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

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1   **Abstract**

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

25   **Keywords**

26   carbon dioxide; CCS; contingency planning; corrective measures; CO₂ geologic storage; leakage; risk assessment

27

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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].

Figure 1. Elements of risk management for CO₂ leakage from geologic reservoirs

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.

Figure 2. Functional subsystems for risk identification

Table 1. Examples of Origin FEPs and their corresponding Indicators

Origin FEP	Symbol { <i>O</i> }	Indicator	Symbol (<i>i</i>)
Caprock high-permeability zone	01	permeability	α
Caprock-absent zone	02	size of the opening	λ
Caprock fracture due to over-pressurization	03	size of fracture	β
Exceeding capillary pressure due to over-pressurization	04	capillary pressure	δ
Natural fault or fracture	05	size of fracture	β
Induced fault or fracture due to over-pressurization	06	size of fracture	β
Induced fault or fracture due to CO ₂ geochemical reactions	07	size of fracture	β
Induced fault or fracture due to seismic activity	08	Size of fracture	β

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 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 α . 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 .

Origination	Propagation	Destination	Likelihood of Leakage $\{L_j\}$	Value of Flow VF	Impact-Value of Leakage VI	
		$\{D = FrW O1, P\}(\alpha) = \{D = FrW\}$	$\{O1, P, D = FrW\}(\alpha)$	$VF_{FrW}(\alpha)$	$VI_{FrW}(\alpha)$	
		$\{D = O \& G O1, P\}(\alpha) = \{D = O \& G\}$	$\{O1, P, D = O \& G\}(\alpha)$	$VF_{O \& G}(\alpha)$	$VI_{O \& G}(\alpha)$	
		$\{D = Other O1, P\}(\alpha) = \{D = Other\}$	$\{O1, P, D = Other\}(\alpha)$	$VF_{Other}(\alpha)$	$VI_{Other}(\alpha)$	
				0	0	0

Leakage Likelihood $\{L\}(i)$: for CO₂ leakage to occur, the CO₂ 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).

$$\{L\}(i) = \{P\}(i) \cdot \{P|O\}(i) \cdot \{D|O, P\}(i) = \{P, O, D\}(i) \quad (1)$$

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 CO₂ leakage scenarios in Figure 3, corresponding to three distinct *Origin-Pathway-Endpoint* trajectories. Specifically, we assume CO₂ 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 CO₂ 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 α . The modelled range of α 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 α . 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 α 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].

Figure 4. Sketch of CO₂ leakage through caprock high-permeability zone

Figure 5. Example probability distributions of CO₂ leakage scenarios

Because *O1* is the only possible leakage FEP, CO₂ will either leak through it or remain in the designated storage aquifer *Safe*. As explained already, by definition, the CO₂ 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* α , given that the high-permeability zone *O1* actually exists. For CO₂ to leak through *O1*, the CO₂ plume should first reach *O1* then move

through *O1* into *Pathway*. In this case, we assume that the likelihood of CO₂ 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 α increases, capillary entry pressure decreases until it finally drops below the capillary pressure at the base of the caprock, at which point CO₂ can escape through the high-permeability zone in the caprock. Therefore, once α exceeds 0.1 mD, *Propagation* increases rapidly. Still, at the highest permeability range of $\alpha > 10$ mD, $\{P|O1\}$ is set at 0.7. Here, we make a realistic assumption that even though CO₂ can escape through *O1*, there is still a probability of $1 - \{P|O1\} = 0.3$ that the CO₂ plume may not reach *O1* 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* $\{O1\}$ and *Propagation* $\{P|O1\}$. Therefore, $\{D|O1, P\}$ is equal to $\{D\}$, which is constant across the whole feasible range of α . Informed by related findings in existing literature [56, 62], this example assumes that the leaked CO₂ 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 CO₂ 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 CO₂ 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 α , 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 CO₂ Leakage

Value models are functions that aim to quantify the consequences of potential CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ leakage in one monetary metric [63, 64, 65, 66]. To that end, we propose two monetary value models that quantify the consequences of CO₂ leakage in the subsurface and on the surface.

Value of Damage in the Subsurface – $VD_{sub}(i)$: corresponds to the cost of any leakage-induced damages to the subsurface resources. While directly dependent on VF and therefore on *Indicator*, separate VD_{sub} models can be designed for *FrW*, *O&G*, and *Other*, influenced by regulatory requirements. For *FrW*, VD_{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_{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_{sub} may be limited to a non-compliance penalty imposed by the regulatory agency.

Value of Damage on the Surface – $VD_{sur}(i)$: 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_{sur} . Similar to VD_{sub} , distinct VD_{sur} models can be designed for *FrW*, *O&G*, and *Other*, and all VD_{sur} models remain dependent on VF and thus on *Indicator*. Examples of factors that can be accounted for in designing VD_{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_{sub} and VD_{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_{sub}) and therefore higher disutility of these resources on the surface (VD_{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.

$$VI(i) = VD_{sub}(i) + VD_{sur}(i) = VD_{sub}(VF) + VD_{sur}(VF) \quad (2)$$

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/m².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 m² 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* α . For very low values of α , VF is in the order of 10^{-7} kg/m².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* α (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_{sub}), and the aquifer is the primary source of freshwater for a large county with a predominantly agricultural economy (high VD_{sur}). 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 $\alpha \geq 1$ 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 VD_{sub}), and oil revenues form a small part of the county's income (low VD_{sur}). Figure 6b simulates one example trend for the damage costs associated with CO_2 leakage into $O\&G$: for $10^{-3} \leq \alpha \leq 0.1$ mD, the oil producer handles the increased flux of leaked CO_2 by progressively adjusting its existing oil extraction techniques and schedule; however, for $\alpha \geq 0.1$ 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* α . Finally, we note that both VF and VI are discretized over the same seven intervals of α used to discretize leakage probabilities.

Figure 6. Example value models of CO_2 leakage scenarios

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 α 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 CO₂ leakage into *O&G* and *Other* are tolerable. However, the impact of CO₂ 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 CO₂ 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 CO₂ leakage.

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 CO₂ plume encountering an existing *FEP* $\{P_e|O\}$, and the probability of the CO₂ 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 CO₂ 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 CO₂ 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.

$$\{O\}(i) = \{O|EFEP\}(i) \cdot \{EFEP\} + \{O|No EFEP\}(i) \cdot (1 - \{EFEP\}) \quad (3)$$

$$\{P|O\}(i) = \{P|O, EFEP\}(i) \cdot \{EFEP\} + \{P|O, No EFEP\}(i) \cdot (1 - \{EFEP\}) \quad (4)$$

$$\{D\} = \{D|EFEP\} \cdot \{EFEP\} + \{D|No EFEP\} \cdot (1 - \{EFEP\}) \quad (5)$$

$$\{I\} = \{I|EFEP\} \cdot \{EFEP\} + \{I|No EFEP\} \cdot (1 - \{EFEP\}) \quad (6)$$

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.

Figure 8. Translating the risk assessment matrix to a contingency planning matrix

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_{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_{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_{prox} , the number of dispatched incident-response teams may quantify R_{vari} . In this regard, the ranges of R_{prox} and R_{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 $P_{prox} = \{< 1/2000; 1/2000 - 1/1000; 1/1000 - 1/500; 1/500 - 1/100; > 1/100\} \text{ km}^{-1}$, corresponding to the inverse radial distance below which contingency-planning resources should be accessible; larger $\{L\}$ is translated into larger R_{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 2. Selection criteria for the three-tier system

Criteria	Tier 1	Tier 2	Tier 3
Geographic location	operation site	local vicinity of the operation site	regional vicinity of the operation site
Governance structure	operating party and its contractors, regulatory agency	operating party and its contractors, regulatory agency, local stakeholders	operating party and its contractors, regulatory agency, local stakeholders, regional stakeholders
Resources ownership, proximity, and variety	owned by the operating party and its direct contractors least unique, complex, and specialized trade-off: more proximate but less various resources	owned by the operating party, its direct contractors, and local stakeholders moderately unique, complex, and specialized	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

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 CO₂ 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 constraints, 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.

Figure 9. Tier system tradeoff between resource proximity and resource diversity

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 CO₂ 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 CO₂ 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 CO₂ 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.

1

Table 3. Example corrective measures for incident-response [31, 38, 46, 48, 80]

Corrective Actions	Objective	Target Formation	Scale of Deployment	Deployment Components	Index
Reduce CO ₂ injection rate to reduce pressure-buildup	control	<i>Origin</i>	particular location	existing wells	A
Stop CO ₂ injection to reduce pressure-buildup	control	<i>Origin</i>	particular location	existing wells	B
Partially extract CO ₂ from the storage reservoir to reduce pressure-buildup	control	<i>Origin</i>	particular location; multiple locations	existing wells; new wells; pumps	C
Extract CO ₂ at leakage point	control	<i>Origin</i>	particular location	new wells; pumps	D
Extract water from the storage reservoir to reduce pressure-buildup	control	<i>Origin</i>	particular location; multiple locations	existing wells; new wells; pumps; water treatment	E
Inject water in upper formations of the storage reservoir as a hydraulic barrier	control	<i>Pathway</i>	multiple locations	existing wells; new wells; pumps	F
Inject water to dissolve the leaking CO ₂	control	<i>Pathway</i>	particular location	existing wells; new wells; pumps	G
Inject sealing material at leakage point or pathway (e.g. cement, gels, polymers)	control	<i>Origin, Pathway</i>	particular location	new wells; pumps; sealants	H
Extract CO ₂ from storage reservoir and re-inject it into another reservoir	remediate	<i>Origin</i>	particular location; multiple locations	existing wells; new wells; pumps	I
Extract contaminated freshwater, treat, then re-inject	remediate	<i>Endpoint (FrW)</i>	particular location; multiple locations	existing wells; new wells; pumps; water treatment	J
Treat freshwater in the subsurface (e.g. inject microbes to restore pH)	remediate	<i>Endpoint (FrW)</i>	particular location	existing wells; new wells; chemicals or microorganisms	K
Extract oil or gas, treat, then use	remediate	<i>Endpoint (O&G)</i>	particular location; multiple locations	existing wells; new wells; pumps; separators	L
Inject water to enhance recovery	remediate	<i>Endpoint (O&G)</i>	particular location	existing wells; new wells; pumps; water treatment	M

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3

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

Corrective Measure	Tier 1	Tier 2	Tier 3
Risk profile 1	A, E	B, E	B, E, C
Risk profile 2	A, E, K	B, E, K	B, E, J
...	...	...	...
Risk profile 9	B	B, D	B, D, M

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5.1.5. Human and Equipment Resources

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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

1 As shown in Figure 11, the decision-making hierarchy within the operating party reflects the priorities of the
2 contingency plan, expressed earlier in Section 5.1.3. For Tier 1, the primary decision makers are the onsite
3 operators. The decisions should first secure the safety of operating personnel during risk-preparedness and
4 incident-response, which is under the broad supervision of the HS&E team and site management. In addition,
5 securing effective incident-response requires the presence of skilled and knowledgeable reservoir engineers and
6 modelers who can refine and update preset corrective-action plans when necessary. Coordinating the logistics of
7 resources' mobilization and deployment is also critical. Tiers 2 and 3 require the deployment of further resources
8 as well as dealing with local and regional stakeholders. To that end, additional administrative support and the
9 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.

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.

1 The updated RAM allows visualizing the three major steps of risk assessment: risk identification, risk analysis,
2 and risk evaluation, resulting in a comprehensive set of leakage risk profiles with quantified likelihood, impact,
3 and tolerance levels. Upon dividing the overall storage site into functional subsystems, various leakage *Origins*,
4 *Pathways*, and *Endpoints* are identified; leakage scenarios of the same *Origin*, *Pathway*, and *Endpoint* trajectory
5 form a risk profile. Subsequently, the likelihood of each leakage scenario is analyzed as a series of conditional
6 probabilities for leakage *Origination*, *Propagation*, and *Destination*, all of which change as a function of a
7 measurable *Indicator*. Equivalently, multiple value-models are developed to quantify the leakage flow and
8 impact, which covers the damages caused both in the subsurface and on the surface. Finally, through tolerance
9 levels specified for both likelihood and impact, it becomes possible to evaluate what risks are too high and should
10 be mitigated, and what risks are too small can be safely ignored.

11 The updated RAM can then be translated to a CPM. Fundamentally, preparing for leakage risks and responding to
12 leakage incidents require a wide range of resources. To that end, the likelihood and impact dimensions of risk
13 assessment are translated to resource proximity and variety, respectively. To ensure both quick mobilization and
14 thorough deployment of corrective and remediating resources, more likely or frequent risks require more
15 proximate resources while more impactful risks require more unique, specialized, or complex resources. In
16 addition, the minimum and maximum risk tolerance levels are translated to contingency thresholds, defining the
17 upper and lower boundaries for preparedness and response. Subsequently, to facilitate the assignment of the right
18 resources to each leakage scenario, all foreseeable risks are categorized under three contingency tiers: Tier 1, Tier
19 2, and Tier 3. By design, Tier 1 trades more impactful, less likely risks for less impactful, more likely risks while
20 Tier 3 does the opposite.

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

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

40 Nonetheless, like all models, the proposed methodological framework may still face a unique set of challenges
41 and limitations when implemented for real CO₂ storage projects. For completion, we list some of these limitations
42 and challenges, which present future opportunities to expand and enhance this work. First, we note the
43 subjectivity of probability assignment and interpretation in the proposed RAM; different experts might observe
44 the exact same field data and still assign different probabilities for a leakage scenario. Indeed, such challenge is
45 not unique to RAM but rather common across probabilistic assessment models. One way to address this challenge
46 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.

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1 Appendix A: Drawbacks of Alternative Three-Tier Systems

Figure A1. Drawbacks of alternative tier-system approaches for contingency planning

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.

1 Appendix B: Tier-Based Contingency Planning

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Table B1. Tier-based response strategies for contingency planning

	Element	Tier 1	Tier 2	Tier 3
Response Strategies	General operational procedures	- Secure human health and safety - Mobilize and deploy resources onsite - Recover normal business operations as soon as practically possible	- Secure human health and safety - Mobilize and deploy resources onsite and in the local vicinity of storage site - Activate responsibility zones among local stakeholders - Provide external support against local health, economic, or environmental damages - Recover normal business operations as soon as practically possible	- Secure human health and safety - Mobilize and deploy resources onsite, and in local and regional vicinity of storage site - Activate responsibility zones among local and regional stakeholders - Provide external support against local and regional health, economic, or environmental damages - Recover normal business operations as soon as practically possible
	Specific operational procedures	Apply corrective measures to control (stop or contain) and remediate leakage	Apply corrective measures to control (stop or contain) and remediate leakage	Apply corrective measures to control (stop or contain) and remediate leakage

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Table B2. Tier-based human and equipment resources for contingency planning

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

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