Translating Risk Assessment to Contingency Planning for CO₂ Geologic Storage: A Methodological Framework

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May 2016
Abstract

In order to ensure safe and effective long-term geologic storage of carbon dioxide (CO₂), existing regulations require both assessing leakage risks and responding to leakage incidents through corrective measures. However, until now, these two pieces of risk management have been usually addressed separately. This study proposes a methodological framework that bridges risk assessment to corrective measures through clear and collaborative contingency planning. We achieve this goal in three consecutive steps. First, a probabilistic risk assessment (PRA) approach is adopted to characterize potential leakage features, events and processes (FEP) in a Bayesian events tree (BET), resulting in a risk assessment matrix (RAM). The RAM depicts a mutually exclusive and collectively exhaustive set of leakage scenarios with quantified likelihood, impact, and tolerance levels. Second, the risk assessment matrix is translated to a contingency planning matrix (CPM) that incorporates a tiered-contingency system for risk-preparedness and incident-response. The leakage likelihood and impact dimensions of RAM are translated to resource proximity and variety dimensions in CPM, respectively. To ensure both rapid and thorough contingency planning, more likely or frequent risks require more proximate resources while more impactful risks require more various resources. In addition, the minimum and maximum risk tolerance levels are translated to contingency thresholds, and all tolerable risk scenarios are categorized under three contingency tiers: Tier 1, Tier 2, and Tier 3. We highlight how the upper, lower, and inter-tier contingency boundaries should be collaboratively pre-negotiated between the operating party and multiple relevant stakeholders to ensure effective preparedness and response. Finally, we present a model contingency plan to demonstrate how all newly introduced concepts integrate together. Specifically, we focus on explaining how the designed contingency tiers facilitate important aspects of contingency planning, primarily: evaluating leakage and initiating response; designing a corrective measures matrix (CMM) that assigns specific control and remediation measures to each leakage scenario; mobilizing, deploying, and sustaining necessary human and equipment resources; and formulating a decision-making hierarchy, a notification protocol, and a communication scheme to effectively administer the CO₂ storage site.

Keywords
carbon dioxide; CCS; contingency planning; corrective measures; CO2 geologic storage; leakage; risk assessment
1. Introduction

Fifty five large-scale carbon capture and storage (CCS) projects exist or are planned around the world today, the majority of which are located in North America, Australia, Europe, and China [1]. Ensuring reliable long-term storage of carbon dioxide (CO₂) in subsurface geologic formations is important to gain public support and accelerate the deployment of CCS [2, 3, 4]. To that effect, huge research and policy efforts have been devoted to the development of technologies and regulations that secure safe operations of CO₂ storage sites, with a wide range of requirements and guidelines on risk management [1, 5, 6].

Different regulatory and legislative bodies have adopted different requirements to permit CO₂ geologic storage, specifically regarding the need for risk assessment and corrective-measure plans to address potential CO₂ leakage. In the United States, the Federal Environmental Protection Agency requires a “corrective action plan” and an “emergency and remedial response plan” with specific timelines, and it provides detailed guidance on how to provide the requisite information [7, 8]. Nonetheless, the Agency does not request formal documentation on risk assessment [9]. In Canada, the environmental protection responsibilities are shared between the federal and provincial governments [10]. The federal government adopted the CSA Z741 standard, which covers “risk assessment” and “risk treatment” [11, 12]. On the provincial level, Alberta’s legislation does not require “risk assessment” or “corrective action” plans, but the legislation allows imposing both requirements through regulation [13, 14, 15]. In addition, while British Columbia’s currently proposed regulations mandate a “corrective measures / contingency plan” and a “description of measures to prevent significant leakage” as part of the application for a storage permit [16], Saskatchewan’s CO₂ storage operations are managed under existing oil and gas regulations [10]. Similar policy framework exists in Australia. Through environmental guidelines, the Commonwealth government calls for “continuous risk assessment as an essential element of the environmental impact assessment”, but the legislation governing greenhouse gas storage does not require submitting plans for risk assessment or corrective measures [17, 18]. At the state level, Victoria demands a “risk management plan” before granting an injection and monitoring license [19] whereas Queensland does not [20]. In the European Union, the European Commission published a CCS Directive, which requires both a “risk assessment plan” and a “corrective measures plan” [21]. In two of the associated four guidance documents, the Commission provides a detailed description of the requested plans, which includes example templates, proposed areas of investigation, as well as recommended tools and formats [22, 23]. Finally, China’s legal framework for managing CO₂ storage is still under development, with no existing rules on risk assessment and corrective measures [24, 25].

With these different approaches to risk management, a clear link between risk assessment and corrective action for CO₂ leakage is often missing. This reality controverts the wide agreement among industry experts and policy makers on the need to connect the various aspects of risk management, including the need to design corrective measures based on risk analysis before permitting operations [8, 23, 26, 27, 28, 29, 30]. The aim of this work is to propose a methodological framework that bridges risk assessment to corrective measures through clear and effective contingency planning. This framework achieves two tasks, which summarize the novelty of this work. First, it expands the formulation of a risk assessment matrix (RAM) to make it more action- and decision-oriented, which subsequently facilitates its translation to a contingency planning matrix (CPM). Second, it explains the significance of the various CPM elements, not only for mapping corrective measures to potential leakage scenarios but also for facilitating critical coordination between the operating party and the regulatory agency overseeing CO₂ storage.

In pursuing both goals, the proposed framework utilizes the extensive body of literature on risk assessment and corrective measures for CO₂ leakage, offering a mean to bridge the utilization of existing tools instead of proposing new ones. In addition, when demonstrating its applicability, this framework considers scenarios of CO₂ leakage that start and ends in the subsurface and propagates through geologic pathways only. When applied in real life, and using similar techniques to the ones presented in this paper, the framework can be expanded to include scenarios of CO₂ leaks that propagate through man-made pathways and reach the surface.
In the subsequent sections of this paper, we first provide a brief overview of the terminology used in the risk management of CO\textsubscript{2} storage, highlighting some existing literature on risk assessment methodologies and corrective measures. Next, we discuss how to update the risk assessment matrix, introducing the concept of risk profiles of CO\textsubscript{2} leakage. As the main focus of this paper, a contingency planning matrix is then developed based on the updated risk assessment matrix, and its tier structure is discussed. Lastly, we leverage the contingency planning matrix to design a model contingency plan, covering multiple sections on preparing for leakage risks and responding to leakage incidents. When discussing specific response strategies within the plan, we show how different corrective measures can tackle different risk profiles under different contingency tiers, effectively linking all elements of risk management for CO\textsubscript{2} leakage from geologic storage.

2. Risk Management: Assessment, Mitigation, and Contingency Planning

Before discussing the details of the proposed framework, it is important to establish a consistent risk-management terminology that we can refer to throughout this paper. As depicted in Figure 1, managing the risk of CO\textsubscript{2} leakage from geologic storage formations includes three essential steps: assessment of risk, mitigation and avoidance of intolerable risk, and contingency planning for tolerable risk. A robust risk assessment involves the identification, analysis, and evaluation of potential leakage scenarios. After identifying a comprehensive set of scenarios, each scenario is analyzed qualitatively or quantitatively to determine its likelihood of occurrence and its impact on subsurface formations and surface ecosystems. Leakage risks are then evaluated according to external mandates by the regulatory agency and internal procedures by the operating party, resulting in a set of risk tolerance levels. While risks below the minimum tolerance levels can be safely ignored, risks exceeding the maximum tolerance levels need to be mitigated or avoided altogether through a variety of preventative measures [22, 26, 27].

On the other hand, leakage scenarios within the tolerance range are managed through contingency planning, which aims to prepare for leakage risks and respond to leakage incidents if they occur [28, 31, 32]. Learning from the oil and gas industry, we envision a tier-system approach to contingency planning for CO\textsubscript{2} leakage, which integrates five essential elements: thresholds, response initiation through triggers, response strategies that include corrective measures, human and equipment resources, and administration and coordination schemes [23, 33, 34, 35, 36, 37]. While thresholds refer to specific levels of leakage likelihoods and impacts that bound risk-preparedness, triggers refer to specific irregular measurements or observations that initiate incident-response. Additionally, corrective measures cover subsurface and surface activities that aim to both control (stop or contain) the leakage and remediate its impacts [32, 38]. To that end, thresholds and triggers shape when corrective measures should be implemented while human and equipment resources and administration and coordination schemes define what and how corrective measures should be implemented.

The aforementioned sequential process of risk management shows that the effective design and deployment of corrective measures for CO\textsubscript{2} leakage necessitates a robust contingency plan, which in turn should be based on the findings of a comprehensive risk assessment. In our attempt to present a methodological framework that integrates all three elements of risk management, we focus primarily on contingency planning, which has received comparatively little attention in literature. Nonetheless, contingency planning is linked to risk assessment and corrective measures by utilizing the large body of existing literature on both topics [39, 40, 38]. Specifically, we use the features, events, and processes (FEP) methodology for risk identification [41] and Bayesian event trees (BET) for risk analysis [40, 42, 43]. The RISQUE method is another valuable resource to assess impacts and elicit informed probabilities from experts [44, 45]. Subsequently, for corrective measures, we use representative examples of containment and remediation activities to combat leakage events in the subsurface [46, 47, 48].
3. Updating the Risk Assessment Matrix

A risk assessment matrix (RAM) is usually represented as a two-dimensional plot of leakage impact versus leakage likelihood. Our focus on the RAM is motivated by its application in some existing CCS policies [22, 49] and projects [29, 50] and by its ability to visualize all three steps of risk assessment. The leakage scenarios depicted in a RAM result from risk identification; the likelihood and impact of each scenario are the outcome of risk analysis; and the determination of insignificant, tolerable, and intolerable scenarios emerge from risk evaluation. When quantified, a RAM represents a leakage scenario as a single risk point with the likelihood and the impact calculated based on expected-average or worst-case estimates [45, 51]. Other RAMs are qualitative, so a leakage scenario is allocated into a single high, medium, or low risk zone [29, 52].

While helpful for visualizing and comparing risks, current applications of RAM can still be improved. For example, a realistic leakage scenario may span more than one risk level depending on several factors, some of which are uncertain. Such factors include the rate of leakage, the features of the storage reservoir and surrounding geologic formations, and the vulnerability of surface ecosystems. In addition, it is hard to distinguish the relative significance of the various risk drivers in current RAM depictions of leakage. For instance, it cannot be inferred whether a high likelihood of leakage through a fault into a freshwater aquifer is due to the high probability that a fault exists or due to the high probability that an aquifer is nearby the fault given that the latter exists. Adopting a quantifiable probabilistic risk assessment (PRA) approach that combines FEP and BET offers one way to address those issues, resulting in a more inclusive RAM and therefore facilitating the transition to a CPM.

PRA relies on systems analysis, decision analysis, and Bayesian reasoning to assess a set of mutually exclusive and collectively exhaustive scenarios of CO₂ leakage in the subsurface [53]. This approach includes four steps. First, for risk identification, the overall subsurface system is divided into a series of independent functional subsystems. Potential leakage scenarios are defined as trajectories that combine multiple subsystems, and FEP guides specifically the categorization of subsystems where a CO₂ leakage may start. Second, the likelihood of each leakage scenario is assessed as a series of conditional probabilities that change as a function of a measurable
criterion, which is typically a relevant geological feature. Third, multiple value models are developed to help quantify the impact of leakage on the subsurface and surface ecosystems. The second and third steps cover risk analysis, and combining the first three steps results in a BET that systematically describes all foreseeable conjunctions of leakage events. In the fourth step, specific tolerance levels are determined for both the likelihood and the impact of leakage in order to evaluate what risks should be mitigated and what risks can be safely ignored. Eventually, the overall outcome of this PRA is a RAM that depicts a comprehensive set of risk profiles of CO₂ leakage with quantified likelihood, impact, and tolerance levels.

### 3.1. Functional Subsystems for Risk Identification

For CO₂ leakage through geologic pathways, the system is defined as the set of geologic formations in the subsurface, above and including the storage reservoir. As depicted in Figure 2, this system can be divided into three functional subsystems: Origin, Endpoint, and Pathway.

**Origin** refers to the functional subsystem which is designated to contain the CO₂ under normal conditions. Physically, it encompasses the storage reservoir and any selected containment zones. Origin can be further decomposed into a list of subsystems, namely, a comprehensive count of the geologic irregularities – features, events, or processes (FEP) – through which CO₂ may leak and the rest of the formation where CO₂ remains safely stored; we categorize the former subsystems as FEP and refer to the latter subsystem as Safe. Although FEPs are site-specific, an example list is presented in Table 1.

**Endpoint** refers to the functional subsystem where the leaked CO₂ finally reaches. Endpoint can be further decomposed into a list of subsystems, which we limit to three: FrW, O&G, and Other. FrW refers to all subsurface aquifers containing freshwater. O&G refers to all geologic formations containing oil or gas resources. For simplicity, freshwater, oil, and gas are assumed to be the only human-valuable subsurface assets. Accordingly, Other includes all geologic formations that trap the leaked CO₂ yet are not classified as freshwater aquifers or oil and gas reservoirs.

#### Table 1. Examples of Origin FEPs and their corresponding Indicators

<table>
<thead>
<tr>
<th>Origin FEP</th>
<th>Symbol {O}</th>
<th>Indicator</th>
<th>Symbol (i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caprock high-permeability zone</td>
<td>01</td>
<td>permeability</td>
<td>α</td>
</tr>
<tr>
<td>Caprock-absent zone</td>
<td>02</td>
<td>size of the opening</td>
<td>λ</td>
</tr>
<tr>
<td>Caprock fracture due to over-pressurization</td>
<td>03</td>
<td>size of fracture</td>
<td>β</td>
</tr>
<tr>
<td>Exceeding capillary pressure due to over-pressurization</td>
<td>04</td>
<td>capillary pressure</td>
<td>δ</td>
</tr>
<tr>
<td>Natural fault or fracture</td>
<td>05</td>
<td>size of fracture</td>
<td>β</td>
</tr>
<tr>
<td>Induced fault or fracture due to over-pressurization</td>
<td>06</td>
<td>size of fracture</td>
<td>β</td>
</tr>
<tr>
<td>Induced fault or fracture due to CO₂ geochemical reactions</td>
<td>07</td>
<td>size of fracture</td>
<td>β</td>
</tr>
<tr>
<td>Induced fault or fracture due to seismic activity</td>
<td>08</td>
<td>Size of fracture</td>
<td>β</td>
</tr>
</tbody>
</table>
Pathway: refers to the functional subsystem between the Origin and the Endpoint. Physically, this area encompasses all subsurface formations through which CO₂ migrates after leaving an Origin formation until reaching an Endpoint formation.

3.2. Bayesian Event Tree for Risk Analysis

The Bayesian Event Tree (BET) is an effective way to track the likelihood and consequences of the various scenarios of CO₂ leakage. A BET models the likelihood of CO₂ leakage through three sequential and uncertain events: Origination, Propagation, and Destination. As we explain shortly, these events govern the progression of CO₂ leakage through the aforementioned Origin, Pathway, and Endpoint subsystems. Subsequently, for every leakage prospect, the BET allows modeling the leakage consequences using various value models; we introduce two: Value of Flow (VF) and Value of Impact (VI). An example BET is shown in Figure 3, followed by a detailed description of its various components and the procedure to construct it. Important to note, the depicted BET and all related figures are purely hypothetical; they aim to demonstrate the concepts outlined here and provide a roadmap for implementing them.

3.2.1. Probability of CO₂ Leakage

For a leakage to occur, three uncertain events must take place sequentially. As explained below, each event is assigned a probability, and the overall likelihood of a leakage scenario is the product of those probabilities.

Origination \{ O \}(i): refers to the probability of the existence of a specific Origin, which could be an FEP or Safe. For an FEP, this likelihood may vary with the subsystem’s exact characteristics. Therefore, \{ O \} for an FEP is expressed as a function of an Indicator i, which is a selected attribute of the analyzed FEP. Indicator attributes should be chosen to best-match their FEP subsystems. Table 1 presents a suggested attribute for each of the listed FEP. For instance, \{ O1 \}(\alpha) is the probability of existence of a caprock high-permeability zone O1 and is a function of permeability \alpha. In mathematical terms, Origination \{ O \} can be represented as a step-wise function of Indicator i, which is discretized over its total feasible range.

Propagation \{ P|O \}(i): refers to the probability of CO₂ entering the Pathway from a specific Origin, given that this Origin actually exists. Propagation is conditioned on Origination, so \{ P|O \} can be also represented as a step-wise function over the full discretized range of Indicator i. By definition, \{ P|Safe \} must be always zero. Propagation may be considered a pinch-point, the point in the analysis at which it doesn’t matter – for subsequent analysis – how the system reached its current state but how it proceeds from that state [54, 55]. In this case, if Propagation is positive, CO₂ may escape from the Origin to the Pathway. Subsequent analysis focuses on investigating where the CO₂ migrates from the Pathway regardless of how it reached the Pathway.

Destination \{ D|O, P \}(i): refers to the probability of CO₂ entering a specific Endpoint from the Pathway, given that it already reached the Pathway through an existing Origin. Here again, because Destination is conditioned on Origination and Propagation, \{ D|O, P \} can be also represented as a step-wise function over the full discretized range of Indicator i. Also, by definition, \{ D|Safe \} is zero because CO₂ cannot reach an Endpoint unless it escapes through an FEP first. Destination is primarily dependent on hydrogeological factors that govern the transport of CO₂ in the Pathway, including the injection locations and rates, local hydrology, and geologic configuration. However, consistent with the pinch-point definition of Propagation, CO₂ transport in the Pathway is unlikely to be dependent on the specific type of FEPs in the Origin. Therefore, one simplifying assumption is to treat Destination as independent of the Propagation \{ P|O \} and Origination \{ O \}(i). In this case, \{ D|O, P \}(i) = \{ D \}, which means that Destination is a constant (uniformly distributed) function of Indicator i.
Figure 3. Example Bayesian event tree (BET) for risk analysis of CO₂ leakage

Mutually exclusive and collectively exhaustive; probabilities must sum to 1.
**Leakage Likelihood \( \{L\}(i) \):** For CO\(_2\) leakage to occur, the CO\(_2\) must find an *Origin* FEP, move through the *Origin* FEP into the *Pathway*, and then enter into an *Endpoint*. Therefore, intuitively, the Leakage Likelihood is the product of *Origination*, *Propagation*, and *Destination*, as illustrated in (1).

\[
\{L\}(i) = \{P\}(i) \cdot \{P|O\}(i) \cdot \{D|O,P\}(i) = \{P,O,D\}(i)
\]  

(1)

The formulation in (1) provides three important insights. First, if *Origination*, *Propagation*, or *Destination* is zero, the Leakage Likelihood is also zero, and assessing the uncertainty of subsequent event(s) becomes unnecessary. Second, because \( \{L\} \) is a function of \( i \), the likelihood of a specific leakage scenario from a particular FEP is a function of the characteristics of that FEP. Finally, the analyzed leakage scenarios must be mutually exclusive and collectively exhaustive. This means that exactly one of the BET scenarios must occur, and the probability of all scenarios must add up to one. In fact, due to conditional probability assessment, the branch probabilities at each node of the tree should also sum up to one. To that end, we note that a leakage scenario need not involve a single *Origin* and a single *Endpoint*. Site-specific data may suggest a leakage incident that occurs through multiple FEPs and reaches multiple Endpoints, in which case this leakage incident should be presented as a separate scenario. Such approach ensures that all foreseeable leakage scenarios are accounted for; specifically, it guards against “perfect storms”, where multiple leakage events of very low likelihood occur all at once and cause a collective impact greater than the sum of their individual impacts.

To demonstrate the PRA methodology above, we analyze a subset of three CO\(_2\) leakage scenarios in Figure 3, corresponding to three distinct *Origin-Pathway-Endpoint* trajectories. Specifically, we assume CO\(_2\) storage in a deep saline aquifer (*Safe*), and we examine the risk of leakage from a high-permeability zone (*O1*) in the reservoir’s shale caprock to a freshwater aquifer (*FrW*), an oil reservoir (*O&G*), and another sealed geologic formation (*Other*). Figure 4 depicts the relevant functional subsystems: *Origins* (*Safe*, *O1*), *Pathway*, and *Endpoints* (*FrW*, *O&G*, *Other*). Subsequently, Figures 5a-d show hypothetical probability distributions of the sequential leakage events: *Origination* and *Propagation* through the FEP, *Destination* into *FrW*, *O&G*, and *Other*, as well as the overall Leakage Likelihood. The numerical data is hypothetical and is provided for illustrative purposes only. In practice, the probability inputs would be obtained based on expert opinions and/or statistical information generated from site characterization and reservoir modeling; examples of such probabilistic data for the representation of CO\(_2\) leakage risk already exists in literature [45, 56, 57, 58, 59, 60].

Because *O1* and *Safe* are the only two possible *Origins*, the probability distribution in *Origination* is split between \( \{O1\} \) and \( \{Safe\} \). Illustrating *Origination* as function of Indicator, Figure 5a is a log-log plot that shows the probability of existence of a high-permeability zone in the caprock \( \{O1\} \) with a permeability of \( \alpha \). The modelled range of \( \alpha \) is comparable to that reported by Wang and Small [57], and Griffith [58], for caprock high-permeability zones and fractures. As shown in Figure 5a, \( \{O1\} \) is discretized over seven intervals of \( \alpha \). Assuming a typical shale-seal permeability of \( 10^{-4} \) millidarcy (mD) [58, 61], the permeability of a leakage-inducing FEP can only exceed this value, so \( \{O1\}(\alpha < 10^{-4}) \) is set at zero. On the other extreme, we assume that it is highly unlikely to find a caprock zone with permeability greater than 10 mD, so \( \{O1\}(\alpha > 10) \) is set at \( 10^{-5} \). For \( \alpha \) between \( 10^{-4} \) and 10 mD, \( \{O1\} \) decreases almost exponentially from 0.1 to \( 10^{-4} \). Subsequently, in this specific example, the probability of having no high-permeability zone in the caprock becomes \( \{Safe\} = 1 - \sum_{\alpha} (\{O1\}(\alpha)) \approx 0.839 \). Though hypothetical, this assumed probability distribution for *Origination* is informed by, and is therefore consistent with, the findings of select literature that addresses uncertainty in reservoir characterization and modeling; for instance, the results by Wang et al. allow inferring a similar probability distribution from measurements of moderate pressure buildup in the storage zone [57].
Because $O1$ is the only possible leakage FEP, CO$_2$ will either leak through it or remain in the designated storage aquifer Safe. As explained already, by definition, the CO$_2$ cannot propagate from Safe into Pathway, so $\{P|Safe\}$ is zero. Figure 5b is a log-log plot of Propagation $\{P|O1\}$ as a function of Indicator $\alpha$, given that the high-permeability zone $O1$ actually exists. For CO$_2$ to leak through $O1$, the CO$_2$ plume should first reach $O1$ then move...
through 01 into Pathway. In this case, we assume that the likelihood of CO$_2$ transport through the FEP is very small below a specific permeability threshold of $\alpha = 0.1$ mD. In reality, this threshold could correspond to capillary entry pressure; as $\alpha$ increases, capillary entry pressure decreases until it finally drops below the capillary pressure at the base of the caprock, at which point CO$_2$ can escape through the high-permeability zone in the caprock. Therefore, once $\alpha$ exceeds 0.1 mD, Propagation increases rapidly. Still, at the highest permeability range of $\alpha > 10$ mD, $\{P|01\}$ is set at 0.7. Here, we make a realistic assumption that even though CO$_2$ can escape through 01, there is still a probability of $1 - \{P|01\} = 0.3$ that the CO$_2$ plume may not reach 01 in the first place.

Figure 5c plots Destination as function of Indicator. Consistent with the definition of Propagation as a pinch-point, Destination is assumed to be independent of Origination 01 and Propagation $\{P|01\}$. Therefore, $\{D|01,P\}$ is equal to $\{D\}$, which is constant across the whole feasible range of $\alpha$. Informed by related findings in existing literature [56, 62], this example assumes that the leaked CO$_2$ from the saline aquifer is least likely to travel all the way up to the shallow freshwater aquifer, so $\{D = FrW\}$ is set at 0.05. It is much more likely that the CO$_2$ gets trapped at a deeper geologic formation along the way, probably in a subsequent sealed formation (Other) or perhaps in a nearby oil reservoir. Accordingly, $\{D = Other\}$ and $\{D = O&G\}$ are set at 0.7 and 0.25, respectively. Here, we assume that the leaking CO$_2$ may reach exactly one of the three aforementioned Endpoints, so the values of $\{D\}$ for FrW, O&G, and Other must add up to 1.

Multiplying each probability distribution function in Figure 5c by those in Figures 5a and 5b results in three Leakage Likelihood profiles as a function of $\alpha$, corresponding to the three distinct leakage trajectories. Figure 5d shows a log-log plot of the three $\{L\}(\alpha)$ profiles. As can be noticed, leakage seems to be less likely at both very high and very low permeability. This observation can be attributed to two conflicting factors: low Propagation but high Origination at low permeability and low Origination but high Propagation at high permeability. In fact, the leakage probabilities at high permeability $\{L\}(\alpha > 10)$ are consistent with some literature findings for similar leakage events through high-permeability zones and fractures in the caprock [45, 56].

### 3.2.2. Value of CO$_2$ Leakage

Value models are functions that aim to quantify the consequences of potential CO$_2$ leakage incidents. As explained in existing literature, these consequences may be characterized in different metrics and might span a wide spectrum of social, environmental, economic, and public-safety issues [62, 56]. In this study, we suggest three value models to complement the aforementioned probabilistic assessment.

**Value of Flow – VF(i):** quantifies the amount of the leaked CO$_2$ into each Endpoint subsystem, which can be expressed as a mass flux, mass flowrate, or total mass during a specific period of time. While site-specific, VF is usually correlated to Indicator. This correlation can be derived from characterizing or simulating fluid-flow in the analyzed subsurface, regardless of the leakage likelihoods. Because the flow of leaked CO$_2$ is measurable, VF offers a direct way to quantify the consequences of leakage.

At a particular Endpoint, higher VF signifies more severe consequences of leakage. However, a leakage of a specific VF may lead to different consequences in different Endpoints. Therefore, while useful for characterizing the consequences of CO$_2$ leakage at individual Endpoints, VF cannot be used for consistent comparison of the consequences of leakage across multiple Endpoints. Important for risk assessment and contingency planning, performing such comparison requires translating VF into monetary terms, whose significance is the same across all leakage scenarios; proper valuation renders a U.S. dollar spent on controlling leakage into FrW equivalent to a U.S. dollar spent on controlling leakage into O&G. Relying on concepts and tools in decision analysis and natural resources economics, it is possible to express the various social, environmental, economic, and safety consequences of CO$_2$ leakage in one monetary metric [63, 64, 65, 66]. To that end, we propose two monetary value models that quantify the consequences of CO$_2$ leakage in the subsurface and on the surface.
Value of Damage in the Subsurface – \( VD_{\text{sub}}(i) \): corresponds to the cost of any leakage-induced damages to the subsurface resources. While directly dependent on \( VF \) and therefore on Indicator, separate \( VD_{\text{sub}} \) models can be designed for \( FrW \), \( O&G \), and Other, influenced by regulatory requirements. For \( FrW \), \( VD_{\text{sub}} \) might be a function of several parameters, including water pH, hardness, and salination, as well as the concentration of any trace metals or oil and gas contaminants carried by the leaked CO\(_2\) stream [38, 56, 67]. For \( O&G \), \( VD_{\text{sub}} \) may be a function of the quantity and quality of recovery from producing and future reservoirs, both of which may deteriorate with CO\(_2\) leakage. Finally, since Other subsystems are assumed to have no valuable assets, their corresponding \( VD_{\text{sub}} \) may be limited to a non-compliance penalty imposed by the regulatory agency.

Value of Damage on the Surface – \( VD_{\text{sur}}(i) \): corresponds to the cost of any leakage-induced damages to the surface resources, including environmental and ecological systems and human structures, activities, and health [62]. In other words, this model accounts for the costs of any surface damages or harms caused by diminishing the utility of the subsurface resources. Intuitively, the higher the dependence of ecological and human systems on underground natural resources, the higher their vulnerability to CO\(_2\) leakage, and thus the higher the \( VD_{\text{sur}} \). Similar to \( VD_{\text{sub}} \), distinct \( VD_{\text{sur}} \) models can be designed for \( FrW \), \( O&G \), and Other, and all \( VD_{\text{sur}} \) models remain dependent on \( VF \) and thus on Indicator. Examples of factors that can be accounted for in designing \( VD_{\text{sur}} \) models include the size of human population, per-capita annual income, size of agricultural activities, and number of natural habitats and ecological species that depend on the freshwater aquifers where CO\(_2\) might leak [62, 56].

Leakage Value of Impact – \( VI(i) \): corresponds to the sum of \( VD_{\text{sub}} \) and \( VD_{\text{sur}} \), which allows expressing all consequences of CO\(_2\) leakage in one monetary metric. Consistent with the formulation of both damage values, \( VI \) is a function of \( VF \) and thus Indicator \( i \), as illustrated in (2). Intuitively, a higher leakage rate (\( VF \)) leads to higher contamination of subsurface resources (\( VD_{\text{sub}} \)) and therefore higher disutility of these resources on the surface (\( VD_{\text{sur}} \)). In addition, to facilitate their representation in a BET (Figure 3), all value models are discretized over the same ranges of Indicator \( i \) used to discretize the conditional probabilities of leakage.

\[
VI(i) = VD_{\text{sub}}(i) + VD_{\text{sur}}(i) = VD_{\text{sub}}(VF) + VD_{\text{sur}}(VF) \tag{2}
\]

To complete the risk analysis for the earlier example of CO\(_2\) leakage from a high-permeability caprock zone \( O1 \), we design hypothetical value models for leakage into each of the three Destination subsystems: \( FrW \), \( O&G \), and Other. In reality, leakage rates are very project-specific. In this example, we first assume that \( VF \) is best represented as a mass flux, and its values for \( FrW \), \( O&G \), and Other are very similar, as illustrated in Figure 6a. In addition, we assume that the leaking CO\(_2\) stream remains relatively concentrated around the high-permeability FEP. In accordance with relevant literature findings, \( VF \) equals about \( 10^3 \) kg/m\(^2\).s when the permeability of \( O1 \) is high (\( \alpha > 10 \)). To put this number in context, Benson and Hepple report a comparable estimated flux over a 1000 m\(^2\) surface area from a storage site, which leaks 0.1% of its stored CO\(_2\) per year after receiving 1 million tonnes of CO\(_2\) per year over a period of 50 years [46]. Furthermore, assuming single-phase flow through the high permeability zone, \( VF \) is set to be proportional to Indicator \( \alpha \). For very low values of \( \alpha \), \( VF \) is in the order of \( 10^{-7} \) kg/m\(^2\).s, which falls within the lower range of CO\(_2\) leakage fluxes reported from natural analogues [46, 68].

Subsequently, the \( VF \) models are translated to \( VI \) models, which are similarly very project-specific and therefore difficult to generalize. In our example, \( VI \) is expressed in (arbitrary) monetary units and is dependent on Indicator \( \alpha \) (and therefore on \( VF \)), as shown in Figure 6b. We assume a high \( VI \) for \( FrW \); the leaked CO\(_2\) alters the aquifer’s pH and contaminates it with trace metals (high \( VD_{\text{sub}} \)), and the aquifer is the primary source of freshwater for a large county with a predominantly agricultural economy (high \( VD_{\text{sub}} \)). Figure 6b shows four levels of \( VI \) for \( FrW \), simulating the costs of four deterioration levels in water quality – defined in terms of acidity and trace-metal concentration. One real-life (albeit simplified and perhaps extreme) interpretation of this trend would be as follows: for \( 10^{-4} \leq \alpha \leq 10^{-3} \) mD, water quality worsens but remains suitable for human and natural use; for \( 10^{-3} \leq \alpha \leq 10^{-2} \) mD, water becomes unsafe for drinking; for \( 10^{-2} \leq \alpha \leq 1 \) mD, water becomes unsafe for all
human use; and for $\alpha \geq 1 \text{ mD}$, water becomes unsafe for human, cattle, poultry, agriculture, and wildlife use. On the other hand, we assume a relatively low $VI$ for $O&G$; the oil reservoir is depleting, so the leaked CO$_2$ mildly deteriorates the quality and/or quantity of oil recovery (low $VP_{sub}$), and oil revenues form a small part of the country’s income (low $VD_{sur}$). Figure 6b simulates one example trend for the damage costs associated with CO$_2$ leakage into $O&G$: for $10^{-3} \leq \alpha \leq 0.1 \text{ mD}$, the oil producer handles the increased flux of leaked CO$_2$ by progressively adjusting its existing oil extraction techniques and schedule; however, for $\alpha \geq 0.1 \text{ mD}$, the large flux of leaked CO$_2$ requires a whole new extraction method, resulting in a significant increase in operating costs. Furthermore, we assume that the regulatory agency penalizes the operating party for CO$_2$ leakage into the Other zone. The penalty is fixed, so $VI$ is independent of $VF$ and Indicator $\alpha$. Finally, we note that both $VF$ and $VI$ are discretized over the same seven intervals of $\alpha$ used to discretize leakage probabilities.

![Figure 6. Example value models of CO$_2$ leakage scenarios](image)

### 3.3. Tolerance Levels for Risk Evaluation

After analyzing the likelihood and impact of all foreseeable leakage scenarios, it is important to evaluate which of the resulting risk scenarios are **insignificant**, **tolerable**, or **intolerable**. To that end, **maximum and minimum tolerance levels** can be identified for the Leakage Likelihood $\{L\}$ and the Leakage Value of Impact $VI$, consistent with existing literature on the ALARP principle [26]. When $\{L\}$ is lower than its minimum tolerance level, it is evaluated as insignificant, and the corresponding leakage risks can be safely ignored. However, when $\{L\}$ is higher than its maximum tolerance level, it is evaluated as intolerable, and the corresponding leakage risks must be mitigated. Similar minimum and maximum tolerance levels can be determined for $VI$. Because the monetary metric of $VI$ can consistently characterize all consequences of leakage, the tolerance levels for $VI$, like those for $\{L\}$, are applicable across all leakage scenarios. When the likelihood and impact of a leakage scenario are between their maximum and minimum tolerance levels, the leakage risk is deemed tolerable and is managed through contingency planning.

Defining effective tolerance levels may prove to be challenging, given the relatively limited experience in operating large-scale CO$_2$ storage projects for long periods of time. Nonetheless, such boundaries can still be set by relying on existing experience in similar industries, primarily oil and gas [69]. Following up on the example of CO$_2$ leakage through a caprock high-permeability zone, we assume that minimum and maximum tolerance levels for $\{L\}$ should be set at $10^7$ and 0.1, respectively. Similarly, the minimum and maximum tolerance levels for $VI$ are set at $10^2$ and $10^3$, respectively. While re-emphasizing that all numerical values are purely hypothetical, one example to rationalize these threshold values would be to set the monetary unit in million U.S. dollars and to assume an international energy firm managing the CO$_2$ storage project. In such a world, a $VI$ below $0.01$ million may be easily accommodated within the project’s budget. However, learning from past spill incidents in the oil
and gas industry [70, 71, 72], a VI above $1,000 million might compromise not only the economic feasibility of the project but also the financial stability of the whole firm.

3.4. Combined Representation of Risk Assessment Elements

The three discussed elements of risk assessment can now be jointly represented in a RAM. Because the likelihood and impact of leakage are discretized over the same ranges of Indicator, it is possible to plot all leakage scenarios on a two-dimensional RAM, with VI on one axis and \{L\} on the other. The result is a set of risk profiles exhibiting two key characteristics. First, each risk profile identifies a potential leakage trajectory from a specific Origin, through the Pathway, and into a specific Endpoint. Second, each data point in the risk profiles corresponds to a leakage scenario in the BET, with a quantifiable Indication i, Leakage Likelihood \{L\} and Leakage Value of Impact VI. Accordingly, the collective risk profiles summarize the findings of risk identification and risk analysis. Subsequently, for risk evaluation, the minimum and maximum tolerance levels for VI and \{L\} can be plotted on the RAM, marking clear boundaries for insignificant, tolerable, and intolerable risks. All BET scenarios can and should be plotted on the RAM except those with a zero probability or impact of leakage. The risks associated with these scenarios are insignificant by design, so they can be safely excluded.

Carrying on with our hypothetical example of leakage through a caprock high-permeability zone, the RAM in Figure 7 is a log-log plot of VI versus \{L\}. The three risk profiles, corresponding to leakage from the high-permeability zone O1 into FrW, O&G, and Other, span a range of likelihoods and impacts. The exact \{L\} and VI of a leakage trajectory is dependent on the permeability \(\alpha\) of O1. In that regard, the plotted risk profiles exclude the leakage scenarios corresponding to \(\alpha < 10^{-4}\) mD, whose probability is assumed zero. In addition, applying the tolerance levels for \{L\} and VI shows that the risks associated with CO\(_2\) leakage into O&G and Other are tolerable. However, the impact of CO\(_2\) leakage into FrW is intolerable if the permeability of O1 is \(\alpha > 1\) mD, so the associated risks must be mitigated before proceeding with the project. Equivalently, the likelihood of CO\(_2\) leakage into FrW is insignificant if \(\alpha < 0.1\) mD, so the associated risks can be safely ignored.

![Figure 7. Example risk assessment matrix (RAM) for CO\(_2\) leakage.](image)

This PRA approach to RAM offers multiple advantages. Broadly, the techniques used to identify and analyze leakage risks are flexible and generalizable, so they can be expanded and customized. For example, if multiple freshwater aquifers or oil reservoirs are observed in the vicinity of the storage zone, each can be assessed as a
separate Endpoint, resulting in multiple FrW and O&G subsystems. Equivalently, the conditional probability analysis in the BET can be adjusted to achieve clarity [64]; we briefly discuss four examples of such potential adjustments.

First, depending on available data, the operator may find it clearer to further decompose Propagation \( \{P|O\} \) into two conditional probabilities: the probability of the CO\(_2\) plume encountering an existing FEP \( \{P_e|O\} \), and the probability of the CO\(_2\) plume flowing along the FEP after encountering it \( \{P_f|O,P_e\} \) [60]. In this case, \( \{O,P_e,P_f\} \) replaces \( \{O,P\} \) in the BET to convey the same information: the likelihood that an FEP Origin exists and that the CO\(_2\) plume reaches it then escapes through it. Conversely, in the absence of sufficient data, the operator might find it difficult to assign distinct probabilities to \( \{O\} \) and \( \{O|P\} \). In this case, the operator may directly evaluate the joint probability distribution \( \{O,P\} \), instead.

Second, because it may be hard to definitively know the long-term-future impacts of leakage, the VF for each Endpoint can be translated to three mutually exclusive and collectively exhaustive VI models: high, medium or low. Assuming Destination is a pinch-point, each VI model occurs with probability \( \{I\} \) referred to as Implication, so the overall Leakage Likelihood would be updated to \( \{L\} = \{O,P,D,I\} \). In this case, RAM would depict each Origin-Pathway-Endpoint leakage trajectory as a group of three risk profiles, corresponding to the three possible (high, medium, and low) VI models.

A third BET expansion may account for external events, features, and processes (EFEP), which occur outside the boundaries of the defined system yet may influence the prospects of CO\(_2\) leakage within the system [73]. In this case, the BET probabilities can be conditioned on the occurrence of the EFEP, as illustrated in (3-6). Finally, the operator may also choose to refine the ranges of Indicator \( i \) over which the probability and impact values are discretized; eventually, such refinement yields a more detailed representation of risk profiles in RAM.

\[
\begin{align*}
\{O\}(i) &= \{O|EFEP\}(i) \cdot \{EFEP\} + \{O|No EFEP\}(i) \cdot (1 - \{EFEP\}) \\
\{P|O\}(i) &= \{P|O,EFEP\}(i) \cdot \{EFEP\} + \{P|O,No EFEP\}(i) \cdot (1 - \{EFEP\}) \\
\{D\} &= \{D|EFEP\} \cdot \{EFEP\} + \{D|No EFEP\} \cdot (1 - \{EFEP\}) \\
\{I\} &= \{I|EFEP\} \cdot \{EFEP\} + \{I|No EFEP\} \cdot (1 - \{EFEP\})
\end{align*}
\]

Beyond flexibility and customization, the Bayesian nature of the event tree helps elicit probabilities from experts and keep the RAM up-to-date; as new information becomes available, relevant conditional probabilities can be adjusted. Also, the representation of risk in the form of profiles instead of points allows a leakage trajectory to span multiple risk levels. As we explain next, all these advantages facilitate translating a RAM to a CPM and thus designing an effective contingency plan.

### 4. Translating the Risk Assessment Matrix to a Contingency Planning Matrix

The updated risk assessment matrix (RAM) can now be translated into a contingency planning matrix (CPM), which allows preparing for and responding to tolerable leakage risks. This translative procedure, shown in Figure 8, renders the proposed CPM an effective tool to design and demonstrate four essential elements of contingency planning: required resources, agreed-upon thresholds, preparedness and response tiers, and administration and collaboration schemes.
4.1. Transforming Matrix Dimensions

The axes of the CPM should address the two main goals of contingency planning: risk-preparedness and incident-response. To successfully fulfill both goals, suitable resources must be available. More likely or more frequent risks require more proximate resources, so the Leakage Likelihood \( \{L\} \) in risk assessment is best translated to Resource Proximity \( R_{\text{prox}} \) in contingency planning, which accounts for the closeness and accessibility of the required resources. Equivalently, more impactful risks require a wider variety of resources, so the Leakage Value of Impact \( VI \) in risk assessment is best translated to Resource Variety \( R_{\text{vari}} \) in contingency planning, which accounts for the uniqueness, complexity, and/or specialization of the required resources. Several metrics can be used to quantify these axes of CPM. For example, while an inverse-distance metric may quantify \( R_{\text{prox}} \), the number of dispatched incident-response teams may quantify \( R_{\text{vari}} \). In this regard, the ranges of \( R_{\text{prox}} \) and \( R_{\text{vari}} \) need not be continuous or linear; the operator may choose to define and discretize the ranges of both CPM axes based on the specific conditions and characteristics of the storage project. For example, the continuous range of tolerable Leakage Likelihood \( \{L\} = [10^{-7}, 10^{-1}] \) in Figure 7 may be translated into five discretized values of \( P_{\text{prox}} = \{ < 1/2000; 1/2000 – 1/1000; 1/1000 – 1/500; 1/500 – 1/100; > 1/100 \} \text{ km}^{-1} \), corresponding to the inverse radial distance below which contingency-planning resources should be accessible; larger \( \{L\} \) is translated into larger \( R_{\text{prox}} \) and therefore shorter distance between the resources and the storage site. Finally, the increase in the overall level of risk – defined as the multiplication of \( \{L\} \) by \( VI \) – is translated to an increase in the overall amount of resources that should be available to combat leakage. As such, constant risk-level contours are translated into constant resource-amount contours. Intuitively, contingency planning requires fewer resources for less likely and/or less impactful risks but more resources for more likely and/or more impactful risks.

Ultimately, the translation of RAM axes to CPM axes emphasizes that an effective allocation of resources for contingency planning shall ensure both timely and thorough preparation and response, irrespective of whether the addressed leakage scenario is high or low in likelihood or impact. We further clarify this point by considering two opposing risk scenarios. On one hand, for a high-impact but low-likelihood leakage risk, the proposed guidelines suggest allocating more various but less proximate resources. In addition to facilitating a thorough response, the resources’ high variety can compensate for their low proximity and thus facilitate a timely response. For example, highly various resources may cover unique logistical expenditures that accelerate the deployment of specific response equipment (e.g. expedited air shipping) or teams (e.g. high wages) on short-notice [74], or that boost general response operations (e.g. high rent of temporary accommodation for relocated communities) [75]. Indeed, because of the low likelihood, it would be inefficient to make these resources available on or close to the
storage site permanently. On the other hand, for a high-likelihood but low-impact leakage risk, the proposed guidelines suggest allocating more proximate but less various resources. Here, the resources’ high proximity can preventively compensate for their low variety and thus facilitate a thorough, as well as timely, response. For example, learning from analogues in the oil industry [76], very proximate resources may include on-site devices that enable a rapid – and if necessary, remote – shutdown of operations (e.g. stopping CO₂ injection in case of over-pressurization), which prevents the need for more complex corrective equipment (e.g. drilling a relief well). However, if intervention is delayed and pressurization escalates, such complex resources may become necessary.

4.2. Transforming Matrix Boundaries

Both intolerable and insignificant risks are not presented in the contingency planning matrix. To that end, the tolerance levels in a risk assessment matrix can be considered contingency thresholds in the contingency planning matrix. The minimum risk tolerance levels for likelihood \( \{L\} \) and impact \( (VI) \) are translated to minimum contingency thresholds, below which no contingency planning is required. Equivalently, the maximum tolerance levels for \( \{L\} \) and \( VI \) are translated to maximum contingency thresholds, above which contingency planning is insufficient and risk mitigation is necessary.

4.3. Classifying Risk into Tiers

Because not all tolerable risks are equal in likelihood or impact, distinct tiers of risk-preparedness and incident-response must be defined to address different tolerable risks with different requirements for resources proximity and variety. This study adopts a three-tier system for preparedness and response.

4.3.1. Scope of the Three-Tier System

The three-tier system is borrowed from the oil and gas industry where it has been extensively implemented [35, 77, 78, 79]. Table 3 lists three main criteria to properly assign a tolerable leakage risk to one of the three tiers: the geographic location of the leakage scenario and any resulting response operations; the governance structure among all parties involved in leakage preparedness and response; and the ownership, proximity, and variety of available resources. These tiers are discussed in more detail when presenting a model contingency plan later (Section 5).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Tier 1</th>
<th>Tier 2</th>
<th>Tier 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic location</td>
<td>operation site</td>
<td>local vicinity of the operation site</td>
<td>regional vicinity of the operation site</td>
</tr>
<tr>
<td>Governance structure</td>
<td>operating party and its contractors, regulatory agency</td>
<td>operating party and its contractors, regulatory agency, local stakeholders</td>
<td>operating party and its contractors, regulatory agency, local stakeholders, regional stakeholders</td>
</tr>
<tr>
<td>Resources ownership, proximity, and variety</td>
<td>owned by the operating party and its direct contractors, least unique, complex, and specialized trade-off: more proximate but less various resources</td>
<td>owned by the operating party, its direct contractors, and local stakeholders, moderately unique, complex, and specialized</td>
<td>owned by the operating party, its direct contractors, local stakeholders, and regional stakeholders, most unique, complex, and specialized trade-off: more various but less proximate resources</td>
</tr>
</tbody>
</table>
According to these criteria, Tier 1 is under the direct jurisdiction of the party operating the storage site and its contractors, and it addresses onsite risks that can be handled through standard and generic resources of relatively low complexity and specialization. Tier 2 expands the scope of covered risks to include those that might affect local communities around the operation site, might require the support and intervention of local governmental authorities and public-safety departments, or might necessitate the deployment of more complex or specialized resources. Finally, Tier 3 includes the most risky leakage scenarios whose effects might expand to the regional level, requiring the support and intervention of regional authorities, or necessitating the deployment of extensive, highly complex, or highly specialized resources. In this regard, “regional” in this analysis may refer to district-level, national-level, or multinational-level geographic zones; the exact definition of “regional” depends on the scale and conditions of the CO$_2$ storage reservoir and is thus project-specific.

4.3.2. Representation of the Three-Tier System

As can be noticed in Figure 8, the three contingency planning tiers cover all tolerable risks. Tier 1 prepares for risks and responds to incidents that require the smallest $R_{vari}$ while Tier 3 prepares for risks and responds to incidents that require the largest $R_{vari}$.

The range of $R_{vari}$ covered by Tier 1 shrinks as $R_{prox}$ increases. Tier 1 is primarily administered by the operating party, which, naturally, tends to concentrate its relevant resources close to the storage site that it directly manages. Because of space and logistical constrains, the resources available under this tier tend to be relatively limited in their scope and variety. Accordingly, as shown in Figure 9, Tier 1 covers more proximate but less various resources relative to constant resource-amount contours. In other words, the closer the required resources need to be located to effectively address a leakage, the less complex and specialized they should be to remain covered under Tier 1. However, if the resources need to be more complex and specialized in addition to being nearby, Tier 1 may not be sufficient, in which case the leakage should be covered under Tier 2 by bringing onboard further resources from local stakeholders and communities.

The opposite argument holds for Tier 3. The range of $R_{vari}$ covered by Tier 3 shrinks as $R_{prox}$ decreases. Since Tier 3 requires the engagement of multiple parties within a relatively large geographical area, the scope of resources available for this tier is relatively large. Accordingly, Tier 3 covers more various but less proximate resources relative to constant resource-amount contours. In other words, the farther the required resources can be located to effectively address a leakage, the more complex and specialized they should be to remain covered under Tier 3. However, if the required resources can be less complex and specialized in addition to being distant, Tier 3 may not be necessary, in which case the leakage should be covered under Tier 2.

Another implication of the proposed tier system and resulting contingency planning matrix (CPM) is the ability to address one leakage profile at multiple tiers. Knowing the measure of the geologic Indicator associated with each leakage scenario allows determining its likelihood and impact-value, which in turn allow determining the proper proximity, variety, and amount of resources required for effective preparedness and response. Consequently, as illustrated in Figure 9, a risk profile (corresponding to a leakage trajectory) can be covered under Tier 1 for relatively low likelihood and impact or under Tier 3 for relatively high likelihood and impact.

The boundaries between the three tiers can be thought of as additional contingency thresholds, which necessitate shifting from one strategy of risk-preparedness and incident-response to the other. Thus, besides the maximum and minimum thresholds identified earlier, contingency planning requires defining two tier thresholds: Tier 1-2 threshold determines the boundary between Tier 1 and Tier 2, and Tier 2-3 threshold determines the boundary between Tier 2 and Tier 3. Important to note, however, the intra-boundaries between the three tiers are not set at or dictated by constant resource-amount contours due to the trade-offs highlighted earlier. Appendix A provides further explanation on how the categorization of risk according to constant-risk contours may cause nontrivial pitfalls in contingency planning.
4.3.3. Negotiating Contingency Thresholds

When setting contingency thresholds, the operating party is usually guided by several considerations, including: external regulations and standards, internal safety culture and resource capabilities, compliance with the terms and conditions of insurance policies, and accommodation of the interests of communities affected by the CO₂ storage project. To that end, the exact specification of minimum, maximum, and tier thresholds are usually negotiated through a collaborative effort between the operating party and multiple stakeholders.

To start, although formal minimum and maximum contingency thresholds may be dictated by regulations or industrial standards, their implementation is usually shaped by the administrative procedures and protocols of the legally liable party managing the CO₂ storage site. To that end, the actual enforcement of these thresholds requires clear and effective communication. The operating party has to demonstrate its ability to reduce intolerable risks below mandated maximum contingency thresholds through insurance, safety measures, and system reinforcement. If the operating party fails to demonstrate such capability, the regulatory agency may not permit the project. Alternatively, the operating party may find it beneficial to adopt stricter thresholds than those dictated by regulations. For example, insurance rates may be lower if the project deploys more frequent monitoring or more accurate measurement tools than what is legally required. In this case, the adopted minimum and maximum thresholds would depend on the operating party’s safety culture and resource capabilities: trading more aggressive risk mitigation for less aggressive contingency planning, or vice versa. The regulatory agency would still need to be consulted on such trade-offs.

Equivalently, local, national, or international laws influence how the operating party sets the boundaries between the three contingency tiers. For example, the operating party may be legally required to notify local authorities about small leakage incidents while giving regional authorities the right to unilaterally and directly intervene in the case of large leakage incidents [21]. In this case, the regulatory agency would argue for keeping small leakage incidents within Tier 1 while necessitating Tier 2 (and potentially Tier 3) for large leakage incidents. In addition, the operating party may be legally required to engage with several stakeholders on the CO₂ storage project, including local communities and their emergency-response departments. Those relationships shape the operating party’s own preferences on how to categorize risks into different tiers. For instance, a small company might operate and manage a CO₂ storage site within a county that has a large pool of publically funded resources for contingency planning. In this case, to minimize costs, the operating party would be inclined to allocate fewer risks under Tier 1 and more risks under Tier 2 and Tier 3. Alternatively, the operating company might already have a
large inventory of emergency-response equipment, guided by its established safety procedures and long history of international operations. In this case, to maximize operational and decision-making autonomy, the operating party would be inclined to allocate more risks under Tier 1 and fewer risks under Tier 2 and Tier 3.

5. A Model Contingency Plan

The proposed RAM and CPM are essential building-blocks in the construction of an effective and comprehensive contingency plan. To demonstrate their role, we present an overview of the basic elements of a model contingency plan for CO₂ leakage through geologic pathways, illustrated in the exhibit “Outline of a Model Contingency Plan.” Although the model plan includes four major sections, we devote our attention to the design of the contingency tiers in the third section, where the various elements of RAM and CPM are mostly relevant. Accordingly, while this paper proceeds with a detailed discussion of the elements of the contingency tiers in the proposed model contingency plan, a brief description of the remaining three major sections of the plan is included in the referenced exhibit.

5.1. Tiers of Risk-Preparedness and Incident-Response

5.1.1. Thresholds

As explained in the derivation of the proposed CPM, a total of six thresholds should be identified in a contingency plan: two minimum contingency thresholds corresponding to minimum tolerance levels of risk likelihood and impact; two maximum contingency thresholds corresponding to maximum tolerance levels of risk likelihood and impact; Tier 1-2 threshold bordering between Tier 1 and Tier 2; and Tier 2-3 threshold bordering between Tier 2 and Tier 3.

5.1.2. Leakage Evaluation

Two types of leakage assessment frameworks are important to establish: one for risk-preparedness and one for incident-response. Each framework should include a checklist to characterize the leakage and categorize it under one of the three contingency tiers.

**Risk-Preparedness**: in order to adequately prepare for risk, each leakage scenario should be evaluated through a checklist that identifies its: 1) Indicator, Origin, Pathway, and Endpoint; 2) Leakage Likelihood \( \{L\} \); and 3) consequences quantified through a predicted Leakage Value of Impact \( VI \). As explained earlier and illustrated in Figure 8, \( L \) and \( VI \) in RAM are translated to \( R_{prox} \) and \( R_{vari} \) in the CPM, respectively. Then, using the CPM, the adequate tier to prepare for this prospective leakage scenario is specified at the intersection of the obtained \( R_{prox} \) or \( R_{vari} \) with the corresponding risk profile, as we demonstrate in Figure 10a and 10b, respectively. Ultimately, the extent of risks covered under each contingency planning tier influences the amount, type, and location of resources that should be assigned to that tier.

**Incident-Response**: an effective response to a detected CO₂ leakage requires a careful yet prompt evaluation of the leakage consequences. Therefore, the response checklist for a leakage incident should identify its: 1) Indicator, Origin, Pathway, and Endpoint; and 2) consequences measured in any feasible form, including Value of Flow \( VF \), Value of Damage in Subsurface \( VD_{sub} \), Value of Damage on Surface \( VD_{sur} \), or Leakage Value of Impact \( VI \). If \( VI \) is not the quickest or most practical way to directly measure the leakage consequences, other value-models \( VF, VD_{sub}, VD_{sur} \) may be used as proxy. Then, using a customized form of (2) and the guidelines presented in Section 3.2.2, the measured consequences can be translated to \( VI \), which in turn can then be translated to \( R_{vari} \). Subsequently, using the CPM, the adequate tier to respond to this leakage incident is specified at the intersection of the obtained \( R_{vari} \) with the corresponding risk profile, as shown in Figure 10b. In this case,
we note that the $R_{prox}$ axis – derived from the likelihood $\{L\}$ – plays no role in choosing the contingency tier; it is maintained in Figure 10b for the sole purpose of properly plotting the risk profiles.

Outline of a Model Contingency Plan

Directory

A directory is the first section any holder of the contingency plan should have access to in order to reach all decision-making stakeholders. The directory lists the contact information of people that are directly involved in risk-preparedness and incident-response, including personnel from the operating company, contractors, regulatory agency, local and regional governmental authorities, and community representatives.

Introduction

This section defines the purpose, scope, and relevance of the contingency plan [33]. This section should also introduce the party in-charge of designing and updating the contingency plan document; such party may be the site-operating firm, a specific team within that firm, or a contracted team by that firm.

• **Scope**
  A comprehensive contingency plan should cover risks associated with surface (e.g. well blowouts) and subsurface releases, through both man-made and geologic pathways. Accordingly, in this analysis of subsurface leakage through geologic pathways only, this section should list: all possible Origins, Endpoints, and Pathways, the surface location of Origins; and the location of major human structures (e.g. cities) and ecosystems (e.g. vulnerable habitats) at and in the vicinity of the storage site. The use of terrestrial maps is important.

• **Purpose and Objective**
  This section defines the roles of the staff members and contractors and the procedures they should follow to prepare for risks and respond to incidents of CO$_2$ leakage from [name] geologic storage reservoir through, in this case, geologic pathways. This section should also outline the objectives of the contingency plan, which may include: ensuring that preparedness and response are consistent with industrial practices and in compliance with regulatory standards; ensuring a full and effective integration and utilization of industry and government resources when needed; and prioritizing corrective-actions.

• **Priorities**
  This section summarizes the main priorities of the contingency plan, which may include: securing human safety during incident-response; minimizing the impact of leakage on human health the environment; minimizing the damage to equipment and assets used in incident-response; minimizing the likelihood of leakage through adequate management of resources; or minimizing disruption to CO$_2$ storage activities.

• **Legal and Regulatory Compliance**
  This section enlists all relevant governmental requirements, regulations, and laws; industrial standards and protocols; as well as international laws and treaties with which the contingency plan complies. This section may also include a list of the required reporting to external stakeholders if a leakage incident occurs.

• **Plan Integration**
  This section enlists other contingency plans and safety protocols by relevant internal and external stakeholders that complement the contingency plan of concern, including: health, safety, and environment (HS&E) policies, standards, and guidelines enforced at the storage site by the operating party or its contractors; governmental plans covering emergency response and relief (e.g. city or county emergency response plans); and industrial plans governing private service centers for emergency response and relief (e.g. Clean Caribbean and Americas [85], Oil Spill Response and East Asia Response Limited [86]).

Tiers of Risk-Preparedness and Incident-Response

• **Thresholds**
• **Leakage Evaluation**
• **Response Initiation**
• **Response Strategies**
  • **General Operations**
  • **Specific Operations: Corrective Measures**
• **Human and Equipment Resources**
• **Administration and Coordination**

Documentation

The contingency plan should be a living document, updated as the project progresses from planning operation, and periodically thereafter as more is learned about the performance of the storage site. To that end, the information included in the contingency plan should be reviewed regularly to incorporate any changes in risk assessment methods, tier-based preparedness and response procedures, resources inventories and allocation, training and maintenance schedules, or personnel directory. The operating party should maintain a detailed record of previous leakage incidents, response measures, best practices, and lessons learned, and it should update the incident-response procedures based on the new information gained from those incidents. In addition, the operating party is responsible for making the contingency plan available to all relevant internal departments and external stakeholders.
Figure 10. Tier allocation procedure for risk-preparedness and incident-response

The leakage characterization checklist for incident-response is different from that for risk-preparedness. First, Leakage Likelihood is not considered in incident-response because the leak has already occurred. Second, because leakage is detectable in incident-response, its consequences can be measured rather than predicted, which should result in a more accurate characterization.

### 5.1.3. Response Initiation

The transition from risk-preparedness to incident-response commences upon the identification of a measurement that exceeds a trigger value. A trigger is best described as an observation that renders VI above its preset minimum tolerance level. Unlike in the case of risk-preparedness where VI is predicted yet is still uncertain, a trigger observation renders VI above its minimum tolerance level with certainty, which in turn means that the minimum contingency threshold has been exceeded – and a response procedure must be initiated – also with certainty. To that end, triggers may be manifested as an irregularity in a wide range of measurable data; examples of triggers include: excessive pressure-buildup in Safe, high level of pH or trace metals in a FrW, or high concentration of dissolved CO$_2$ in the oil recovered from an O&G. In addition, the causes of a trigger may be an FEP from within the analyzed system (e.g. geochemical erosion of the caprock) or an EFEP from outside the analyzed system (e.g. new hydrocarbons’ drilling activities in the vicinity of the storage site or a large earthquake in the vicinity of the storage project).

Whether identified through regular or special monitoring or inspection, and regardless of the instrumentation or methodology used, once a trigger is identified, a response procedure should be initiated to detect then control or remediate leakage. Because leakage detection through trigger identification is the first step in incident-response, contingency plans should specify an extensive list of triggers. To that end, similar to contingency thresholds, response triggers should be selected by mutual agreement between the operator, regulatory agencies, and other appropriate stakeholders. The ability to respond quickly and decisively to abnormal events is one of the primary benefits of pre-negotiating these triggers.

### 5.1.4. Response Strategies

For each type of leakage event, a pre-planned course of action should be developed, depending on which tier it falls under. The response strategy should include two types of actions: general operations and specific operations. A summary table of both operation types is presented in Appendix B.
5.1.4.1. General Operations

Because the general operations are applicable to all leakage incidents, they should be designed and deployed in a way that reflects the priorities identified in the contingency plan. Most notably, the safety of all personnel responding to leakage incidents should be secured; in this case, the safety of the responding teams to subsurface leaks through geologic pathways may be jeopardized due to either leakage causes (e.g. big earthquakes) or leakage consequences (e.g. contaminated drinking water). In addition, general response operations should focus on recovering normal CO$_2$ storage activities as soon as possible.

The responding teams should have a clear action-plan on how to mobilize and deploy resources. This becomes especially important in Tier 2 and Tier 3 where some required resources are not owned by the operating party but rather managed and deployed by external stakeholders (e.g. municipal or state public-safety teams). To that end, Tiers 2 and 3 should fulfill two additional goals through general operations. First, each local and regional stakeholder should be assigned a clear responsibility zone to prevent conflicting decisions and delays in execution. Second, because leakage may impact local and regional populations, the operating party should be ready to provide supplementary support and services beyond its typical business. Examples of such services may include: security, evacuation, accommodation, transportation, and medical supervision for relocated communities; catering services for both the response teams and the affected communities; and financial compensation for damages or harms caused to nearby businesses or institutes.

5.1.4.2. Specific Operations: Corrective Measures

Specific response operations involve choosing proper corrective measures to control or remediate leakage. Several corrective measures have been proposed in literature [31, 38, 46, 48, 80], an example list of which is presented in Table 3. As shown, we envision four primary criteria affecting the feasibility and effectiveness of each corrective measure: objective, target formation, scale of deployment, and cost of deployment. First, it is important to identify whether the goal of the corrective action is to control (stop or contain) the leakage or to remediate its impacts. Second, given the specifics of the leakage trajectory and subsurface configuration, a corrective action may be carried out at the Origin of the leak, on the transport Pathway, or at the Endpoint (e.g. a freshwater aquifer). Third, some corrective measures are best applied only in a particular location of the subsurface formation whereas others could be applied at multiple locations throughout the subsurface. Finally, depending on the chosen technique, different corrective measures require different monetary investments and time commitments to install and operate wells, pumps, separators, or other water-treatment systems.

After identifying a list of feasible and effective corrective measures, the contingency plan should include a corrective measures matrix (CMM) that matches each leakage risk profile (incorporating a group of leakage scenarios of the same Origin-Pathway-Endpoint trajectory) with the best corrective-action techniques under each contingency tier. Although no extensive data currently exists on the best corrective measures for each risk profile, a template of the proposed CMM is presented in Table 4; the matrix is filled-in for illustrative purposes only. As shown, more than one corrective technique can be assigned to each risk profile, and the methods should be listed in order of priority.

Populating the CMM is dictated not only by the technical effectiveness of the corrective measures but also by the economic feasibility of deploying them. To that end, the right portfolio of corrective measures for each risk profile under each tier should balance between the cost of corrective measures and their benefits, expressed in terms of the “avoided damage” that would have occurred otherwise due to leakage. In other words, such cost-benefit analysis compares the VI of a particular leakage scenario to the cost of the corrective measures controlling or remediating it, and it is a common approach in managing risks that may widely impact human and natural ecosystems [81, 82]. Ultimately, designing such a CMM before leakage incidents occur is crucial for ensuring a rapid response to the leakage incidents when they occur.
Table 3. Example corrective measures for incident-response [31, 38, 46, 48, 80]

<table>
<thead>
<tr>
<th>Corrective Actions</th>
<th>Objective</th>
<th>Target Formation</th>
<th>Scale of Deployment</th>
<th>Deployment Components</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce CO₂ injection rate to reduce pressure-buildup</td>
<td>control</td>
<td>Origin</td>
<td>particular location</td>
<td>existing wells</td>
<td>A</td>
</tr>
<tr>
<td>Stop CO₂ injection to reduce pressure-buildup</td>
<td>control</td>
<td>Origin</td>
<td>particular location</td>
<td>existing wells</td>
<td>B</td>
</tr>
<tr>
<td>Partially extract CO₂ from the storage reservoir to reduce pressure-buildup</td>
<td>control</td>
<td>Origin</td>
<td>particular location; multiple locations</td>
<td>existing wells; new wells; pumps</td>
<td>C</td>
</tr>
<tr>
<td>Extract CO₂ at leakage point</td>
<td>control</td>
<td>Origin</td>
<td>particular location</td>
<td>new wells; pumps</td>
<td>D</td>
</tr>
<tr>
<td>Extract water from the storage reservoir to reduce pressure-buildup</td>
<td>control</td>
<td>Origin</td>
<td>particular location; multiple locations</td>
<td>existing wells; new wells; pumps; water treatment</td>
<td>E</td>
</tr>
<tr>
<td>Inject water in upper formations of the storage reservoir as a hydraulic barrier</td>
<td>control</td>
<td>Pathway</td>
<td>multiple locations</td>
<td>existing wells; new wells; pumps</td>
<td>F</td>
</tr>
<tr>
<td>Inject water to dissolve the leaking CO₂</td>
<td>control</td>
<td>Pathway</td>
<td>particular location</td>
<td>existing wells; new wells; pumps</td>
<td>G</td>
</tr>
<tr>
<td>Inject sealing material at leakage point or pathway (e.g. cement, gels, polymers)</td>
<td>control</td>
<td>Origin, Pathway</td>
<td>particular location</td>
<td>new wells; pumps; sealants</td>
<td>H</td>
</tr>
<tr>
<td>Extract CO₂ from storage reservoir and re-inject it into another reservoir</td>
<td>remediate</td>
<td>Origin</td>
<td>particular location; multiple locations</td>
<td>existing wells; new wells; pumps</td>
<td>I</td>
</tr>
<tr>
<td>Extract contaminated freshwater, treat, then re-inject</td>
<td>remediate</td>
<td>Endpoint (FrW)</td>
<td>particular location; multiple locations</td>
<td>existing wells; new wells; pumps; water treatment</td>
<td>J</td>
</tr>
<tr>
<td>Treat freshwater in the subsurface (e.g. inject microbes to restore pH)</td>
<td>remediate</td>
<td>Endpoint (FrW)</td>
<td>particular location</td>
<td>existing wells; new wells; chemicals or microorganisms</td>
<td>K</td>
</tr>
<tr>
<td>Extract oil or gas, treat, then use</td>
<td>remediate</td>
<td>Endpoint (O&amp;G)</td>
<td>particular location; multiple locations</td>
<td>existing wells; new wells; pumps; separators</td>
<td>L</td>
</tr>
<tr>
<td>Inject water to enhance recovery</td>
<td>remediate</td>
<td>Endpoint (O&amp;G)</td>
<td>particular location</td>
<td>existing wells; new wells; pumps; water treatment</td>
<td>M</td>
</tr>
</tbody>
</table>

Table 4. Example corrective measures matrix (CMM) for incident-response

<table>
<thead>
<tr>
<th>Corrective Measure</th>
<th>Tier 1</th>
<th>Tier 2</th>
<th>Tier 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk profile 1</td>
<td>A, E</td>
<td>B, E</td>
<td>B, E, C</td>
</tr>
<tr>
<td>Risk profile 2</td>
<td>A, E, K</td>
<td>B, E, K</td>
<td>B, E, J</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Risk profile 9</td>
<td>B</td>
<td>B, D</td>
<td>B, D, M</td>
</tr>
</tbody>
</table>

5.1.5. Human and Equipment Resources

In addition to distinguishing between resources proximity and variety, which is captured in the CPM, the contingency plan should make a clear distinction between human and equipment resources. Appendix B presents a summary table for categorizing resources accordingly.
Consistent with the type of response strategies defined earlier, human resources should be classified into general- and specialized-response teams. In addition, a detailed inventory should be developed and maintained by the operating party for all internal and contracted incident-response personnel. Such inventory should identify the name, job title, team membership, and contact information for each internal personnel, as well as the formal affiliation for contracted service-providers. For incident-response activities under Tier 2 and Tier 3, the inventory should also identify which personnel should act as liaison with external local or regional response teams (e.g. police, firefighters, industrial response centers) and communities (e.g. residents, schools).

Similar to human resources, the contingency plan should include a detailed inventory of equipment resources – both general and specialized – as well as a detailed timeline for their mobilization. In the case of Tier 1, all equipment is owned by the operating party or its contractors. However, for Tier 2 and Tier 3, the inventory should specify the source of equipment deployed by external local or regional stakeholders.

Finally, integral to securing effective response is human training and equipment maintenance. In addition to initial training, responding personnel should undergo regular refresher sessions in order to update their knowledge and skills as the project progresses. In fact, beyond Tier 1, joint drills with external (local and regional) parties become necessary [34]. Equivalently, equipment stockpiles used for safety as well as for leakage analysis, monitoring, control, and remediation should undergo periodical inspection and testing to ensure proper functionality.

5.1.6. Administration and Coordination

Effective administration of the tier-based contingency planning is key to secure proper implementation, communication, and accountability. Establishing an administrative framework for each tier involves identifying a clear hierarchy for decision-making, a notification protocol to report leakage incidents, and a communication-flow scheme to keep all relevant parties informed and updated. While the decision hierarchy and communication scheme are needed for both risk-preparedness and incident-response, the notification protocol is only relevant if a leakage incident occurs.

![Figure 11. Example decision-making hierarchy of the operating party for contingency planning](image-url)
As shown in Figure 11, the decision-making hierarchy within the operating party reflects the priorities of the contingency plan, expressed earlier in Section 5.1.3. For Tier 1, the primary decision makers are the onsite operators. The decisions should first secure the safety of operating personnel during risk-preparedness and incident-response, which is under the broad supervision of the HS&E team and site management. In addition, securing effective incident-response requires the presence of skilled and knowledgeable reservoir engineers and modelers who can refine and update preset corrective-action plans when necessary. Coordinating the logistics of resources’ mobilization and deployment is also critical. Tiers 2 and 3 require the deployment of further resources as well as dealing with local and regional stakeholders. To that end, additional administrative support and the involvement of more executive decision-makers become necessary.

Figure 12: Example notification protocol of the operating party for incident-response

Figure 13: Example communication scheme for contingency planning
Figure 12 shows an example notification protocol that may be followed by the operating party to report leakage to all relevant parties. One aspect to note is that each notification step should have a clearly defined timeframe. Internal corporate policies might dictate the timeframe of internal notifications whereas applied regulations and/or agreements might determine the notification periods for external stakeholders. Developing this notification procedure and the aforementioned decision-making hierarchy allows all parties to engage in an organized communication flow, which can be summarized in the example communication scheme illustrated in Figure 13.

Equally important is coordination and collaboration among all parties involved in the contingency plan in order to maximize efficiency and minimize mistakes and costs. We have already introduced two venues for collaboration in contingency planning: the negotiations between the operating party and the regulatory agency on setting the contingency thresholds and response triggers, as well as the joint training exercises among all response teams. An additional example of collaboration is illustrated in Figure 14, showing multiple cooperative pathways to pool resources for Tier 2 and Tier 3.

<table>
<thead>
<tr>
<th>Collaboration to fulfill Tier 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Joint Tier 1 resources of multiple operators in industry</td>
</tr>
<tr>
<td>• Joint Tier 1 resources of multiple local public-safety teams</td>
</tr>
<tr>
<td>• Specialized Tier 2 resource hub, funded and administrated by multiple operators in industry</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Collaboration to fulfill Tier 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Joint Tier 2 resources of multiple operators in industry</td>
</tr>
<tr>
<td>• Joint Tier 2 resources of multiple regional (national) emergency-response institutes</td>
</tr>
<tr>
<td>• Specialized Tier 3 resource hub, funded and administrated by multiple operators in industry</td>
</tr>
</tbody>
</table>

Figure 14. Collaborative approach to securing resources for Tiers 2 and 3

Under Tier 1, coordination is relatively easy, for most dispatched experts and equipment for leakage preparedness and response are managed directly by the operating party or its contractors. However, under Tiers 2 or 3, the operating party’s internal and contracted teams need to further coordinate with local and regional partners. In this case, different parties might have different priorities or be accustomed to different managerial styles, in which case coordination becomes challenging. To that end, major contingency planning decisions will require negotiation and compromise, and they are better handled when all affected parties have participated in the development and approval of the contingency plan.

6. Conclusion

Although existing regulations on CO₂ geologic storage require both assessing leakage risk and controlling or remediating leakage incidents through corrective measures, these two pieces of risk management are usually addressed separately. This study proposes a methodological framework for contingency planning, which links risk assessment and corrective measures. We achieve this goal in three consecutive steps: updating the representation of the risk assessment matrix (RAM); translating the risk assessment matrix to a contingency planning matrix (CPM) that incorporates a tier contingency system; and then using the emerging tiers as the basis for developing a model contingency plan for risk-preparedness and incident-response, which encompasses corrective measures. While this study focuses on the risks of CO₂ leakage in the subsurface and through geologic pathways, the proposed framework can be expanded to include other types of risks, including leakage at the surface or through man-made pathways.
The updated RAM allows visualizing the three major steps of risk assessment: risk identification, risk analysis, and risk evaluation, resulting in a comprehensive set of leakage risk profiles with quantified likelihood, impact, and tolerance levels. Upon dividing the overall storage site into functional subsystems, various leakage Origins, Pathways, and Endpoints are identified; leakage scenarios of the same Origin, Pathway, and Endpoint trajectory form a risk profile. Subsequently, the likelihood of each leakage scenario is analyzed as a series of conditional probabilities for leakage Origination, Propagation, and Destination, all of which change as a function of a measurable Indicator. Equivalently, multiple value-models are developed to quantify the leakage flow and impact, which covers the damages caused both in the subsurface and on the surface. Finally, through tolerance levels specified for both likelihood and impact, it becomes possible to evaluate what risks are too high and should be mitigated, and what risks are too small can be safely ignored.

The updated RAM can then be translated to a CPM. Fundamentally, preparing for leakage risks and responding to leakage incidents require a wide range of resources. To that end, the likelihood and impact dimensions of risk assessment are translated to resource proximity and variety, respectively. To ensure both quick mobilization and thorough deployment of corrective and remediating resources, more likely or frequent risks require more proximate resources while more impactful risks require more unique, specialized, or complex resources. In addition, the minimum and maximum risk tolerance levels are translated to contingency thresholds, defining the upper and lower boundaries for preparedness and response. Subsequently, to facilitate the assignment of the right resources to each leakage scenario, all foreseeable risks are categorized under three contingency tiers: Tier 1, Tier 2, and Tier 3. By design, Tier 1 trades more impactful, less likely risks for less impactful, more likely risks while Tier 3 does the opposite.

The CPM tier system becomes the cornerstone in the development of a contingency plan. The model contingency plan presented in this study demonstrates how the three tiers set the primary criteria for: implementing response strategies; designing a corrective measures matrix (CMM) that assigns specific control and remediation measures to each leakage profile; obtaining, mobilizing, deploying, and sustaining the human and equipment resources needed for incident-response; and formulating a decision-making hierarchy, a notification protocol, and a communication scheme that allow the operating party to effectively administer the CO₂ storage site. After addressing these main topics, it becomes easy to develop the remaining sections of a contingency plan, which include a directory of response personnel, background information on the project scope and priorities, a list of triggers that may initiate response, and a record of previous leakage incidents, best practices, and lessons learned.

Ultimately, the proposed methodological framework presents a dynamic and collaborative approach to risk management for CO₂ geologic storage. Revised experts’ opinions, best practices from previous leakage incidents, and new learnings from site operations, all can be captured in the Bayesian probabilities of leakage likelihoods as well as the value models of leakage consequences, resulting in an updated set of risk profiles. This redistribution of risk would be translated into a redistribution of resources under each contingency tier as well as the renegotiation of boundaries among tiers. Through transparent communications and proactive collaboration among all stakeholders, these systematic updates ensure that the right leakage risk scenario is covered under the right contingency tier using the right resources, and that the right corrective measure is deployed quickly and decisively if a leakage occurs. Consequently, both technological and administrative innovations improve the preparedness for and correction of leakage incidents.

Nonetheless, like all models, the proposed methodological framework may still face a unique set of challenges and limitations when implemented for real CO₂ storage projects. For completion, we list some of these limitations and challenges, which present future opportunities to expand and enhance this work. First, we note the subjectivity of probability assignment and interpretation in the proposed RAM; different experts might observe the exact same field data and still assign different probabilities for a leakage scenario. Indeed, such challenge is not unique to RAM but rather common across probabilistic assessment models. One way to address this challenge would be to ensure a clear and consistent understanding of each analyzed uncertainty by all consulted experts; our
approach strives to achieve this goal by relying on sequential conditional probabilities in the Bayesian event tree to untangle the various uncertain attributes of a leakage event. Also important is using uniform and unbiased protocols for probability elicitation from experts. While such initiatives are already underway [45, 62], it would be valuable to explore how to adapt existing protocols in others fields for the specific context of CO₂ leakage risks [83, 84]. Another related challenge is the potential need for extensive input data in order to support detailed probabilistic analyses. An important question that remains to be addressed in this regard is: how to balance between the RAM accuracy and simplicity? And how to test and verify that the analysis is detailed enough?

With CPM, one potential challenge may be the need for multiple metrics to quantify the $P_{prox}$ and $P_{vari}$ axes. For example, the site operator may find it necessary to categorize the complexity of resources not only by the number of dispatched expert teams but also by the size of deployed equipment. Accordingly, one may envision translating one RAM into a collection of CPMs, each with two unique metrics quantifying its two axes. To that end, it might be useful to explore a proper procedure to design such collection of CPMs while preserving the overarching three-tier contingency system they share.

Moving forward, however, an immediate next-step should be testing the application of the proposed framework through a real case-study that uses real data corresponding to a real CO₂ storage project. By constructing the RAMs, CPMs, and CMMs for multiple sequential stages of the project’s operational timeline, such case-study can demonstrate this framework’s ability not only to analyze leakage risks and develop contingency plans but also to track and update them over time.

7. Acknowledgement

The authors thank the Department of Management Science and Engineering and the Department of Energy Resources Engineering at Stanford University for funding this work. The authors also thank Professor John Weyant from the Department of Management Science and Engineering at Stanford University, as well as Associate Editor Dr. Jean-Philippe Nicot and the reviewers of this Journal, for their informative and valuable comments on this work.
References


Appendix A: Drawbacks of Alternative Three-Tier Systems

The proposed tier system for contingency planning in Figure 9 avoids potential pitfalls in alternative tier-system designs, as depicted in Figure A1. The resource-variety tier system in Figure A1a divides the tolerable risk zone into three tiers based only on the impact of leakage and thus the variety of needed resources; it covers the least impactful leakage scenarios under Tier 1 and the most impactful scenarios under Tier 3. The problem with this approach is that it ignores the need for different levels of Resource Proximity to prepare for and respond to leakage incidents of different likelihoods but of the same impact.

Conversely, the resource-proximity tier system in Figure A1b divides the tolerable risk zone into three tiers based only on the likelihood of leakage and thus the proximity of needed resources; it covers the least likely and infrequent leakage scenarios under Tier 1 and the most likely and frequent scenarios under Tier 3. The problem with this approach is that it ignores the need for different levels of Resource Variety to prepare for and respond to leakage incidents of different impact levels but of the same likelihood.

Additionally, the resource-amount tier system divides the tolerable risk zone into three tiers based on the overall level of risk, or equivalently, based on the overall amount of available resources; leakage scenarios of the lowest risk levels (lowest likelihood and impact) are covered under Tier 1 whereas those of the highest risk levels (highest likelihood and impact) are covered under Tier 3. This resource-amount tier system may be designed in two forms using continuous or discretized resource-amount contours, as illustrated in Figures A1c and A1d, respectively. The problem with this approach is that it equates leakage scenarios requiring most proximate but least various resources to those requiring least proximate but most various resources. The adopted tier system in this study avoids this problem due to the tradeoff illustrated in Figure 9 and explained in Section 4.3.2.
## Appendix B: Tier-Based Contingency Planning

### Table B1. Tier-based response strategies for contingency planning

<table>
<thead>
<tr>
<th>Element</th>
<th>Tier 1</th>
<th>Tier 2</th>
<th>Tier 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General operational procedures</strong></td>
<td>• Secure human health and safety&lt;br&gt;• Mobilize and deploy resources onsite&lt;br&gt;• Recover normal business operations as soon as practically possible</td>
<td>• Secure human health and safety&lt;br&gt;• Mobilize and deploy resources onsite and in the local vicinity of storage site&lt;br&gt;• Activate responsibility zones among local stakeholders&lt;br&gt;• Provide external support against local health, economic, or environmental damages&lt;br&gt;• Recover normal business operations as soon as practically possible</td>
<td>• Secure human health and safety&lt;br&gt;• Mobilize and deploy resources onsite, and in local and regional vicinity of storage site&lt;br&gt;• Activate responsibility zones among local and regional stakeholders&lt;br&gt;• Provide external support against local and regional health, economic, or environmental damages&lt;br&gt;• Recover normal business operations as soon as practically possible</td>
</tr>
<tr>
<td><strong>Specific operational procedures</strong></td>
<td>• Apply corrective measures to control (stop or contain) and remediate leakage</td>
<td>• Apply corrective measures to control (stop or contain) and remediate leakage</td>
<td>• Apply corrective measures to control (stop or contain) and remediate leakage</td>
</tr>
</tbody>
</table>
Table B2. Tier-based human and equipment resources for contingency planning

<table>
<thead>
<tr>
<th>Element</th>
<th>Tier 1</th>
<th>Tier 2</th>
<th>Tier 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human resources</td>
<td>• Categorize into general and specific response teams</td>
<td>• Categorize into general and specific response teams</td>
<td>• Categorize into general and specific response teams</td>
</tr>
<tr>
<td></td>
<td>• Inventory internal and contracted response personnel</td>
<td>• Inventory internal and contracted response personnel</td>
<td>• Inventory internal and contracted response personnel</td>
</tr>
<tr>
<td></td>
<td>• Conduct regular training programs, focusing on achieving, testing,</td>
<td>• Identify liaison personnel to external local response teams</td>
<td>• Identify liaison personnel to external local and regional response</td>
</tr>
<tr>
<td></td>
<td>and validating suitable competence (not only awareness or knowledge)</td>
<td>and stakeholders</td>
<td>teams and stakeholders</td>
</tr>
<tr>
<td></td>
<td>to perform the designated role</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment resources</td>
<td>• Inventory owned and contracted, general and specialized equipment</td>
<td>• Conduct regular training programs, focusing on achieving, testing,</td>
<td>• Conduct regular training programs, focusing on achieving, testing,</td>
</tr>
<tr>
<td></td>
<td>• Test and maintain equipment regularly to ensure proper operations</td>
<td>and validating suitable competence (not only awareness or knowledge)</td>
<td>and validating suitable competence (not only awareness or knowledge)</td>
</tr>
<tr>
<td></td>
<td>• Ensure equipment storage is optimal for easy mobilization</td>
<td>to perform the designated role</td>
<td>to perform the designated role</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Conduct joint training sessions with local stakeholders</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Conduct joint training sessions with local and regional stakeholders</td>
<td></td>
</tr>
</tbody>
</table>