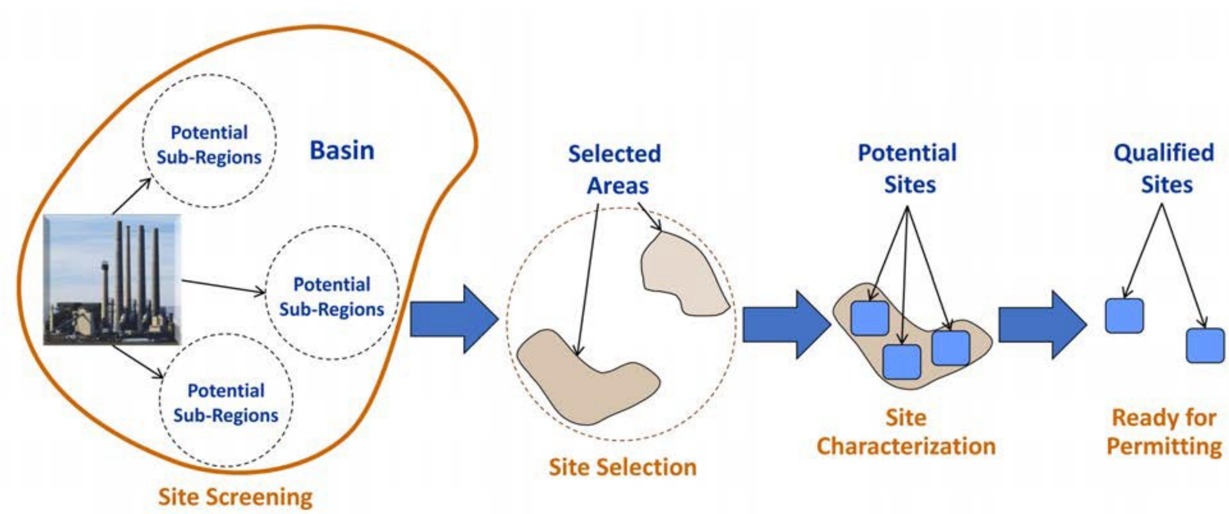

Figure 7: NRAP recommended practices for site characterization follow prior site selection efforts and aid in the development of a qualified site that is a candidate for permit development (NETL, 2017e).

2.2. RECOMMENDED PRACTICES

1. **Characterize GCS system components**
   a. **Gather available data –** Review available field and literature data to determine the characteristics of the important GCS system components (i.e., reservoir, sealing caprock, groundwater aquifers, and intermediate formations). Define ranges of values for key parameters to capture associated uncertainty.
   b. **Acquire additional necessary data –** Identify data gaps and collect data with greatest value to affect future decisions related to permitting, site development, and risk management.
2. **Define potential unintended migration pathways –** Consider all potential leakage pathways (e.g., along the injection well, along legacy wells, through faults and fractures in sealing caprock, spill points) within the area of influence defined for the project. Develop hypothetical leakage scenarios that describe the route by which fluid could escape from primary containment and migration through identified leakage pathways to receptors of concern (e.g., Underground Sources of Drinking Water (USDW) and the atmosphere). Develop a preliminary, qualitative assessment of the likelihood of leakage along identified routes, and potential severity of such leakage.
3. **Define and simulate system response to planned injection –** Using the acquired data, create a reservoir model that is representative of the GCS storage system. Simulate the planned CO_2 injection, considering both the injection and post-injection period. Run multiple reservoir simulations in which uncertain properties are varied over the range of values (e.g., P10, P50, P90) identified through the characterization process. Use the projected extent of the CO_2 plume and pressure-affected area to determine the area of influence for the project (described in Section 4, Developing a Risk-Based AoR).
4. **Quantify unintended migration risks and potential impacts –** Create a system model that simulates the relationship between the reservoir, the potential leakage pathways, and the receptors at the GCS site. Run stochastic simulations of leakage scenarios in which uncertain model parameters are varied over the range of values defined during the characterization process. Assess the severity of impacts to potential receptors. Evaluate data gaps and sensitivity of the model to known and unknown data. Summarize risk profiles for injection scenarios over time.
5. **Update model –** New monitoring and site performance data will be gathered and interpreted throughout all phases of the project life cycle. As needed, these data can be used to update estimates of key parameters, update reservoir and system models, and re-run simulations to improve confidence in forecasts and inform stakeholder decision making.

2.3. SUPPORTING INFORMATION

Data acquisition is the core of the site characterization process. These data inform geologic model, reservoir simulation, and leakage risk assessment modeling that serve as the basis for assessing and building confidence in the suitability of a site for GCS.

2.3.1. <u>Methods of Data Acquisition</u>

There are multiple methods that can be used to obtain data to constrain model parameter input. Each of these have strengths and weaknesses in the types and quality of information that they can provide, and they have varying associated burden with respect to cost and effort required to collect, process, interpret, and integrate into decision-support models. Some widely used methods are:

- Literature review/survey
- Engineering approximations and estimates based on established relationships (e.g., hydrostatic gradient)
- Seismic surveys (e.g., two-dimensional (2D), three-dimensional (3D), vertical seismic profiles (VSP))
- Stratigraphic well drilling (e.g., lithologic and hydrogeologic properties, logging, fluid sampling, core sampling, and subsequent analyses)
- Well logging
- Wellbore imaging, e.g., formation micro-imaging (FMI)
- Well tests (pumping and/or injection tests)
- Geomechanical lab tests/core tests
- Microseismic/induced seismicity monitoring
- Down-hole injection tests to assess permeability, porosity, and fracture points

Examples of parameters that may be derived from pre-injection characterization activities and used in model representations include, but are not limited to:

- Injection pressure (bottom hole)
- USDW zone initial fluid pressure
- USDW chemistry (major and trace elements, pH, electrical conductivity, etc.)
- Initial reservoir pressure
- Initial reservoir fluid properties (water, CO_2, and hydrocarbon-rich phase) properties
- Elevation of the USDW
- Elevation of the injection zone
- Porosity of injection zone
- Permeability of injection zone
- Thickness of injection interval
- Salinity of reservoir fluid
- Water saturation of injection interval
- Capillary pressure
- Reservoir rock compressibility
- Storage reservoir relative permeability of brine and CO_2
- Location of any geologic features or artificial penetrations (e.g., faults, wells, and mines) that may connect the injection zone to USDWs
- Boundary conditions – flow rate and/or pressures at the edges of the model domain and near injection/extraction well locations

These data are applied within static geologic models representing the characterized system, and subsequently in dynamic reservoir simulations and integrated models of whole GCS system performance. These models and model forecasts should be used to understand the sensitivity of forecasts to parameter, model, and operational uncertainty through parametric studies and/or Monte Carlo-type simulation. Choices about what data should be collected is a function of the utility of those data to inform project decisions; new data should be applied to constrain parameter and model uncertainty to update geologic, reservoir, and systems models.

2.3.2. Storage Design and Reservoir Simulation

During the site design and permitting phase, a geologic model of the geologic carbon storage system is developed, and the initial design of CO_2 injection operations is selected—analogous to a preliminary field development plan in standard oil and gas exploration and production practice. Dynamic numerical simulation of the planned CO_2 injection (forecasts the GCS system CO_2 saturation plume and pressure response through injection and post-injection periods). A modeling approach should be used that captures important physical and geochemical interactions between the injectate, the reservoir, and the sealing caprock. There are several numerical simulation software packages that have been demonstrated to provide credible forecasts of CO_2 injection and storage (both through benchmarking exercises and field demonstrations) that would be acceptable for use in numerical modeling of reservoir behavior. A summary of several of these computational tools and their linkage to the Class VI permitting process is provided by Lackey et al. (2022). The implications on practitioner choices of simulation tool, model parameter representations, domain size and boundary conditions, approaches for reduced-order representations, and model resolution/grid refinement approach should be well understood so that uncertainties can be propagated through to site leakage risk assessments, factored into site development and operational decision-making, and appropriately communicated to project stakeholders.

Note: Changes from pre-injection geomechanical conditions due to CO_2 injection may induce changes to the formation or activation/dilation of existing fractures in the seal that have the potential to become pathways for unintended fluid migration. Characterizing conditions that could lead to such changes is described in Section 3, Assessing the Geomechanical Risks at a GCS Site: Characterization of the State of Stress and Geomechanical Conditions.

2.3.3. Data Output, Interpretation, and Probabilistic Metrics

Reservoir models of planned injection will be applied to generate forecasts to estimate the extent of the pressure affected area and the CO_2 plume, as they evolve over time. By sampling independent parameters over a reasonable uncertainty range, operators can generate probabilistic estimates of plume extent for different operational scenarios, through all project phases.

Operators will need to both forecast the likelihood of leakage out of the storage complex and understand the possible impact that leakage may have on overlying resources.

Capturing Important Plume Dynamics

Reservoir simulation should extend from the beginning of injection operations to a point in simulated time after the CO_2 plume migration ends and the pressure elevation in the storage interval is no longer sufficient to cause movement of fluids into overlying groundwater aquifers. Determination of a reasonable endpoint for simulations can be based on visual inspection of simulation results (e.g., videos of CO_2 plume and critical pressure front evolution) or can use spatial moment approaches that provide information on the dynamics of the 3D plume (Harp et al., 2019b). This ensures that simulation results cover the duration required to assess risks and inform decision-making for injection operations, post-injection, and site closure.

Leakage Risk

Practitioners should assess the following reservoir metrics, and examine the sensitivity of the metrics to the uncertainty ranges of input parameters:

- Pressure-affected area and CO_2 saturation plume evolution at the site, over time
- Cumulative leakage of brine and CO_2 into overlying aquifer(s) over time
- Cumulative leakage of CO_2 into the atmosphere over time
- Leakage rate of brine and CO_2 into overlying aquifer(s) over time
- Leakage rate of CO_2 into the atmosphere over time
- Cumulative distribution functions for the above metrics

Aquifer Impact

Information about groundwater aquifers should serve as the basis to construct (or select) a numerical model or ROM to quantify the impact of brine and/or CO_2 leakage into those aquifers. Results of simulations summarizing the time-dependent probability of aquifer impact can be generated for the following quantities, by running simulations using a range of values for uncertain parameters:

- Change in total dissolved solids (TDS) concentration vs. time
- Change in pH vs. time
- Change in concentration of other constituents of concern (e.g., As, Pb, Cd, Ba, benzene, naphthalene, phenol) vs. time
- Affected aquifer volume (x-, y-, and z-directions) vs. time

In summary, robust site characterization serves as the basis for determining the suitability of the GCS system for the proposed injection, for quantifying the likelihood and magnitude of potential leakage out of the storage reservoir and into receptors of concern, and for assessing the potential environmental impact of that potential leakage. This characterization, along with subsequent performance forecasts and risk assessment, help to inform decisions about injection design, operation, monitoring, risk management, and closure. As such, it is important to: 1) adequately characterize the storage system and capture important parameter uncertainty, 2) build system models that propagate uncertainty through to site performance forecasts, 3) update parameter estimates and forecasts as needed to constrain uncertainty and build confidence in site performance and related stakeholder decisions, and 4) transparently communicate uncertainty to stakeholders to support decision-making. In this way, robust site characterization serves not only to inform design of a storage project and provide supporting justification for injection well permitting, but also serves as the foundation for subsequent decisions and actions made at a successful GCS site.

3. ASSESSING THE GEOMECHANICAL RISKS AT A GCS SITE: CHARACTERIZATION OF THE STATE OF STRESS AND GEOMECHANICAL CONDITIONS

3.1. PURPOSE

Large-scale injection of CO_2 can alter the state of stress at GCS sites. These changes from pre-injection geomechanical conditions may cause changes to the formation, reactivation of existing faults, or opening of fractures in the seal that have the potential to become pathways for CO_2 leakage. To understand these risks, operators should adequately characterize the geomechanical state of stress. These data are also useful for quantifying risks of induced seismicity and leakage caused by unintentional geomechanical responses at potential GCS sites during all project phases. This topic is covered in more detail in a separate NRAP report, *Recommended Practices for Managing Induced Seismicity Risk Associated with Geologic Carbon Storage* (Templeton et al., 2021).

These recommended practices are aimed at guiding operators in assessing the geomechanical risk by properly characterizing the site and considering the uncertainty associated with key parameters relevant to geomechanical conditions from site screening to post-injection site closure.

3.2. RECOMMENDED PRACTICES

The following list discusses the conceptual steps involved in characterizing the state of stress at a candidate GCS site:

1. **Assess pre-injection geomechanical conditions:**
    a. **Gather available data:** Review existing data from the site and region to understand the regional geologic and geomechanical environment. The primary goal of this step is to identify:
        - The key intervals (i.e., reservoir, sealing and underlying formations)
        - Potential heterogeneity in stress field
        - Any pre-existing structural features and orientation (e.g., faults, fractures, reservoir compartmentalization)
        - The level of background seismicity
        - The regional trends in pore pressure
        - The state of stress

    b. **Evaluate initial stress field based on available data:**
        - Define an initial range of values for each parameter that captures its associated uncertainty.
        - Evaluate the state of stress based on this range of values for key parameters using probabilistic approaches.

    c. **Acquire additional necessary data** – Identify data gaps and collect data with the greatest value to improve state of stress assessment and affect future decisions relevant to geomechanical risk (e.g., mini-frac tests to measure in-situ stress).

    d. **Re-evaluate the stress field with new data**

2. **Simulate expected geomechanical behavior associated with injection** – Model the stress field changes (poroelastic effects) based on:
    - Initial state of stress uncertainty determined in previous step.
    - Range of anticipated pore pressure perturbations associated with injection as derived from reservoir simulations (refer to Section 2, Risk-Based GCS Site Characterization) or maximum expected injection pressure.
    - Range of geomechanical properties (i.e., elastic properties) of key intervals.
3. **Quantify geomechanical risks associated with CO_2 injection:**
    - **Quantify risk of induced shear failure –** Analyze fault stability given the state of stress probability distribution and based on a Mohr-Coulomb criterion to estimate the critical pressure (maximum pressure allowed) to reactivate faults.
    - **Quantify risk of unintentional hydraulic fracturing –** Evaluate the risk of hydraulic fracturing as a function of average reservoir pore pressure.
4. **Re-evaluate operational conditions based on existing risk** (e.g., targeted formations, depth, operating pressure, etc.)
5. **Collect monitoring data and perform history match to inform decisions –** As part of the conformance evaluation, measured field data, including pressure, and micro seismicity will be monitored during operation. Additional data (e.g., surface deformation, distributed strain, etc.) can be obtained as part of the monitoring plan, providing additional information on the geomechanical behavior of the system.
6. **Update the model and geomechanical risks:**
    - Determine if the updated model reduces uncertainty.
    - Check that the system's performance is within the agreed-upon threshold and manage pressure effectively, if needed (e.g., operate below Mohr-Coulomb Criteria).

3.3. SUPPORTING INFORMATION

Key components of the quantification of the geomechanical risk at a GCS site are the assessment of the initial stress field before injection and the evaluation of the geomechanical behavior associated with the injection in the subsurface system.

3.3.1. Initial State of Stress Characterization

Prior knowledge about geomechanical conditions is limited at greenfield GCS sites. Even in legacy petroleum fields, oil and gas production is likely to have modified the original stress state, and operators may not have fully assessed overlying formations. As such, evaluation of the pre-injection state of stress in the subsurface is critical for all potential CO_2 storage sites.

The initial stress field depends on multiple parameters that can be measured or estimated with a degree of uncertainty. Previous studies and analyses can be used, and unknown properties can be sampled from a reasonable range. The minimum parameters required to estimate geomechanical risk include the initial pore pressure, elastic properties of each formation, density profile of all overlying formations, directional orientation and magnitude of the three principal stresses, existence of faults or fractures, and analysis of seismic events. Various stress indicators can be used to estimate the stress magnitudes and directions and may include extended leak-off tests, mini-frac stress measurements, earthquake focal mechanisms, wellbore breakouts and drilling-induced fractures, and hydraulic tests on pre-existing fractures (HTPF). These parameters, along with their associated acquisition methods, are summarized in Table 1. For an authoritative and comprehensive description of suggested stress measurement methods refer to the Parts 1–4 of the ISRM suggested methods for rock stress estimation (Hudston et al., 2003).

It is recommended to take advantage of available data as much as possible and to supplement these data with further characterization to ensure a safe and reliable GCS site. Ideally, these additional characterization activities will be selected based on cost and efficiency considerations (Burghardt, 2018). Collecting new stress measurements in key intervals of the system is critically important (i.e., reservoir, confining and underlying formations). The state of stress is significantly different in reservoir, caprock, and basement formations. This potential heterogeneity, both vertical and lateral, is critical to understand.

Table 1: List of Reservoir Properties and their Acquisition Method(s) for State of Stress Characterization (Chiaramonte et al., 2008)

Parameter	Acquisition Method
Vertical Stress	Density logs
Minimum principal stress magnitude	Down-hole fracture injection tests
Maximum horizontal stress magnitude	Wellbore failure modeling, earthquake moment tensor data, sleeve fracturing, dipole sonic log
Stress orientation and faulting regime	Orientation of wellbore failure, dipole sonic logs, stress measurement databases
Pore pressure	Pressure monitoring, wireline formation tester
Elastic properties	Core measurements, sonic logs, seismic velocity data
Faults, fractures	Seismic surveys (2D, 3D, cross-well seismic imaging, borehole microseismic), wellbore imaging (FMI logs)
Earthquake focal mechanisms	Seismic catalogs

Probabilistically quantifying the likelihood of reactivating critically oriented faults or creating new hydraulic fractures can be accomplished by modifying traditionally deterministic geomechanical models to accept uncertain inputs. Uncertainty quantification in the construction of geomechanical models can focus on a probabilistic approach using Bayesian methods (Burghardt, 2018) or by performing sensitivity analysis on key parameters (Chiaramonte et al., 2015). During operations, the state of stress model will then be updated when more information becomes available. Further field data are used to validate deterministic model inputs.

3.3.2. Evaluation of Geomechanical Risks

Reactivation of pre-existing fractures (whether they are associated with seismicity, or not) and unintentional hydraulic fracturing are the main geomechanical risks posed by changes in pre-injection geomechanical conditions.

Once the initial stress field is defined with a range of uncertainties, the expected geomechanical behavior associated with injection should be simulated based on planned operating conditions and pressure perturbations expected from reservoir simulation. The permeability and porosity field will influence the pore pressure distribution and its variation over time. It is important to recognize that the accuracy of the geomechanical analysis is highly dependent on the quality of the pore-pressure estimation.

The most accurate approach to geomechanical simulation is using a two-way coupling between the fluid flow and geomechanical models. Given the uncertainties involved, a one-way coupling, with the pore-pressure field forecasted by reservoir simulation used as an input to a geomechanical simulator, is likely adequate in most circumstances. Analytical geomechanical analyses, usually based on a uniaxial vertical strain assumption, offer much less accuracy and have been shown to underestimate the change in stress induced by injection (Burghardt, 2017).

To avoid unintentional hydraulic fracturing, the effective stress must remain compressive throughout both the reservoir and sealing formations. This compressive stress is accomplished when the pore pressure is less than the minimum principal *total* stress throughout the domain of interest. To properly evaluate this criterion, reliable measurements of the minimum principal stress are needed in both the reservoir and primary sealing formation. It is possible for a fracture to initiate in the caprock and not within the reservoir (Fu et al., 2017), so it is critical that the analysis include both formations. To quantify the risk of unintentional hydraulic fracturing, one proposed approach is to define a maximum tolerable probability of fracturing (e.g., 1%, 3%. etc.) and then evaluate the associated maximum allowable injection pressure over time using that definition (Burghardt, 2018).

The analysis of fault stability will also ideally be performed with a probabilistic approach that accounts for uncertainty in key parameters. For example, while the orientations of some faults are more stable, the safest approach is to assume that undetected critically oriented fractures exist. The risk can be evaluated using the Mohr-Coulomb criterion. Reactivation of existing fractures may be an acceptable risk, but this level of risk acceptance should be defined (e.g., does not jeopardize seal integrity, etc.).

While the geomechanical risk should be evaluated prior to injection, it is critical to continually re-evaluate these risks during operations in light of both new characterization and monitoring data collected. This will facilitate the fundamental goal to maintain pore pressure below an agreed-upon threshold. This pressure management requires active and continuous monitoring of subsurface pressure (bottom-hole) so pressures can be accurately forecasted and compared to reservoir simulations.

4. DEVELOPING A RISK-BASED AoR

4.1. PURPOSE

This workflow demonstrates the delineation of a risk-based AoR using a definition that is analogous to the U.S. Environmental Protection Agency (EPA) regulatory definition of the AoR—the area surrounding the injection well(s) over which operators should inspect and/or monitor for unintended fluid migration out of the subsurface storage complex and potentially into a USDW (EPA, 2013b). USDWs are protected groundwater aquifers that supply, or could supply, a public water system, with TDS below a 10,000 mg/L threshold that are not specifically exempted (identified as having no potential to serve as a source of drinking water). Operators of GCS injection operations monitor the AoR from the beginning of injection operations until the end of the PISC period. The two main factors that govern the extent of the AoR are the size of the free-phase CO_2 plume and the extent of the pressure affected area created by injection—i.e., pressure sufficient to drive formation fluids out of the storage reservoir, through a leakage pathway, and into a USDW.

The conventional AoR is calculated by first determining the critical reservoir pressure that has the potential to lift reservoir fluids along conductive pathways to USDWs, and then delineating the area of the reservoir with pressure equal to or exceeding that critical pressure at any time as a result of injection operations. The second consideration that delineates the conventional AoR is the extent of the dense-phase CO_2 plume within the reservoir. The conventional AoR is the maximum extent of area with reservoir pressure forecasted to equal or exceed the critical pressure or the areal extent of the dense-phase CO_2 plume within the storage reservoir, whichever is greater. The conventional AoR will be periodically recalculated as required by regulation or needed to inform site operation and closure decisions and based on data and information acquired over the project life.

In a risk-based approach, the AoR is delineated based on a probabilistic representation of reservoir response to CO_2 injection, potential leakage to a USDW, and potential degradation of water quality in that USDW (based on application of the concept of net degradation thresholds for groundwater aquifer impact). Methods for determining appropriate thresholds for net degradation for aquifer impacts due to leaking fluids from carbon storage reservoirs have been described in the literature (Carroll et al., 2014; Last et al., 2016; Yang et al., 2018). This approach considers the baseline temporal and spatial variability in concentration of constituents of concern to determine the no-impact threshold, defined as the statistically significant minimum concentration above background that could represent an impact on water quality due to migration of fluids out of the injection zone. In cases where a constituent is undetectable in the baseline measurements, practitioners may choose different criteria that can serve as a reasonable substitute for no-impact threshold—e.g., the minimum detection limit of the relevant sensors or the maximum acceptable contaminant levels based on applicable regulations.

4.2. RECOMMENDED PRACTICES

1. **Use site characterization data to define the conventional AoR.** These steps are more fully enumerated in Section 2, Risk-Based GCS Site Characterization.
    a. The proposed storage interval should be characterized to define key reservoir properties that control injectivity and plume migration. Previous studies and

characterization datasets can be used, and unknown or uncertain parameter values can be described using conservative, but representative ranges and distributions of values.

b. Characterize possible receptor aquifers. USDW and other intermediate saline formations (above zone monitoring intervals, AZMIs) should be identified and categorized based on lithology, salinity, and/or hydrostratigraphy (classification of geologic structure with respect to its water-bearing characteristics).

c. Perform conventional AoR delineation. Define the conventional AoR (the region surrounding the proposed or operating geologic sequestration project where USDW may be endangered by the injection activity) corresponding to prevailing groundwater regulations based on initial greenfield assumptions.

2. **Incorporate leakage pathways and hydrologic units into a Carbon Storage System model** (see Section 2, Risk-Based GCS Site Characterization)

   a. All legacy wells and other transecting, potential conductive pathways (e.g., faults, fractures) within the conventional AoR should be characterized and incorporated into the system model.

   b. Model storage reservoir response based on the current injection schedule.

   c. Establish the extent of CO_2 saturation plume and pressure increase in the storage reservoir.

   d. Quantify the potential leakage of CO_2 and brine to aquifers through the conductive pathways defined in “a”.

3. **Analyze dynamic model results**.

   a. Define relevant thresholds of groundwater resource degradation with respect to stakeholder, detectability, and regulatory requirements.

   b. Pressures, fluid saturations, and potential degradation to USDWs (which may be zero) must be quantified in order to determine the outer boundary of the risk-based AoR.

4. **Delineate risk-based AoR based on modeled impact on USDWs.**

   a. Delineate the areal extent of the relevant degradation threshold boundary for CO_2 and brine, which defines the risk-based AoR.

   b. Stochastic models should be used to compensate for the sparse measurements typical of pre-injection site characterization data and modeling.

   c. An ensemble of models covering the range of possible variation should be used to quantify the variation in the degradation threshold boundary and for delineating a conservative risk-based AoR.

5. **Update risk-based AoR**. Periodic updates to the pre-injection risk-based AoR should be performed to coincide with conventional AoR reevaluations required by prevailing regulation, but it may also be appropriate to consider impacts of proposed or implemented operational changes (e.g., changes in injection rate or other operational parameters to manage the storage reservoir or mitigate leakage risks).

4.3. SUPPORTING INFORMATION

The site characterization information needed to establish a risk-based AoR can be extensive. There is, in particular, a need to identify all legacy wells that penetrate into the injection zone and the USDW. A brief description of types of site characterization data needed to develop a computational model of sufficient quality to delineate a risk-based AoR is listed in Section 2, Recommended Practices to Characterize GCS Sites.

4.3.1. Establishing the Conventional AoR

There are several different conventional AoR calculation methods associated with different reservoir/aquifer conditions, with the general isotropic formula being (EPA, 2013b):

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

where:

ΔP_{if}	increase in pressure that may be sustained in the injection zone without driving fluid migration into the lowermost USDW
P_u	initial pressure at the base of the lowermost USDW
ρ_i	density of the injection zone fluid
g	acceleration of gravity
z_u	depth to the base of the lowermost USDW
z_i	depth to the top of the injection zone
P_i	initial pressure in the injection zone

To properly calculate the conventional AoR, the pre-injection pressure of the injection zone must be categorized as one of the following:

1. Case 1: Underpressured ($\Delta P_{if} > 0$): the hydraulic head in the injection zone is lower than the hydraulic head in the USDW.
2. Case 2: Hydrostatic ($\Delta P_{if} = 0$): the fluid pressure in the injection zone is in hydrostatic equilibrium with the fluid pressure in the USDW (i.e., hydraulic heads are equal).
3. Case 3: Overpressured ($\Delta P_{if} < 0$): the hydraulic head in the injection zone is higher than the hydraulic head in the USDW. The overpressured case is particularly challenging for determination of AoR because of the potential for fluids to flow from the storage reservoir to the USDW through leakage pathways *even without any injection* (Oldenburg et al., 2016).

After field data have been gathered and input to a computational model of the reservoir, the following steps are undertaken to delineate the conventional AoR under Case 1 (where $\Delta P_{if} > 0$). Estimating the conventional AoR under Cases 2 and 3 (where $\Delta P_{if} \leq 0$) is beyond the scope of this document. Studies relating to an overpressured AoR are considered in Oldenburg et al. (2014, 2016) and Burton-Kelly et al. (2021).

Step 1: Determine the extent of the injection zone where pressure buildup in response to CO_2 injection is greater than or equal to ΔP_{if} (i.e., the region that is above the critical pressure), which determines the boundary of the area in which vertical fluid migration could potentially occur between the injection zone and the USDW via an open conduit under the injection scenario (hereafter "pressure front").

Step 2: Inspect model results to determine the maximum extent of the pressure front. After simulating a prescribed injection schedule, the computational model will show the changing reservoir pressure as CO_2 enters the reservoir at each time step. The maximum extent of the pressure front will be the total area of the reservoir with pressure greater than or equal to ΔP_{if} at each time step. When the injection schedule constitutes an equal injection volume every year, the maximum extent of the pressure front will occur at the end of the last year of injection. In other cases, depending on conditions, pressures built up near the injector may dissipate throughout the reservoir after injection stops, halting further migration of the pressure front.

Step 3: Inspect model results to determine the maximum extent of the dense-phase CO_2 plume. If the injection schedule includes the same volume every year, then the maximum extent of the CO_2 plume may occur either at the very end of injection or early in the PISC period. As CO_2 dissolves into the reservoir fluids, the free-phase CO_2 plume may diminish over time; however, long-term gravity/capillary-driven flows can spread the CO_2 plume after injection stops even if dissolution is occurring.

Step 4: Delineate the conventional AoR. This area is represented based on the combined maximum areal extents of both the pressure front (Step 2) and the free-phase CO_2 plume footprint (Step 3).

4.3.2. Establishing a Risk-Based AoR

While the extents of the pressure front and separate-phase CO_2 plume show the potential risk of leakage to a USDW via an open conduit or wellbore, they do not provide quantitative information about the impacts to USDW that could result, should a leak occur. The risk-based approach refines the conventional AoR definition by using a system model to calculate the pressure and CO_2 changes in the storage reservoir in response to CO_2 injection and then, relying on these modeled values, estimates the impacts to USDW from CO_2 and/or formation fluid leakage through one or more fluid pathways (Figure 8 a-c). This approach allows the site operator to identify a risk-based AoR that is protective, given a specified level of impact.

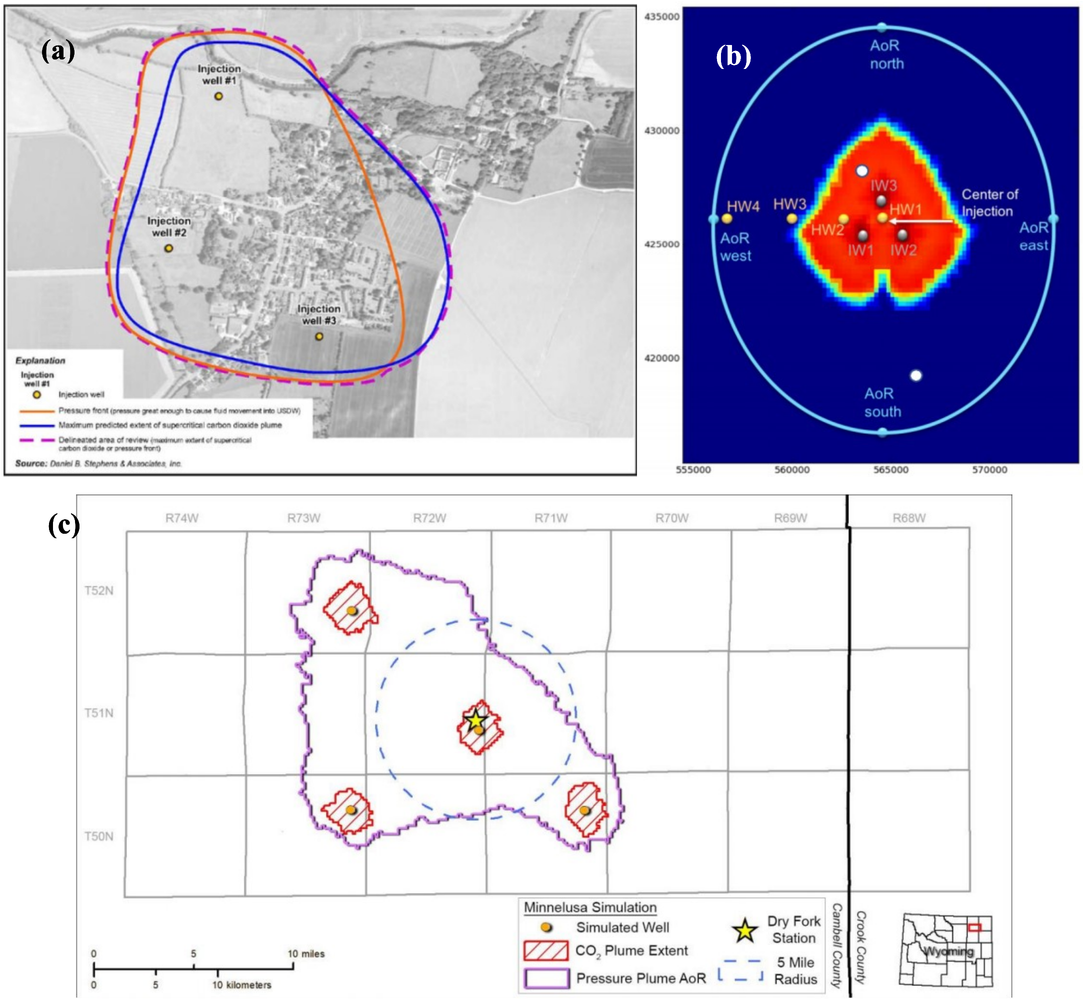

Figure 8: Hypothetical AoRs based on different injection scenarios. (a) A dense-phase CO_2 plume (blue) that is not completely inside the pressure plume (orange), such that the delineated AoR (dashed purple) must be set around the maximum extent of each. (b) A CO_2 plume (red) encircled by a pressure plume for a single injector (White et al., 2018). (c) Multiple injectors with CO_2 plumes in red and the total pressure plume in purple (Quillinan et al., 2018).

While groundwater response to, and impacts from, potential CO_2 or brine leakage are geochemically complex, the most-commonly considered indicators of groundwater impact are increases in TDS and reduction in groundwater pH. TDS impacts could occur if formation water with higher TDS were forced into USDW. Similarly, CO_2 leakage or leakage of carbonated brine could result in an increase in dissolved carbonate, lower pH, and subsequent dissolution of minerals in the aquifer rock.

Figure 9 shows an example map of spatially-varying potential net degradation (risk of TDS impact and fluid migration driven by pressure increase) diminishing towards an outer boundary of the system. The region beyond the 0.10 contour line (pale orange and yellow region) may be interpreted as having less than ten percent probability of TDS impacts to the USDW based on pressure buildup in the storage reservoir and potential conduits within this portion of the storage project footprint. An appropriate risk-based AoR for this system would be determined based on acceptable risk tolerances for the project, which could range from a zero-probability boundary to a no net degradation threshold. During site screening and pre-injection site characterization, the quality of the AoR delineation will be based on the quality of the underlying data acquisition strategy.

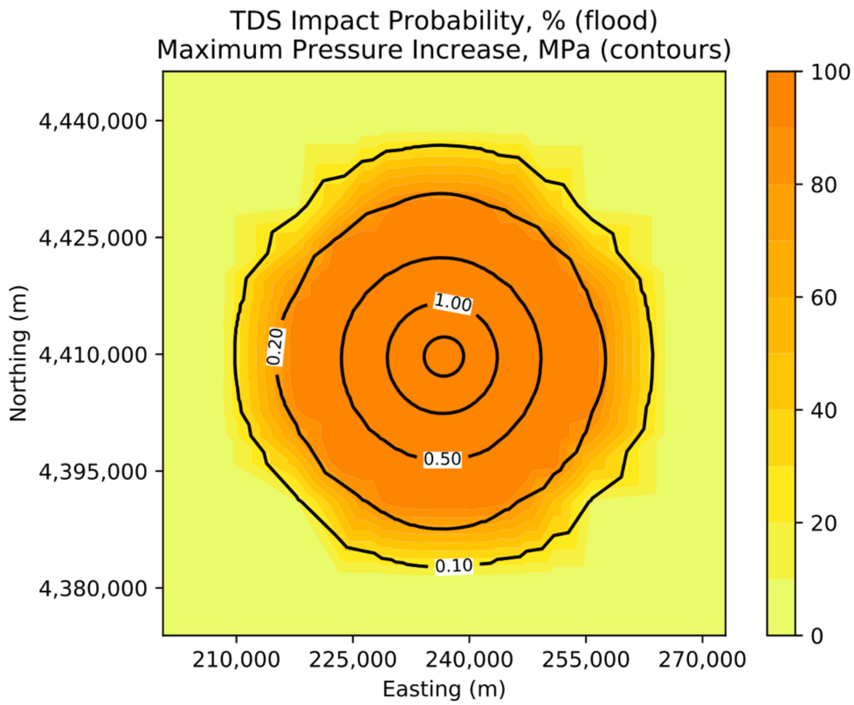

Figure 9: Example of weighted risk profiles for TDS change impacting aquifer chemistry based on maximum pressure increase (Bacon et al., 2020).

Advantages of the risk-based AoR delineation approach include that it considers how site-specific information can serve to constrain the spatial extent of possible groundwater impact, provides a workflow to use new information and growing knowledge of field and performance data to refine and reduce uncertainty in the AoR over time, and supports adaptive design of site monitoring and other site operational decisions.

5. RISK-BASED STRATEGIC MONITORING

5.1. PURPOSE

Monitoring at GCS sites serves a number of important functions throughout the project lifetime. During site characterization, various datasets are acquired to improve understanding of the subsurface and natural system variability (refer to Section 2: Risk-Based GCS Site Characterization). Once the site is considered for a permit application and construction, monitoring baseline parameters and changes in these parameters to be detected are established. During injection and post-injection phases, monitoring provides assurance of containment effectiveness, detection of unintended fluid migration, supporting evaluation of conformance in reservoir response, carbon storage accounting and crediting, and regulatory and permitting compliance. Monitoring also allows for mitigation actions evaluation and supports risk communication and public confidence in groundwater protection and site closure decision-making.

These recommended practices for risk-based strategic monitoring consider specifically the design of monitoring to support the detection of unintended fluid migration from primary containment. Aspects of monitoring related to potential induced seismicity are considered separately in the corresponding NRAP Recommended Practices for Induced Seismicity Risk Management (Templeton et al., 2021).

Effective monitoring provides data and information that serve as the basis to assure regulators and the public that injected CO_2 is safely stored. The ability of a monitoring plan to detect unintended fluid migration early (before potential impact occurs) is critical to support timely and effective risk management decision-making to reduce or avoid environmental impacts. These data are also crucial to establishing an appropriate risk-based estimate of the necessary period of PISC.

An effective monitoring plan should be capable of detecting significant unintended fluid migration into intermediate saline aquifer formations below protected groundwater and avoid impact to protected groundwater aquifers. Monitoring activities may include a combination of direct, well-based monitoring (e.g., pressure, temperature, fluid composition measurements) and indirect, geophysical methods (e.g., time-lapse seismic, electrical, electromagnetic, and gravity surveys). Risk-based monitoring efforts should be dynamic, flexible, and conducted with varying spatial density and time intervals based on assessed risk relating to the probability of unwanted migration and the consequence of that potential migration as the project progresses. For example, the monitoring needs begin with a focus near the injectors at the onset of injection operations but are required at much more distant locations covering larger areas during the PISC period. A risk-based approach to monitoring design is the primary means by which operators can balance the magnitude and intensity of the monitoring efforts with the finite resources to support those efforts.

5.2. RECOMMENDED PRACTICES

1. **Characterize the site and develop an a priori system model.** GCS site system performance forecasts should be developed based on best-available site characterization data and models (see Section 2, Risk-Based GCS Site Characterization).

2. **Define conditions to detect.** Based on available site characterization data and preliminary understanding of site performance, define the conditions of interest for detection (failure, e.g., groundwater quality impact; diagnostic, e.g., the pressure change in the formation above the storage complex, or conformance and CO_2 accounting).
3. **Select candidate monitoring technologies.** Based on the required detection conditions select monitoring technologies most likely to detect the conditions of interest. Depending on the project phase, the appropriate technologies may change.
4. **Evaluate detectability of condition of interest**. A suite of measurements and candidate techniques should be considered. Field measurements from sites in similar geological settings or results from forward simulation of geophysical monitoring should be evaluated to estimate the detectability of conditions of interest.
5. **Define threshold criteria for detection.** Identify the amount of change that needs to be detected to inform stakeholder decisions.
6. **Design the adaptive site monitoring network.**
    a. Develop synthetic site monitoring data for individual known and unknown leakage pathways and identified receptors of interest based on site-specific IAM model.
    b. Define an initial monitoring plan (monitoring technologies and their spatial/temporal intensity) that ensures storage conformance (see Section 6, Assessing GCS System Conformance for more details), protection of groundwater resources, and detects unwanted fluid migration.
    c. Evaluate monitoring network sufficiency.
    d. Modify the network (technology and/or deployment design) as needed to ensure detectability of the conditions of interest.
7. **Use monitoring design/detectability to inform decision-making.** Method-specific monitoring detection capabilities support decisions at GCS sites throughout the project life cycle. These capabilities are also used to support risk management or mitigation decisions, and post-injection site closure decisions (See Section 8, Defining a Risk-Based Period of PISC in Support of Site-Closure Decision-Making).

5.3. SUPPORTING INFORMATION

A monitoring design that assures the detection of unwanted fluid migration from containment at a GCS site (both migration into intermediate aquifers and impactful leakage into receptors of concern) along known possible leakage pathways (e.g., wells, faults) is an integral part of the GCS site design. Figure 10 illustrates components and steps that are involved in risk-based monitoring design. The goal is to maximize confidence in containment assurance and detectability of unintended fluid migration while minimizing time to detection, monitoring intensity, and costs. This conceptual framework also allows for the updating of subsurface models, and dynamic adaptation of the design based on monitoring data. The determination of fluid migration detectability is based on modeling of monitoring for each technique of interest, including considerations of types and levels of noise present at a typical site. Consideration of constraints (e.g., cost/number of sensors, spatial/temporal limitations in monitoring), and the dynamics of site behavior is an important step before adapting and optimizing site-scale monitoring.

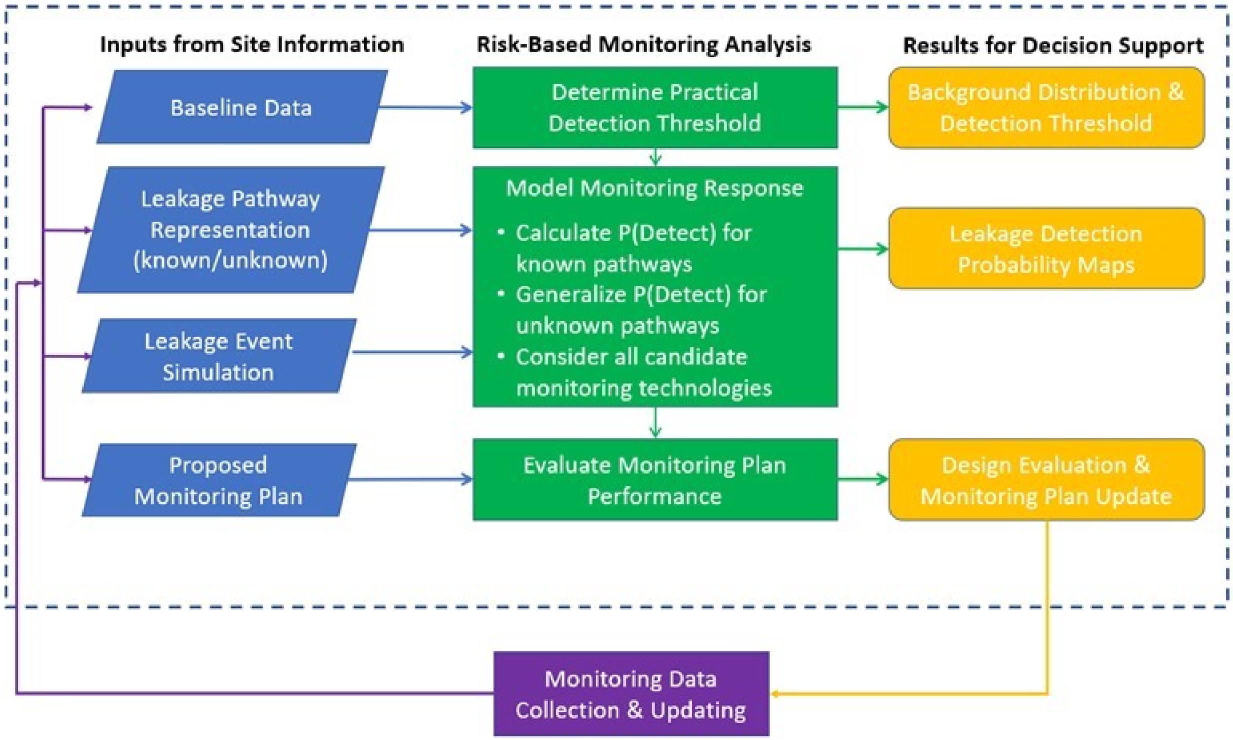

Figure 10: Simplified representation of steps involved in risk-based monitoring design, analysis, design evaluation, and updating (modified from Yang et al., 2018).

The monitoring design evaluation can be done with several representative or stochastic models. In addition to treating uncertainty/variability in the subsurface characteristics, stochastic modeling frameworks can also characterize the impact of potential unidentified leakage pathways on site monitoring design. Full stochastic modeling that links the physical response of the system with the modeling of geophysical monitoring can be extremely computationally burdensome. In some cases, reduced-order modeling/fast forecasting could be employed to make such modeling and interpretation practicable. Detectability estimates should be verified using quantitative thresholds derived from stochastic simulations or interpretation of inversion images to ensure these estimates are reasonable in the context of relevant field experience.

5.3.1. Define the Condition of Interest to Detect

The first step in risk-based monitoring design is to identify the conditions that are of interest to detect to support decision-making and diagnose conditions of concern or impact. This includes detection of impactful leakage (e.g., leakage to receptor(s) of concern – groundwater resources, surface water, or atmosphere) or leakage into intermediate formations. The latter can be used to identify a condition that is not by itself a concern but may be indicative of potential future impact to the receptors of concern (e.g., a pressure and/or saturation change in a porous-permeable interval overlying the primary seal).

Simulations' spatial and temporal resolution should be based on a requirement to resolve the smallest changes of interest for detection and supports the required accuracy for modeling of monitoring. Modeling of geophysical monitoring using coarse simulations of the physical system (e.g., not capturing a feature of interest) could impact the estimate of system change detectability.

Forecasts (deterministic or stochastic) of the response of the GCS subsurface system serves as the basis for modeling the detectability of changes in that system. Changes in the monitoring response are calculated based on characterized system properties, and simulated GCS system response. As with the modeling of site system responses, parameter, model, and scenario uncertainties should be considered when evaluating system change detection and system performance diagnosis. If appropriate, fast forecasting models, reduced complexity or data-driven inversion techniques could be used to analyze ensembles of geophysical responses.

5.3.2. Monitoring Technologies.

Subject matter experts on GCS project teams will develop a preliminary assessment of monitoring requirements based on the understanding of practical detection limits of various monitoring technologies, understanding of the specific site, budget constraints and regulatory requirements. *The Best Practices: Monitoring, Verification, and Accounting (MVA) for Geologic Storage Projects* (NETL, 2017a), Daley and Harbert (2019), and Gasperikova et al. (2022) contain a relatively current analysis of effective monitoring technologies. Figure 11 provides a generalized representation of the spatial coverage and detection resolution of various candidate monitoring technologies. Typically, complementary monitoring technologies will be applied in combination to support detection of multiple conditions of interest, and to enable joint interpretation that could improve the resolution of detection and/or confidence in detection and diagnosis. Beyond expert judgement, quantitative and probabilistic approaches can be used to better understand the detectability of conditions of interest using one or more monitoring techniques. These approaches will be considered in subsequent steps.

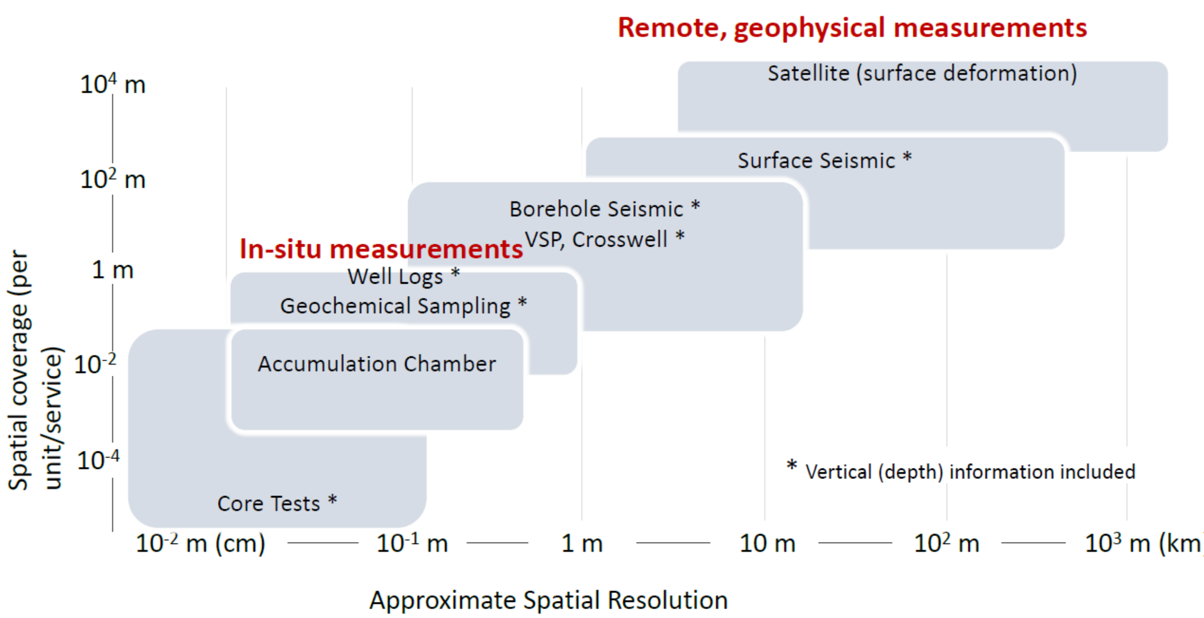

Figure 11: Comparison of the approximate spatial coverage and anomaly spatial resolution of various direct/in-situ and indirect/geophysical monitoring technologies.

Following stochastic modeling of site system response, and using other relevant site characterization data, numerical monitoring simulations estimate the magnitude of the monitoring signal that would be generated from that forecasted change to the system (e.g., the pressure, fluid saturation, or compositional change caused by fluid migration). Each monitoring technology has a specific detectability limit that dictates the data acquisition configuration (e.g., for seismic survey 2D vs. 3D, source-receiver offset, receiver separation, source strength and characteristics, receiver sensitivity, etc.).

5.3.3. Monitoring Network Design

A monitoring network for known and unknown leakage pathways should consider the following design criteria:

1. An optimization framework with multiple objectives (e.g., a monitoring array that yields a minimum time to the first detection of a condition of interest (e.g., well leakage or groundwater impact) as constrained by a set of budgetary, sampling, and sensitivity limitations)
2. Risk-based probability of detection
3. Regulatory or stakeholder requirements
4. Data collection for verification of site model (e.g., monitoring observations are collected and compared against the forecasted responses or calculated responses to evaluate concordance)

Results of monitoring method-specific leak detection and monitoring network effectiveness are applied to support decisions at GCS sites throughout the project life cycle. This includes: site screening; an initial monitoring design for testing, planning, and permitting; risk management and mitigation decisions support during the injection and post-injection; adaptive monitoring design; and PISC decision support.

6. ASSESSING GCS SYSTEM CONFORMANCE

6.1. PURPOSE

Conformance refers to (1) the degree to which the subsurface GCS system is understood as measured by the agreement between model forecasts of the system and measurements of static and dynamic field data (concordance), and (2) the ability of the system to contain CO_2 while remaining within acceptable, projected risk thresholds (performance). The purpose of this workflow is to present an approach for evaluating conformance throughout the life of a GCS project using statistical methods to update reservoir models while ensuring model fidelity and accuracy within agreed upon tolerances given uncertainties in model input. The goal is for the conformance assessment workflow to honor the uncertain nature of the subsurface, provide a quantitative measure of the degree of understanding of the system for effectively storing CO_2, and to support decision-making throughout the project life.

6.2. RECOMMENDED PRACTICES

1. **Collect appropriate characterization and monitoring data.** Conformance evaluation requires measured field data (both static and dynamic, e.g., rock properties and geologic structure (static), pressure and saturation at wells, downhole and surface geophysical data and analysis including by remote sensing (dynamic) for use in evaluating models of reservoir performance).
2. **History match for concordance.** When making projections with an updated model, monitoring data should be compared to the model forecasts iteratively over time. Some popular approaches include:
   - Bayesian inversion ensemble-based approaches, e.g., Ensemble Kalman Filter (EnKF), Ensemble Smoother with Multiple Data Assimilation (ES-MDA)
   - Gradient-based approaches, e.g., Levenberg-Marquardt (LM)
   - Stochastic global approaches, e.g., Particle Swarm Optimization (PSO)
3. **Check the updated model's concordance.** Periodically update the model as new data are available and determine if the updated model reduces uncertainty. Quantify the robustness of the model (check sensitivity of model outputs on uncertainty in inputs, e.g., pressure, average vertical saturation).
4. **Check that the system's performance is within agreed-upon thresholds.** If model forecasts of system performance are within tolerance, proceed with the project. Assess whether monitoring data indicate that the GCS system is not performing to expectations or model forecasts indicate that the system will perform poorly at some point in the future.
5. **Assess conformance based on results of #3 and #4 above.** If the model is in concordance with new monitoring data and current and projected site performance is acceptable, then the site can be deemed conforming, and operations can continue. Otherwise, model updating may be required to improve concordance of forecasts and/or responsive actions may be required to mitigate unacceptable site performance. Responsive actions to unacceptable site performance may include modifying design of injection operations, initiating remedial measures, or ceasing injection operations (See

Section 7, Evaluating Risk Management/Mitigation Scenarios to Inform Risk Management Decisions).

6.3. SUPPORTING INFORMATION

Conformance assessment is a process in which evaluation of GCS site performance relative to engineering standards and regulatory requirements and evaluation of model concordance with monitoring observations is used as the basis to constrain uncertainty, update models, and inform stakeholder decision-making. Concordance refers to agreement between observed data and their corresponding modeled values (Oldenburg, 2018). If a model is not in concordance with observed data, a history match (Chadwick and Noy, 2015) or other method should be employed to refine and update the computational model until concordance is met. If the updated model or ensemble of models shows concordance with observations and continues to forecast acceptable performance for the GCS project within the ranges of the specifications in the storage plan, then the site can be said to be in conformance. As additional measurements are taken, the model's ability to forecast future performance, and confidence in decision-making based on those forecasts should improve. The conceptual process of conformance evaluation, with its main steps of performance and concordance evaluation, is shown in Figure 12.

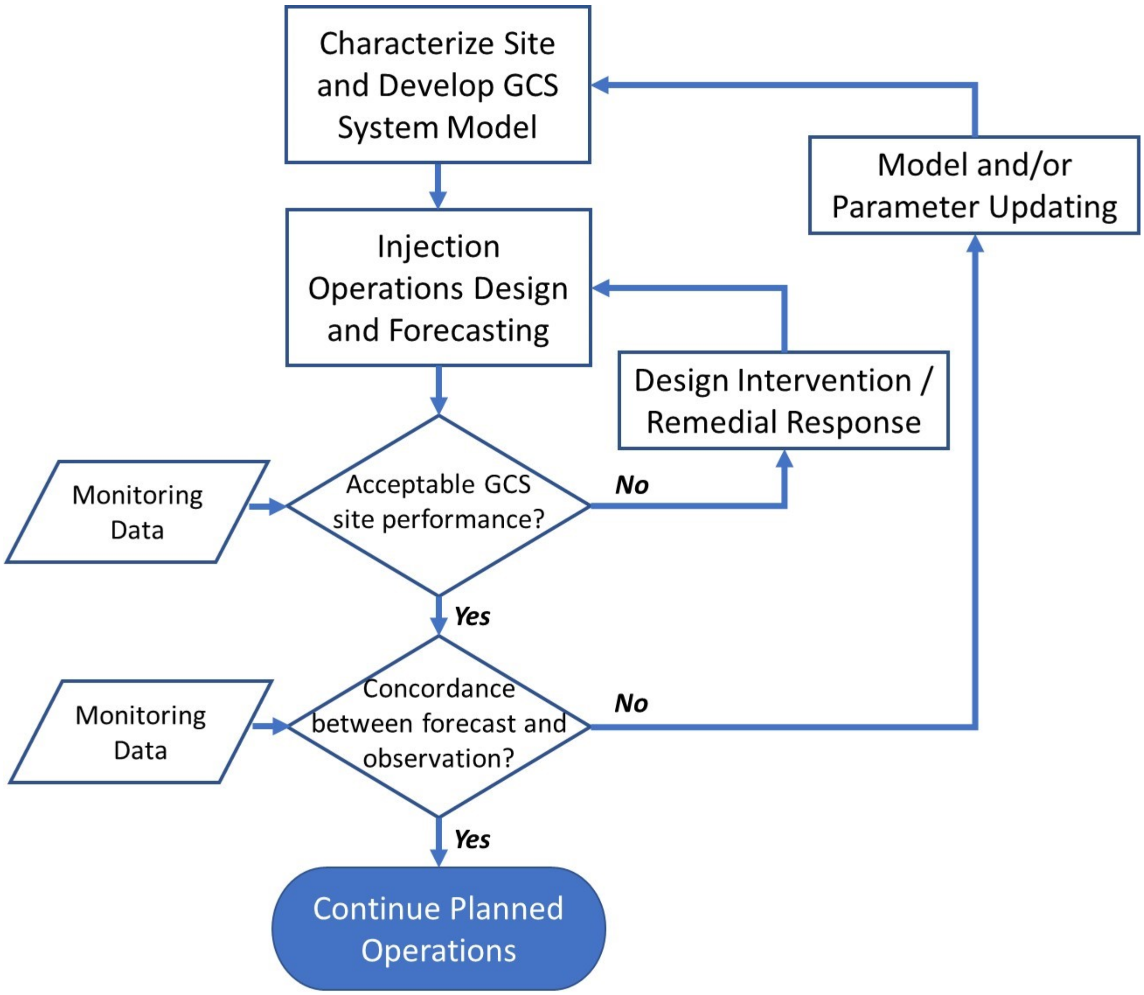

Figure 12: Flowchart illustrating conceptual workflow for GCS operations with conformance assessment.

Figure 13 illustrates the relationship between concordance and conformance and is taken from Harp et al. (2019a), which is slightly modified from Oldenburg (2018). While the purpose of this workflow is to establish methods for measuring conformance, the first step is to evaluate concordance.

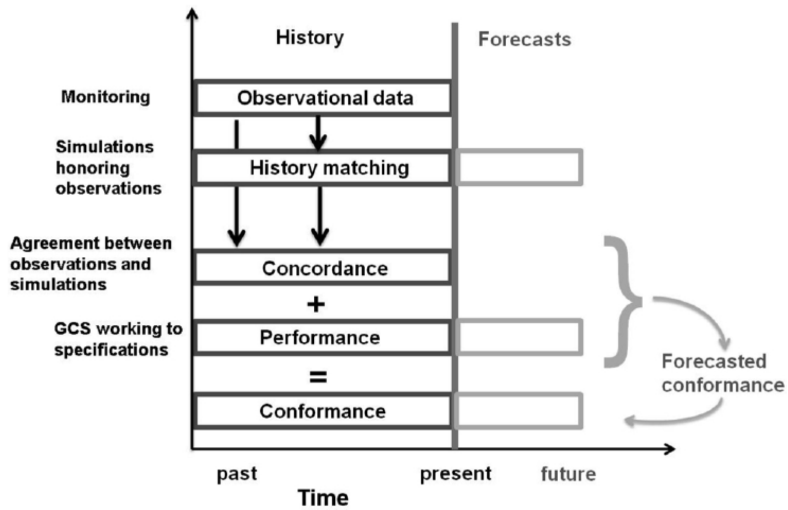

Figure 13: Simplified schematic illustrating conformance as defined in Oldenburg (2018).

6.3.1. Methods of Conformance Evaluation

There are several approaches available for use by operators to evaluate conformance. Two examples of conformance evaluation methods are history matching and conformance robustness analysis.

History Matching

In a history match, measured observations are compared to earlier forecasts of model behavior over the observed time period (Chadwick and Noy, 2015). If the modeled forecasts do not match the measurements, then the source of the discrepancy is identified, reservoir parameters are refined, and the model is updated so that the forecast optimally matches the entire collection (past and current) of measured observations. This process is iteratively applied as new monitoring data are collected and become available, and often the next round of history matching improves the accuracy of forecasts (e.g., CO_2 saturation and pressure observations) and provides for further refinement of the reservoir model(s). Figure 14 illustrates this concept for forecasts of CO_2 saturation; monitoring data can also be used to update estimates of the reservoir permeability field estimates (corresponding data not shown).

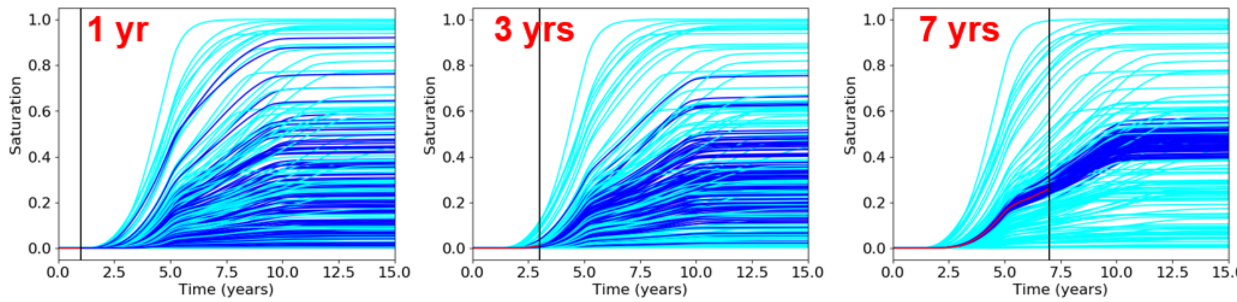

Figure 14: History matching of CO_2 saturation. Measurements collected through different monitoring periods (1, 3, and 7 years) at a monitoring well, and forecasts of CO_2 saturation for the remaining years. Red lines represent the monitoring observation used to constrain uncertainty in forecasts.

Conformance Robustness Analysis

Harp et al. (2019a) demonstrated concepts from information gap decision theory to define a robustness metric for conformance. The main steps of this approach are:

1. Employ a system model in which uncertain properties can be inferred by observed variables.
2. Establish a concordance metric(s) (e.g., the standard error of the estimate of storage reservoir permeability).
3. Establish a performance criterion (or criteria) (e.g., maintaining the maximum allowable pressure at a critical location below the pressure that would cause leakage or seismicity).
4. Build an uncertainty model (e.g., a et-based uncertainty model based on information gap decision theory).

The main goals of conformance evaluation include uncertainty reduction, model concordance, model updating, and ensuring that system performance is within approved tolerances. As more measurements are taken, the model's ability to forecast future performance should improve.

7. EVALUATING RISK MANAGEMENT/MITIGATION SCENARIOS TO INFORM RISK MANAGEMENT DECISIONS

7.1. PURPOSE

A physics-based, probabilistic approach to risk management provides a framework to support operational project decisions in response to deviations in project conformance or monitoring network observations of leakage. Effective processes for identification of mitigation options and avoidance of potential unwanted fluid migration must be in place to give stakeholders and operators confidence that projects can proceed safely.

A properly designed monitoring network should detect events early enough that the impacts may be minimized through mitigation efforts. As projects proceed, monitoring networks measure metrics such as pressure, deformation, plume location, and water quality and provide these data to update project models. The updated models are expected to reduce risk by demonstrating conformance (Section 6). If the site is not in conformance or if a leak is detected, mitigative techniques such as reducing injection rate, producing reservoir fluid from injection or other wells, shutting wells in, or plugging legacy wells may be appropriate. Modification of site monitoring may also be required to understand the effectiveness of risk mitigation measures.

A set of mitigation alternatives such as those described above for the hypothetical impact scenarios of concern should be developed during the site planning/permitting stage—a contingency plan analogous to the Emergency and Remedial Response Plan (ERRP) as defined in the U.S. EPA UIC's Class VI permit application (EPA, 2013b). This contingency plan should be revised, as needed, or as required by prevailing regulation, throughout the project lifecycle—particularly as new knowledge of site performance or hazards is gained, or when site operations are substantially modified.

Integrated models for assessment of site-specific GCS performance and risk can be coupled with estimation of leakage detectability based on a selected monitoring design (Section 4) to enable direct comparison of operational decisions that could mitigate or avoid impactful leakage.

7.2. RECOMMENDED PRACTICES

1. **GCS Scenario Description**
    a. Identify important site FEPs
    b. Characterize system components (e.g., reservoir and seal depth, thickness, structure, porosity, and permeability; seal permeability, thickness, and possible fracture characteristics; and wells and fault locations and attributes, intermediate seal layers, groundwater aquifers) and important uncertainties. (See Section 3, Assessing the Geomechanical Risks at a GCS Site: Characterization of the State of Stress and Geomechanical Conditions)
    c. Develop/select models for various components; build integrated model coupling system components to enable forecast of GCS site risks
    d. Run GCS site IAM for base case, with uncertainty quantification

2. **Develop a priori risk-based monitoring plan** (see Section 5, Risk-Based Strategic Monitoring) including potential leakage pathway assessment, selection of monitoring technologies to be deployed, their configuration, and the temporal and spatial resolution of sampling for each technology, given case-specific considerations (geographic features, site-wide opportunities, spatial access limitations, budgetary limitations, etc.)
   a. Evaluate the probability of detecting hypothetical unwanted fluid migration as a function of key parameters, including uncertainties for:
      - Each monitoring technology and
      - All monitoring technologies in the monitoring plan in coordination.

   Given that the probability of unwanted fluid migration and the intensity of monitoring and combinations of technologies can be expected to vary over time, the probability of detection will also evolve over time.
3. **Estimate the acceptability of risk for the base case**, taking into account:
   a. Probability of occurrence of an unwanted condition (e.g., leakage to USDW) is forecast from GCS site simulations that randomly sample independent parameter distributions (i.e., IAM Monte Carlo simulation)
   b. Severity of effects of that unwanted condition are forecast from GCS site IAM Monte Carlo simulation. (Normalization may be required, taking this from a quantitative IAM result to a semi-quantitative index)
   c. Probability of detection over time is calculated as a function of the monitoring design specifications and monitoring technology effective detection thresholds
   d. Evaluate the criticality of the potential failures (function of probability of failure occurrence and severity of impact) and risk priority (the product of criticality and detectability of an unwanted condition)
4. **RPN comparison for different scenarios**
   a. Where scenarios include operational choices, monitoring design details, and assessed risks, calculated criticalities and RPNs can be compared to inform decision making.
   b. Values for each individual index can be examined independently and in combination to understand which indices make the greatest contribution to the calculated criticality and RPN values.
   c. Document hypothetical scenarios where system is NOT in conformance with expectations (e.g., a potentially leaky well has a much higher effective permeability than initially expected and determined based on monitoring during GCS site operations) and a response to the unwanted condition will be needed.
5. **Define acceptable responses for a set of unlikely, but possible adverse situations**. The integrated assessment model forecasts and criticality assessment can offer an objective means of comparatively assessing the relative effectiveness of candidate interventions in reducing risks to ALARP levels.
   a. Assess the "do-nothing" alternative
   b. Develop a priori planning emergency and contingency plans for possible emergency situations.

c. This conceptual framework aids in risk communication between stakeholders and can help build confidence (aided by performance data, conformance analyses, and updated models) in implementing responses, should such an emergency occur.

7.3. SUPPORTING INFORMATION

As a part of pre-injection planning, a GCS project should have a corrective action plan and a contingency plan for response to possible adverse situations. A corrective action plan describes what needs to be done within the AoR before injection begins and when a site is no longer in conformance, whereas an contingency plans describe the actions that need to be taken immediately following an event.

7.3.1. Remediation and Emergency Response

Within a contingency plan, remediation is preferred to emergency response, as an important part of risk management is addressing risks before they require emergency response. An example event would be an observed low brine leakage rate detected through monitoring of a legacy well. Addressing this leakage early may simply involve managing the pressure around that location to avoid any further leakage, as opposed to requiring emergency remediation of a fouled aquifer after decades of leakage impacts.

Contingency plans should be reviewed and updated during the project lifetime. Several suggestions are made below to address potential risks requiring response in corrective action plans and contingency plans. These alternatives generally fall into the category of interventions that address the leakage pathway or those that modify the storage reservoir response (pressure and or CO_2 saturation plume management). Implementation of reservoir management alternatives will trigger reevaluation of (regulatory and risk-based) AoR and require modification of the monitoring plan to ensure effectiveness of intervention. Alternatives include:

1. **"Kill" the legacy well.** This involves pumping heavy drilling mud into the annular space and/or production string of a well.
2. **Plug the legacy well.** Pump new cement into the well, closing it off. This may require drilling through old cement and recementing.
3. **Drill a production well to remove brine from the reservoir near the leakage pathway.** While this creates a new potential leakage pathway, it also manages pressure and prevents fluid conductance.
4. **Reperforate the well to redirect injection and modify flow and pressure distribution.** This can be helpful when flow distribution occurs within thinner intervals than anticipated, causing larger plume sizes.
5. **Drill a new injection well to distribute pressure buildup.** Well spacing is an important consideration in field development planning and modified injection designs will impact reservoir response and trigger updated estimation of regulatory and risk-based AoR.
6. **Lower the injection volume or rate.** This will decrease the pressure profile in the cone of influence and may be enough to prohibit fluid conductance through the legacy well.

7. **Shut the injection well in.** This is a standard option and is usually employed until the source of the hazard can be identified.

In both the corrective action plan and the remedial response contingency plan, scenario planning is essential for risk management. Scenarios should use "if-then" statements to properly plan for contingencies. For example:

- **If** the pressure buildup at legacy well #6 exceeds 550 psi by year 12 of injection,
- **then** a pressure relief well can be drilled within 6 months. The cost will be $3.4 million to the project.

7.3.2. Linking Risk Criticality to Detectability

Using quantitative, site, and case-specific integrated assessment model results to inform RPNs would help with comparisons of the probability of an unwanted condition occurring, the magnitude of impact of the unwanted condition, and the probability that the unwanted condition will remain undetected. For the base case considered, the probability of detection should conform with some reasonable engineering expectation or other requirements over the full period of operation. Since values (probabilities) for each index will change over time, indices and RPNs should be shown as time varying.

7.3.3. Phased Implementation of Corrective Action and Monitoring and Injection Operations

An important method of risk management is phasing corrective action, monitoring, and injection. The benefit of implementation in phases is that time-dependent costs of corrective action and monitoring can be allocated to future years. Phased corrective action and monitoring approaches can be submitted during pre-injection permitting. Phasing corrective action can allow timing to coordinate corrective actions with plume development and pressure front considerations. Phasing out monitoring wells can also be done during the PISC period, reducing monitoring expenses.

8. DEFINING A RISK-BASED PERIOD OF PISC IN SUPPORT OF SITE-CLOSURE DECISION-MAKING

8.1. PURPOSE

After injection operations have ended, operators must continue monitoring the GCS site to demonstrate compliance with closure criteria—e.g., non-endangerment of USDWs. Once an operator can demonstrate that long-term CO_2 containment is assured and obtains regulatory approval, the PISC monitoring can end and the site can be closed with regulatory approval.

The purpose of this workflow is to define a risk-based approach for PISC and site closure. Activities include establishing an initial risk-based PISC period for the project, periodic reevaluation of the AoR and monitoring for reservoir leakage, and understanding the behavior of CO_2 and pressure plumes until they no longer represent risks of loss of containment.

8.2. RECOMMENDED PRACTICES

Risk-based evaluation of PISC monitoring requirements and building a risk-based justification for site closure is a compound exercise that draws from several activities detailed in other sections of this recommended practices document. The workflow described herein involves the following steps:

1. **Determine the Initial PISC Period**
    - **Update system model** – Start with the stochastic GCS system model developed for the site characterization and risk-based AoR determination. Use the information gathered during site characterization to build a comprehensive GCS system model that includes potential leakage pathways and receptors.
    - **Evaluate site leakage risks over time** – Use the updated system model to simulate leakage risks at the GCS site over the proposed injection and post-injection period. Consider a post-injection period that is sufficient to capture the time frame in which leakage from the storage reservoir no longer represents a risk to USDWs. Run simulations in a stochastic manner that captures the uncertainty associated with key components of the carbon storage system (e.g., reservoir, leakage pathways, aquifer).
    - **Determine leak impact** – Analyze simulation results in context with the proposed monitoring system design (e.g., well location, leak detection threshold) to determine the impact of all simulated leakage scenarios.
    - **Define risk-based PISC period** – The time after which the potential leakage events no longer result in quantifiable impacts to USDWs in the post-injection period is the risk-based PISC period.
2. **Determine when Conditions are Suitable for Site Closure**
    - **Evaluate conformance** – As injection continues and monitoring data are collected, the uncertainty associated with key model parameters is reduced. Updating the GCS site model periodically during the CO_2 injection period will improve the operator’s ability to project plume behavior and evaluate conformance during the PISC period.

Demonstrating that the CO_2 and pressure plumes are evolving as forecasted is a key component in closing the storage complex.

- **Evaluate Non-Endangerment**
    a. Determine leakage risk – using a combination of stochastic leakage modeling and real-time sensor measurements, track key metrics (e.g., reservoir pressure and CO_2 saturation) to determine if the plume is at risk of leaking into USDWs.
    b. Evaluate impact of leakage – Evaluate impact of potential leakage to the USDWs.
- **Closure Decision –** Once conformance and non-endangerment are demonstrated the PISC period can considered complete, and the site can be closed.

8.3. SUPPORTING INFORMATION

After the injection phase of a GCS project is complete, a site transitions into a phase of site care and observation before a closure decision is approved by regulatory authorities. Operators should demonstrate a site's qualification for closure based on site performance and monitoring data and their conformance with monitoring observations (See Section 6, Assessing GCS System Conformance). If leakage risk significantly decreases after injection ceases, the PISC period timeframe may be reasonably reduced (Bacon et al., 2019). Long-term monitoring represents a significant fraction of a GCS project's total cost, therefore, there is value to develop credible initial estimates of a project's PISC time period, and to develop defensible, quantitative analyses to support a justification during the PISC period for closure—based on a demonstration of acceptable and diminishing remaining risk.

Site performance data (e.g., pressure measurements, flow rate, and monitoring data) as well as additional field data collected during site monitoring (when available) to update site models (pre-injection, during injection, and post-injection). It is expected that model uncertainty will significantly decrease with increasing monitoring time (Chen et al., 2020). The reduction in uncertainty facilitates informed decision-making during the PISC period.

8.3.1. Data Output and Interpretation

Much of the data output and interpretation has been discussed in previous sections, and readers are directed to those documents for a more complete description of the various tools and analyses available to operators for characterizing a GCS site. The focus of this section is to highlight the means by which site-specific forecasts of GCS site performance and assessed leakage risk can be used together with monitoring information to constrain uncertainties in future risk behavior and inform decisions about site closure. The basis for such a decision requires the following:

- Confidence that the GCS site has been adequately characterized and all credible leakage scenarios (path and possible leakage-inducing conditions) have been considered.
- Confidence that the future reservoir behavior (plume migration and pressure-affected area) after the targeted closure date will not cause an unacceptable increase in the driving force for leakage for any of the identified leakage scenarios.

- Confidence that models of leakage scenarios are adequate and appropriate, and that forecasts of leakage and associated risks are acceptable given uncertainties in those forecasts (stated differently: the decision to accept remaining risk and close the site is sufficiently robust relative to the uncertainty in forecasts).
- Confidence in sufficiency of monitoring data (and their interpretation) to support an assertion that no unacceptable impact to groundwater or leakage to the atmosphere have occurred through the observation period or are likely to occur in the future.
- An assertion that impactful leakage, if it were to have occurred, would have been observed from site monitoring efforts before the targeted time of closure.

This brings together concepts of improving confidence in models and forecasts based on observation throughout site operation phase and post-injection monitoring period, and confidence that remaining uncertainty in forecasts is sufficiently small to make a justified decision to close the site.

8.3.2. Model Updating

Throughout injection operation and post-injection site care phases, the integrated GCS system model will be updated, as needed, based on information from operational and monitoring data. It is generally expected that model updating will serve to constrain uncertainty in the GCS system model as additional monitoring data are accumulated (Chen et al., 2020). By the time injection operations cease, operators should have relatively high confidence in forecast of future reservoir behavior and leakage risk. This, in turn, builds confidence in the protection of resources of concern and supports decision-making on the appropriate timeframe for site care and closure.

9. PROBABALISTIC ASSESSMENT OF CONTAINMENT ASSURANCE FOR STORAGE ACCOUNTING

9.1. PURPOSE

The primary function of a GCS site is to safely store large volumes of captured CO_2 away from the atmosphere for periods of time sufficient to mitigate its radiative forcing effects. Evaluating the effectiveness of long-term containment can build stakeholder confidence that the GCS project will keep CO_2 out of the atmosphere for a period relevant for mitigating atmospheric warming. Site-specific and physics-based quantification of containment effectiveness can also serve as the basis for designing an adequate monitoring, verification, and accounting (MVA) plan to assure effective containment, and to support the justification for financial claims for GCS.

Practical limitations in the monitoring plan's ability to detect and quantify the mass of CO_2 that leaks out of the containment envelope may constrain the confidence in verification and accounting of containment effectiveness. However, inference of containment effectiveness from monitoring observations with no detectable CO_2 migration through the site operation phase will provide an important basis for demonstrating long-term containment effectiveness.

9.2. RECOMMENDED PRACTICES

A risk-based evaluation of containment effectiveness can be considered as a conceptual workflow that comprises the following steps:

1. **Characterize the site and develop an a priori system leakage quantification model.** GCS site system performance forecasts should be developed based on best-available site characterization data and models, as described in Section 2 of this report. This includes development of an integrated system model that incorporates characterization of storage components, receptors, and other system features, events, and processes.
2. **Define the storage complex and containment criteria.** Accounting for the magnitude of potential leakage from geologic containment requires the practitioner to establish both the spatial and temporal bounds over which containment is to be evaluated (i.e., defining the physical extent of the storage complex and the required minimum duration of CO_2 storage). This requires consideration of prevailing regulations, standards, and/or accounting protocols that may prescribe the definition of these bounds and relevant attributes of the physical system.
3. **Stochastic modeling of site leakage performance, over time.** An IAM should be run, sampling important uncertain parameters to generate a set of realizations of storage system performance and fluid migration into geologic intervals outside of the primary storage reservoir.
4. **A priori quantification of CO_2 migration outside of the containment envelope over the defined containment time horizon.** Results of modeling of the physical system can be used to calculate the mass of stored CO_2 that is predicted to migrate out of the containment envelope by the end of the defined containment period (e.g., by regulation or accounting protocol). Implementing forecasts in an integrated assessment framework can account for parameter (e.g., leakage pathway effective permeability/residual saturation), model (e.g., well leakage reduced order model), and/or scenario (e.g.,

injection schedule) uncertainty. Corresponding estimates of containment effectiveness (fraction of CO_2 retained within the defined containment envelope by the end of the defined effective containment period) can be described relative to these uncertainties.

5. **Evaluate ability of the monitoring plan to determine containment effectiveness.** Practitioners should define an appropriate monitoring plan to meet effectiveness of containment assurance goals. For more detailed consideration of risk-based monitoring design for leakage risk assessment, please refer to Section 5, Risk-Based Strategic Monitoring.
   a. The plan should be based on initial forecasts of potential fluid migration, estimates of potential CO_2 loss from containment (a function of the defined spatial and temporal extent), and knowledge of the effectiveness of various means to detect such unwanted fluid migration (ranging from advanced geophysical monitoring techniques to visual inspection).
   b. Alternatively, a site monitoring plan that was developed for a different primary purpose (e.g., to ensure non-endangerment of groundwater resources) should be evaluated to determine its ability to verify and account for containment effectiveness at the GCS site.
   c. Identify limitations of a monitoring plan to detect and quantify CO_2 leakage from the storage complex. This will be useful for the practitioner to build a justification for claiming containment effectiveness based on a lack of detectible loss from containment and inference of storage performance.
6. **Compare forecasts of GCS site containment effectiveness and estimates of fluid migration detectability with field monitoring observations.**
   a. Using the containment/storage permanence criteria defined in Step 2, the estimates of containment effectiveness as described in Step 4 based on GCS site performance simulations developed in Step 3, and estimates of detectability of unwanted CO_2 loss from containment based on site-specific monitoring plan as described in Step 5, practitioners can evaluate (in the context of uncertainty) concordance between forecasts of containment effectiveness and monitoring observations made during site operations.
   b. Based on this concordance assessment, practitioners can infer long-term CO_2 containment effectiveness.

9.3. SUPPORTING INFORMATION

IAM forecasts of GCS site performance incorporate detailed site characterization data and capture relevant behavior of the physical system. These IAM forecasts can be used as the basis to describe a priori containment effectiveness and support stakeholder decisions for injection operation design, site construction, monitoring design, and permitting. These models should account for uncertainty in GCS site characterization propagates to uncertainty in forecasts of long-term containment effectiveness.

Assessment of the ability for a site monitoring design to detect and quantify potential CO_2 leakage out of a defined containment envelope is useful for interpreting real monitoring observations made during site operation and understanding the ability to infer long-term CO_2 containment effectiveness of the GCS site—amidst system uncertainty. Building a robust and credible justification to support a claim that CO_2 is effectively contained may involve a combination of inductive and deductive reasoning.

An IAM represents a framework that can serve as the basis to assess the probability of containment effectiveness (Pawar et al., 2016) given a defined containment spatial envelope and containment assurance timeframe. An ensemble of IAM simulation results from stochastic forward models of leakage and containment effectiveness for a GCS site can be used to infer (e.g., using a Bayesian network model – estimating the probability of CO_2 leakage mass into overlying, monitorable aquifers, given uncertainties in reservoir properties, effective permeability of potential leakage pathways, and permeability of intermediate formations). These simulations can be used as the basis to develop probabilistic, a priori estimates of containment effectiveness.

The level of uncertainty in that estimate of containment effectiveness (or the level of confidence in an assessment of containment effectiveness) will be a function of the uncertainty in forecasts of storage permanence (given model and parameters uncertainty), and the practical resolution CO_2 migration detectability/quantification, given specific monitoring technology attributes and design of the site monitoring plan. Due to system uncertainty and monitoring limitations, it is appropriate to evaluate projections of containment effectiveness and detectability of CO_2 migration out of containment probabilistically, and to describe inferred long-term containment effectiveness with corresponding confidence bounds (or, in the case of Bayesian statistical inference, the posterior probability that containment effectiveness falls within a defined credible interval). This approach can be used as the basis to help build a justification to claim secure geologic storage, provide a defensible, probabilistic approach to claim quantitative credit for geologic storage, and to estimate the likelihood that any fraction of the claimed credit may need to be refunded to the creditor based on available monitoring information (Wang et al., 2021).

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APPENDIX A: RELATIONSHIP OF NRAP RECOMMENDED PRACTICES TO GCS LIFE CYCLE PHASES

The U.S. DOE's Recommended Practices Manuals for Carbon Storage describe steps in the development and maturity (readiness for commercial injection) of GCS as analogous to standard petroleum industry project development and maturity assessment (NETL, 2017e). The CO_2 Storage Resource Classification System, modeled after the Petroleum Resources Management System (PRMS) classifies GCS projects according to their maturity status (corresponding to its chance of commerciality) as: Prospective Storage Resources, Contingent Storage Resources, and Storage Capacity (analogous to Prospective Resources, Contingent Resources, and Reserves in PRMS). Sub-classes within each of the major classes further break down classification. Prospective Storage Resources include sub-classes (listed in order of increasing maturity) of: Potential Sub-Regions, Selected Areas, and Qualified Site(s), which correspond, respectively, with evaluation processes of increasing detail: Site Screening, Site Selection, and Site Characterization.

Petroleum Industry	CO_2 Geological Storage
Reserves	**Storage Capacity**
On Production	Active Injection
Approved for Development	Approved for Development
Justified for Development	Justified for Development
Contingent Resources	**Contingent Storage Resources**
Development Pending	Development Pending
Development Unclarified or On Hold	Development Unclarified or On Hold
Development Not Viable	Development Not Viable
Prospective Resources	**Prospective Storage Resources**
Prospect	Qualified Site(s)
Lead	Selected Areas
Play	Potential Sub-Regions

Prospective Storage Resources	
Project Sub-Class	**Evaluation Process**
Qualified Site(s)	Site Characterization
Selected Areas	Site Selection
Potential Sub-Regions	Site Screening

Figure A1: Comparison of Petroleum Industry Classification and CO_2 Storage Resource Classification (reproduced from NETL, 2017e).

Following site characterization, qualified sites transition from Prospective to Contingent Storage Resource, and project development proceeds to the operational phase activities, including:

- **Project and Site Development Planning** – major elements of work considered before project begins, including: project design, budgeting, and permitting considerations
- **Permitting** – the application process to secure regulatory permission for construction, injection and operation of a geologic storage project
- **Drilling and Completion Operations** – implementation of drilling, well installation and materials, well completion, logging and formation testing/assessment, and well commissioning activities
- **Injection Operations** – execution of planned injection operations using approved equipment, operating procedures, monitoring, and data collection plans
- **Post-Injection Operations** – project activities related to site management from cessation of injection, including plugging and abandonment of both injection and monitoring wells, post-injection monitoring, and site closure

These designations of operational phase correspond approximately to phases of a GCS project as defined by the U.S. EPA (2013a): Siting/Evaluation, Permitting, Construction and Testing, CO_2 Injection Operations, Post-Injection Site Care, and Post Closure. Given these definitions, the recommended practices for leakage risk management/containment assurance presented herein apply primarily to qualified sites with Contingent Storage Resources progressing through development stages and Storage Capacity at sites where injection occurs. Some consideration is given, however, to aspects of site characterization of Prospective Storage Resources that are useful to support initial leakage risk assessment.

Table A1: Table summarizing the approximate alignment of GCS site activities as defined in the NETL Best Practices Manuals (2017 a-e), and the recommended practices for risk management presented herein, to the phases of a geologic sequestration project as described by the U.S. EPA (2013a)

<table>
<tr><th>U.S. EPA (2013a)</th><th>NETL Best Practices (2017)</th><th>NRAP Recommended Practices</th></tr>
<tr><td>Siting/Evaluation</td><td>Site Characterization</td><td>Site Characterization & Operational Scenario Evaluation, with Uncertainty</td></tr>
<tr><td>Permitting and Construction</td><td>Project and Site Development Planning
Permitting
Drilling and Completion
Logging, formation testing, and core analysis</td><td>Pre-injection Representations of Site GCS Performance and Risk Assessment</td></tr>
<tr><td>CO_2 Injection Operations</td><td>Injection Operations, Monitoring, and Data Collection</td><td rowspan="2">Operational Updates
Periodic Performance Updating
Monitoring Network Data Collection
Risk Management</td></tr>
<tr><td>Post-Injection Site Care</td><td>Post-injection Operations</td></tr>
<tr><td>Post Closure</td><td>(Not considered)</td><td>(Not considered)</td></tr>
</table>

APPENDIX B: A CATEGORICAL CROSSWALK OF THE NRAP RECOMMENDED PRACTICES, TOOLS, AND PUBLICATIONS

RECOMMENDED PRACTICE	RELEVANT NRAP TOOLS	PUBLISHED NRAP APPLICATIONS
Planning and Execution of Risk-Based GCS Site Characterization	NRAP-Open-IAM, NRAP-IAM-CS, WLAT, PSMT	• Bacon, D.; Locke, II, R. A.; Keating, E.; Carroll, S.; Iranmanesh, A.; Mansoor, K.; Wimmer, B.; Zheng, Z.; Shao, H.; Greenberg, S. Application of the Aquifer Impact Model to Support Decisions at a CO_2 Sequestration Site. *Greenhouse Gases-Science and Technology* **2017,** 7, 1020–1034. 10.1002/ghg.1730. • Carman, C.; Damico, J.; Blakley, C.; White, S.; Bacon, D.; Brown, C. *An Assessment of the National Risk Assessment Program's CO_2 Sequestration Leakage Modeling Tools, Subtask 6.1 – NRAP Assessment Topical Report*; University of Illinois; 2018. • Huerta, N.; Bacon, D.; Carman, C.; Brown, C. *NRAP Toolkit Screening for CarbonSAFE Illinois – Macon County;* Topical Report for CarbonSAFE Macon US DOE 00029381; 2020. • Lackey, G.; Vasylkivska, V. S.; Huerta, N. J.; King, S.; Dilmore, R. M. Managing well leakage risks at a geologic carbon storage site with many wells. *International Journal of Greenhouse Gas Control* **2019,** *88*, 182–194. 10.1016/j.ijggc.2019.06.011. • Liao, C.-W.; Wang, P.-F.; Yang, Y.-M.; Dilmore, R. Preliminary Leakage Risk Assessment for Geologic Carbon Storage Site Selection: A Case Study. 14th Greenhouse Gas Control Technologies Conference (GHGT-14), Melbourne, 2018. • Pawar, R. J.; Chu, S.; Makedonska, N.; Onishi, T.; Harp, D. Assessment of relationship between post-injection plume migration and leakage risks at geologic CO_2 storage sites. *International Journal of Greenhouse Gas Control* **2020,** *101*. https://doi.org/10.1016/j.ijggc.2020.103138
Assessing the Geomechanical Risks at a GCS Site: Characterization of the State of Stress and Geomechanical Conditions	SOSAT	• Appriou, D.; Huerta, N. J.; Zhang, Z. F.; Burghardt, J. A.; Bacon, D. H. Evaluation of Containment and Geomechanical Risks at Integrated Mid-Continent Stacked Carbon Storage Hub Sites; 2020. doi:10.2172/1661184. • Burghardt, J. Geomechanical Risk Assessment for Subsurface Fluid Disposal Operations. *Rock Mechanics and Rock Engineering* **2018.** 10.1007/s00603-018-1409-1.
Developing a Risk-Based Area of Review	NRAP-Open-IAM, NRAP-IAM-CS, DREAM	• Bacon, D. H.; Demirkanli, D. I.; White, S. K. Probabilistic risk-based Area of Review (AoR) determination for a deep-saline carbon storage site. *International Journal of Greenhouse Gas Control* **2020,** *102,* 103153. 10.1016/j.ijggc.2020.103153 • McPherson, B.; Cather, M.; Middleton, R; Chidsey, T; Heath, J; Saunders, M; Lee, S.-Y. *CarbonSAFE Rocky Mountain Phase I: Ensuring Safe Subsurface Storage of*

RECOMMENDED PRACTICE	RELEVANT NRAP TOOLS	PUBLISHED NRAP APPLICATIONS
		Carbon Dioxide in the Intermountain West; 2018. 10.2172/1559990 • White, S. K.; Carroll, S.; Chu, S.; Bacon, D.; Pawar, R.; Cumming, L.; Hawkins, J.; Kelley, M.; Demirkanli, I.; Middleton, R. S.; Sminchak, J.; Pasumarti, A. A Risk-Based Approach to Evaluating the Area of Review and Leakage Risks at CO_2 Storage Sites. *International Journal of Greenhouse Gas Control* **2020,** *93*, 102884. 10.1016/j.ijggc.2019.102884.
Risk-Based Strategic Monitoring	NRAP-Open-IAM, DREAM, PSMT	• Bacon, D. H.; Yonkofski, C. M. R.; Brown, C. F.; Demirkanli, D. I.; Whiting, J. M. Risk-based post injection site care and monitoring for commercial-scale carbon storage: Reevaluation of the FutureGen 2.0 site using NRAP-Open-IAM and DREAM. *International Journal of Greenhouse Gas Control* **2019,** 90, 102784. 10.1016/j.ijggc.2019.102784. • Chen, Y.; Huang, L. Optimal design of 3D borehole seismic arrays for microearthquake monitoring in anisotropic media during stimulations in the EGS Collab project. *Geothermics* ***2019****,* *79*, 61-66. • Chen, T.; Huang, L. Optimal design of microseismic monitoring network: Synthetic study for the Kimberlina CO_2 storage demonstration site. *International Journal of Greenhouse Gas Control* ***2020*****,** *95*, 102981. https://doi.org/10.1016/j.ijggc.2020.102981 • Yonkofski, C.; Tartakovsky, G.; Huerta, N.; Wentworth, A. Risk-based monitoring designs for detecting CO_2 leakage through abandoned wellbores: An application of NRAP's WLAT and DREAM tools. *International Journal of Greenhouse Gas Control* **2019,** *91*, 102807. 10.1016/j.ijggc.2019.102807.
Assessing GCS System Conformance	NRAP-Open-IAM	• Chen, B.; Harp, D. R.; Lu, Z.; Pawar, R. J. Reducing uncertainty in geologic CO_2 sequestration risk assessment by assimilating monitoring data. *Int. J. Greenh. Gas Control*. **2020,** *94*, 102926. https://doi.org/10.1016/j.ijggc.2019.102926. • Doughty, C. A.; Oldenburg, C. M. CO_2 Plume Evolution in a Depleted Natural Gas Reservoir: Modeling of Conformance Uncertainty Reduction Over Time. *Int. J. Greenh. Gas Control* **2020,** *97*, 103026. https://doi.org/10.1016/j.ijggc.2020.103026 • Harp, D. R.; Oldenburg, C. M.; Pawar, R. A metric for evaluating conformance robustness during geologic CO_2 sequestration operations. *Int. J. Greenh. Gas Control* **2019,** *85*, 100–108.
Evaluating Risk Management/Mitigation		• Lackey, G.; Mitchell, N.; Schartz, B.; Lui, G.; Vasylkivska, V. S.; Strazisar, B.; Dilmore, R. A Quantitative Comparison of

RECOMMENDED PRACTICE	RELEVANT NRAP TOOLS	PUBLISHED NRAP APPLICATIONS
Scenarios to Inform Risk Management Decisions		Risk-based Leak Mitigation Strategies at a Geologic Carbon Storage Site. 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16 Lyon, France, October 23–27, 2022.
Defining a Risk-Based Period of Post Injection Site Care in Support of Site Closure Decision-making	NRAP-Open-IAM	• Bacon D. H.; Yonkofski, C.; Brown, C. F.; Demirkanli, D. I.; Whiting, J. M. 2019. Risk-based Post Injection Site Care and Monitoring for Commercial-Scale Carbon Storage: Reevaluation of the FutureGen 2.0 Site using NRAP-Open-IAM v2 and DREAM. *International Journal of Greenhouse Gas Control* **2019,** *90*, 1:102784. doi:10.1016/j.ijggc.2019.102784. • Harp, D.; Onishi, T.; Chu, S.; Chen, B.; Pawar, R. J. Development of quantitative metrics of plume migration at geologic CO_2 storage sites. *Greenhouse Gases: Science and Technology* **2019,** *9*, 687–702. • Lackey, G.; Vasylkivska, V. S.; Huerta, N. J.; King, S.; Dilmore, R. M. Managing well leakage risks at a geologic carbon storage site with many wells. *International Journal of Greenhouse Gas Control* **2019,** *88*, 182–194. 10.1016/j.ijggc.2019.06.011. • Pawar, R. J.; Chu, S.; Makedonska, N.; Onishi, T.; Harp, D. Assessment of relationship between post-injection plume migration and leakage risks at geologic CO_2 storage sites. *International Journal of Greenhouse Gas Control* **2020,** *101*, 103138.
Assessment of Containment Assurance for Storage Accounting		• Wang, Z.**;** Dilmore, R.; Bacon, D.; Harbert, W. Evaluating Probability of Containment Effectiveness at GCS Sites using NRAP-Open-IAM and Bayesian Networks. *Greenhouse Gasses: Science & Technology* ***2021***. https://doi.org/10.1002/ghg.2056

NRAP is an initiative within DOE's Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO_2). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

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