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The Leakage Impact Valuation (LIV) Method for Leakage from Geologic CO_2 Storage Reservoirs

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Abstract

Leakage of brine or carbon dioxide (CO_2) from geologic CO_2 storage reservoirs will trigger numerous costs. We present the Leakage Impact Valuation (LIV) method, a systematic and thorough scenario-based approach to identify these costs, their drivers, and who incurs them across four potential leakage outcomes: 1) Leakage only; 2) leakage that interferes with a subsurface activity; 3) leakage that affects groundwater; and 4) leakage that reaches the surface. The LIV method is flexible and can be used to investigate a wide range of scenarios. The financial consequences of leakage estimated by the LIV method will be specific to the case study, because the consequences of leakage will vary across case studies due to differences geologic, institutional, and regulatory settings.

Keywords: *Carbon Dioxide Storage; Carbon Sequestration; Risk; Financial Consequences; Cost*

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1. Introduction

Geologic storage of carbon dioxide (CO_2) injects CO_2 emissions captured at large point sources into deep permeable geologic reservoirs, where the buoyant CO_2 would be permanently stored beneath low permeability caprock layers [1, 2]. Natural or manmade pathways could breach these caprocks, however, and CO_2 or displaced brine may migrate out of the storage formation. Although the probability of leakage is likely to be very low at appropriately selected and operated sites [1], the possibility of such leakage is a major concern of stakeholders [3, 4] in part because of uncertainty regarding the potential impacts of leakage from geologic CO_2 storage reservoirs. As a result, risk assessment requires an understanding of the consequences, or impacts, of leakage.

We present the Leakage Impact Valuation (LIV) method to estimate the financial consequences of leakage from CO_2 storage reservoirs. These impacts are the costs triggered by leakage events that would not have been incurred during the normal operation of a geologic CO_2 storage site, including those costs incurred by parties other than the geologic CO_2 storage operator. The financial consequences of leakage will be site-specific because of the variability in geologic factors, physical characteristics of the leakage, presence of “receptors” that leakage encounters, and site operating characteristics. The LIV method addresses the variety of potential impacts by developing low- and high-cost storylines for each outcome. These storylines represent plausible outcomes arising from leakage near the lower and upper ends of the spectrum; they are not end points. An approach that uses story lines avoids implying more understanding of the combined natural and manmade system than is knoweable, and focuses on the likely ways in which leakage may evolve, affect the subsurface and other activities, groundwater, the surface, and the stakeholders involved.

The LIV method estimates costs for a single leakage event at a geologic CO_2 storage site that is operating responsibly and meeting state and federal regulations, including U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) program Class VI permit requirements [12]. Financial consequences of leakage can arise from activities such as: (a) finding and fixing the leak, (b) environmental remediation, (c) damages to other subsurface activities, (d) legal expenses to defend against lawsuits, (e) income lost if geologic CO_2 storage site operations are interrupted, (f) obligations under climate change regulations, and (g) additional work by regulators to oversee the response to a leak. Leakage liabilities—the costs that a geologic CO_2 storage operator could be legally obligated to pay—are a subset of the financial consequences of leakage. Our broad definition of financial consequences is necessary in order to understand the potential influence of leakage at multiple scales: at the site, in the community, and in energy system overall.

2. The Leakage Impact Valuation (LIV) Method

The Leakage Impact Valuation (LIV) method is a systematic scenario-based approach to estimating the financial consequences of leakage from geologic CO_2 storage reservoirs. The LIV method considers the features, events, and processes (FEP) that could produce undesirable outcomes during the operational lifetime of a CO_2 storage project, and then monetizes the potential leakage outcomes. Other risk assessment approaches for geologic CO_2 storage may incorporate FEPs [5-8] but they do not assign monetary values in part because those approaches are limited by the methods to project leakage quantities and subsequent dosage levels [9, 10]. One recent study adapted a toxicological risk valuation approach, and suggested methods for identifying pathways for exposure, dosage, and effects [11] using a probabilistic approach to monetize some of the impacts. Probabilistic approaches may appear to be more direct than our scenario-based method, but those approaches require reliable data on the distributions of outcomes and impacts, and those approaches and must manage complicated contingent probabilities between cost components because costs are unlikely to be independent. For example, a leakage event that has high damages will be more likely to incur expensive containment costs and higher environmental remediation costs. Establishing a distribution from which costs are sampled may imply more information about how costs vary and are related to each other than is actually known or reliable. The LIV method develops scenarios that are transparent and internally consistent. The scenarios may be modified and the parameters within the cost categories may be varied in order to perform sensitivity analyses.

2.1. Leakage Outcomes

The LIV method identifies four potential leakage outcomes that are then customized according to the specific characteristics of a potential geologic CO_2 storage site:

1. **Leakage only:** CO_2 or brine escapes confinement but is isolated in the deep subsurface without impacting other subsurface activities or an underground source of drinking water (USDW).
2. **Leakage interferes with another subsurface activity:** One or more subsurface activities are affected by CO_2, brine, or pressure changes.
3. **Leakage impacts a USDW:** CO_2 or brine migrates into a USDW. The Safe Drinking Water Act [12] defines a USDW as any formation with total dissolved solids (TDS) less than 10,000 parts per million (ppm).
4. **Leakage reaches the surface:** CO_2 migrates to the unsaturated zone and/or discharges from the surface to the atmosphere.

For each of these outcomes, low- and high-cost storylines must be developed prior to determining the stakeholders who may be affected and determining the costs that these stakeholders may incur.

2.2. Low- and High-Cost Storylines

Detailed low- and high-cost storylines for each of these four outcomes must be constructed based on the specific geologic conditions, site operating parameters, demographic characteristics, infrastructure, and profiles of subsurface uses in that area. **Table 1** shows an example summary of the low- and high-costs storylines. The second leakage outcome, where leakage interferes with subsurface activities, is separated into three categories of interference: with natural gas production and storage, with oil production, or with waste injection.

Table 1: Leakage Outcomes and Summary of High- and Low-Cost Storylines for Estimating Monetary Impacts of Leakage

LEAKAGE OUTCOME		COST STORYLINE	STORYLINE SUMMARY
Leakage Only		Low	Leakage is detected when the plume is small. Leakage is contained below formations in which other subsurface activities are present. CO_2 injection is halted for five days while the leaky well is reworked.
		High	Leakage is detected when the plume is large. Neither subsurface activities nor the lowermost USDW are affected. An accumulation of CO_2 above the caprock is detected and extracted. A nearby natural gas storage operator files suit claiming decreased injectivity, but the suit is dismissed. CO_2 injection is halted for nine months while a pressure management system is installed.
Inte rfer	Nat ural	Low	A small amount of CO_2 migrates into a natural gas storage reservoir causing minor damage to fittings

			and tubing. The CO_2 content in the resulting mixture is below pipeline standards of 2%. The natural gas storage facility misses one month of operation while damages are repaired and sues the geologic CO_2 storage operator for the costs of damages and business interruption. CO_2 injection is halted for five days while leaky well is reworked.
		High	The CO_2 content of produced natural gas in a nearby natural gas storage operation increases. Unable to meet pipeline requirements, the natural gas storage operator misses one heating season while an amine separation facility is installed to reduce the CO_2 content in the stored produced natural gas below pipeline standards. The natural gas storage operator sues the geologic CO_2 storage operator for damages and business interruption. CO_2 injection is halted for nine months while a pressure managements system is installed.
	Oil Production	Low	Leakage causes a temporary pressure increase in the oil bearing formation, inducing increased oil production. The oil production operator takes no action against geologic CO_2 storage operator. CO_2 injection is halted for five days while the leaking well is reworked.
		High	A nearby oil production operator finds elevated CO_2 in the produced oil and detects damage in fittings and downhole tubing. The remaining value of the oil reserves is worth less than the cost of technical remedies to resume production. The oil production operator sues the geologic CO for the value of the remaining reserves. CO_2 injection is halted for nine months while pressure management system is installed.
	Waste Injection[1]	Low	A nearby waste injection operator experiences decreased injectivity due to increased formation pressure, but projects that capacity and rates will be adequate for the expected life of the operation. Legal action results in a settlement for the value of the lost injection capacity. Injection is halted for five days while a leaking well is reworked.
		High	Increased formation pressure renders an existing waste injection well unable to inject the required volume of fluid. An additional waste injection well is installed, and the waste injection operator sues the geologic CO_2 storage operator for damages and business interruption. CO_2 injection is halted for nine months while a pressure management system is installed.
Affects Groundwater		Low	A small amount of CO_2 migrates into a deep formation that has a total dissolved solids (TDS) level of ~9,000 ppm. This unit is technically a USDW, but the state has abundant water resources and there are no foreseeable uses for water from this unit. U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) regulators require that two monitoring wells be drilled into the affected USDW and three monitoring wells be drilled into the lowermost potable aquifer (TDS <1000 ppm) to verify the extent of impacts from the leak. No legal action is taken. Injection is halted from the time the leak is discovered until monitoring confirms that containment is effective (nine months). The UIC regulator determines that no additional remedial actions are necessary.
		High	A community water system reports elevated levels of arsenic. Monitoring suggests that native arsenic may have been mobilized by pH changes from the presence of CO_2 in the aquifer. A new water supply well is installed to serve the community, and the former water supply wells are plugged and capped. Potable water is provided to the affected households during the six months it takes for the new wells to be installed. Groundwater regulators sue the geologic storage operator to force remediation of affected USDW using pump and treat technology. UIC regulators require remedial action to remove, through a CO_2 extraction well, an accumulation of CO_2 accumulation that has the potential to affect drinking water.

		A nearby natural gas producer files suit alleging that leakage has damaged his natural gas reservoir. The suit is dismissed, but both parties incur significant legal expenses. CO_2 injection is halted for a year.
Reaches Surface	Low	A leaking well provides a pathway whereby CO_2 discharges directly to the atmosphere. Neither CO_2 nor brine leaks into subsurface formations outside the injection formation in significant quantities. The leaking well is promptly plugged, and CO_2 injection is halted for five days.
	High	This storyline includes the high-cost storyline where groundwater. In addition, a hyperspectral survey completed during the diagnostic monitoring program identifies surface leakage in a sparsely populated area. Elevated CO_2 levels are detected by a soil gas survey and by indoor air quality sampling in the basements of several residences. Affected residents are housed in a local hotel for several nights while venting systems are installed in their basements. A soil venting system is installed. CO_2 injection is halted for a year.

[1]*Applicable to injection of hazardous waste, non-hazardous waste, or produced fluids.*

Once the low- and high- cost storylines are established for each of the leakage outcomes, stakeholders who may incur costs are identified. Establishing the storylines prior to identifying the stakeholders allows enforces objectivity and impartiality on the analyst, and thus a more thorough understanding of the array of possible consequences and to whom.

2.3. Identify Stakeholders

Costs that are triggered by leakage from geologic CO_2 storage reservoirs will be incurred by a variety of stakeholders. Costs are assigned to the stakeholder who performs the actions triggered by leakage or who bears a labor burden as a result of activities spawned by the leakage. These costs are proxies for the "exposure" of various stakeholders and their associated level of concern about leakage. The LIV method assigns two types of costs to stakeholders other than the geologic CO_2 storage operator: (i) expenditures for activities made necessary by leakage, and (ii) labor burden that leakage might impose. These costs are based on the average income of the stakeholder group and an estimate of the time that members of that stakeholder group might spend addressing leakage occurrences. Some portions of the costs incurred by the geologic CO_2 storage operator would likely be recovered from their insurer. But, despite their important roles in geologic CO_2 storage operations, the LIV method does not include insurers as one of the identified stakeholders. Insurance claims are a second-order activity, and identifying which portions of the costs incurred by geologic CO_2 storage operators may be recoverable is beyond the scope of the LIV method. **Table 2** presents the ten stakeholders that might be affected by leakage and provides examples of the types of costs these stakeholders may incur.

Table 2: Stakeholders Possibly Affected by Leakage from a Geologic CO_2 Storage Site

STAKEHOLDER	EXAMPLES OF POTENTIAL COSTS
Geologic Storage Site Operator	Expenses for diagnostic monitoring, containment activities, and environmental remediation. Legal expenses to defend against lawsuits and negotiate settlements
Geologic Storage Regulator	Regulatory oversight of leakage related activities.
Subsurface Activity Operator	Expenses for technical remedies if a subsurface activity is affected by leakage. Legal expenses to seek compensation from geologic storage site owner

Subsurface Activity Regulator	Regulatory oversight if leakage affects regulated subsurface activity.
Groundwater User	Time and trouble dealing with alternate water source if groundwater is contaminated by leakage. Expenses for alternate water as well.
Groundwater Regulator	Regulatory oversight is leakage affects groundwater.
CO_2 Producer	Labor burden involved with redirecting CO_2 to an alternate geologic storage site if CO_2 injection must be interrupted due to leakage.
Climate Regulator	Regulatory oversight if leakage complicates emissions reporting.
Surface Owner/Resident	Time and trouble to stay abreast of the leakage situation. Time spent on arrangements for new monitoring wells or containment activities.
Environmental/Health Regulator	Regulatory oversight if leakage affects ecosystems or buildings. Legal expenses to force environmental remediation.

2.4. Cost Categories

The final step in the LIV method is to estimate the costs for each stakeholder according to the leakage outcomes and the low- and high-cost storylines. The LIV method organizes all actions within an outcome into six cost categories and specifies the actions by all stakeholders in each cost category. Costs of these actions are then estimated using published data and interviews with experts. The six cost categories are:

1. **Diagnostic Monitoring:** Leakage requires additional monitoring to: i) find the pathway, ii) characterize extent of the fluids that have leaked, iii) identify and characterize impacts to other subsurface activities, and iv) identify and characterize health or environmental impacts.
2. **Containment Activities:** Activities required to impede the migration of CO_2 or brine out of the injection formation as well as monitoring to verify that the leakage has stopped.
3. **Environmental Remediation:** Regulations or litigation could require environmental remediation if natural resources or ecosystems are affected.
4. **Damages:** Actions necessary to make whole any business or individual harmed by leakage, including the cost of technical solutions and the burden of "time and trouble." Damage costs include business disruption losses and legal expenses incurred to resolve lawsuits.
5. **Climate Program Compensation:** Geologic CO_2 storage sites are potential emissions sources under the EPA mandatory greenhouse gas reporting program [13]. If a leakage event resulted in CO_2 emissions to the atmosphere from venting or surface leakage, costs could be incurred to compensate for those emissions.
6. **Site Closure:** Regulators could require site closure if the containment system is not effective. If efforts to contain leakage are unsuccessful and the injected CO_2 presents an ongoing threat to subsurface activities or resources, a geologic CO_2 injection reservoir might be closed prematurely. Premature closure would affect the Injection Operators return on investment, trigger legal costs, and place a labor burden on regulators. A major cost factor in premature site closure would be whether injected CO_2 could be left in place.

The types of costs incurred by each stakeholder are likely to be extensively distributed over the cost categories. **Figure 1** shows an example mapping of the leakage outcomes, cost categories, and the stakeholders affected.

COST CATEGORY	LEAKAGE OUTCOME																			
	Leakage Only					Interference: Subsurface Activity					Interference: Groundwater					Migration to Surface				
Diagnostic Monitoring	IO		WU	CP	SO	IO	AO	WU	CP	SO	IO	AO	WU	CP	SO	IO	AO	WU	CP	SO
	IR			CR		IR	AR		CR		IR	AR	WR	CR		IR	AR	WR	CR	E/HR
Containment Activities	IO	AO	WU		SO	IO	AO	WU		SO	IO	AO	WU		SO	IO	AO	WU		SO
	IR		WR			IR	AR	WR			IR	AR	WR			IR	AR	WR		E/HR
Environmental Remediation	IO	AO			SO	IO	AO			SO	IO	AO	WU		SO	IO	AO	WU	CP	SO
	IR	AR	WR			IR	AR	WR			IR	AR	WR			IR	AR	WR	CR	E/HR
Damages	IO	AO				IO	AO				IO	AO	WU			IO	AO	WU	CP	SO
	IR	AR				IR	AR				IR	AR	WR			IR	AR	WR	CR	E/HR
Injection Interruption	IO	AO				IO	AO				IO	AO	WU			IO	AO	WU	CP	SO
	IR	AR				IR	AR				IR	AR	WR			IR	AR	WR	CR	E/HR
Climate Program Compensation	IO			CP		IO			CP		IO			CP		IO			CP	
				CR					CR					CR					CR	

IO Injection Operator **AO** Activity Operator **WU** Groundwater User **CP** CO_2 Producer **SO** Surface Owner / Resident
IR Injection Regulator **AR** Activity Regulator **WR** Groundwater Regulator **CR** Climate Regulator **E/HR** Environmental/Health Regulator

Figure 1: Example Stakeholder Exposure by Leakage Outcome and Cost Category

3. Summary

The LIV method is a structured approach for estimating the financial consequences of leakage from geologic CO_2 storage reservoirs. This structured approach focuses on developing thorough storylines associated with leakage events, so that the full extent of the impacts are understood without premature conclusions. The costs that are triggered by leakage will be specific to the site being assessed, in part because of the geology of the injection reservoir, the characteristics of the CO_2 storage formation, the parameters necessary to operate the CO_2 injection, and the proximity and characteristics of nearby activities that are also using the subsurface. Specifying the case study and these conditions is the important first step in systematically estimating the financial consequences of leakage from CO_2 storage reservoirs.

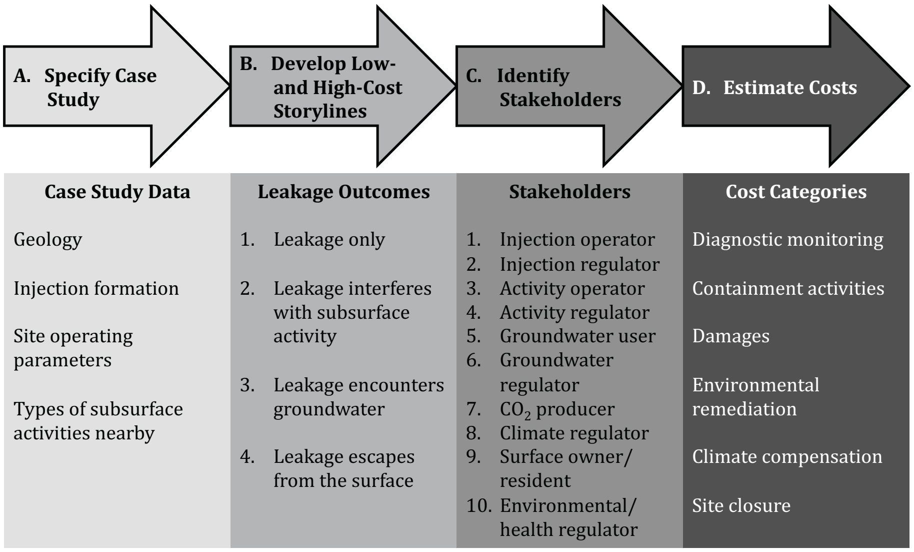

Figure 2: The Leakage Impact Valuation Method for Estimating the Financial Consequences of Leakage from Geologic CO_2 Storage Reservoirs

Figure 2 provides a summary of the LIV method. After specifying the case study and the characteristics of it, the four leakage outcomes must be identified and low-and high-cost leakage scenarios for each outcome must be described. The next step is to identify the wide range of stakeholders who could incur costs from leakage events and determine ways in which these costs could be incurred. The final step in the LIV method is to systematically estimate the costs incurred by each stakeholder under the seven cost categories as described in Section 2.4. The LIV method is flexible and can be used to investigate a wide range of scenarios. The results will be specific to the case study, because the consequences of leakage will differ in other geologic, institutional, and regulatory settings.

The LIV method produces estimates of the financial consequences of leakage from geologic CO_2 storage reservoirs. Understanding leakage *risk*, however, requires that the probabilities of outcomes be assessed in addition to their financial consequences. These probabilities may be derived from simulations of geophysical fluid flow from established models, such as the Estimating Leakage Semi-Analytically (ELSA) model [14]. In addition, these simulation models and their results may be used to provide a measure of where between the low- and high-cost storylines expected leaks may fall. Future research combining the LIV method with the results of geophysical simulations to determine probabilities and extents of leakage, and the three-dimensional geologic environment locating potential leakage pathways, hydrostratigraphic units, and other subsurface activities can monetize leakage risk. Such understanding is important at a number of scales. At the site level, geologic CO_2 storage site operators must understand the relative financial consequences from various potential leakage outcomes in order to design effective risk management strategies. At the community level, siting and permitting decisions depend on input from groups concerned about how leakage might affect them—including landowners, water users, owners of other subsurface activities, government officials, and regulators. At the energy system level, planners need to optimize geologic CO_2 storage siting decisions and assess how potential leakage might affect the role of CCS in the portfolio of climate change mitigation technologies.

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