Reviewing the implications of unlikely but potential CO_2 migration to the surface or shallow subsurface

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Report Overview:

Reviewing the implications of unlikely but potential CO_2 migration to the surface or shallow subsurface

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Introduction

CO_2 leakage from geological storage is considered unlikely from properly selected sites and the potential impacts small when compared to other anthropogenic and natural stressors[1]. However, it is important to predict and understand potential environmental impacts and risks to human health from a range of leak scenarios in order to undertake appropriate monitoring and mitigation necessary to meet both regulatory and societal expectations[2].

Migration of CO_2 to the surface, subsurface or into potable water reservoirs poses a risk, and although is predicted to be rare and limited in quantity, cannot be excluded completely,

[1] Blackford, J., Alendal, G., Avlesen, H., Brereton, A., Cazenave, P.W., Chen, B., Dewar, M., Holt, J. and Phelps, J., 2020. Impact and detectability of hypothetical CCS offshore seep scenarios as an aid to storage assurance and risk assessment, International Journal of Greenhouse Gas Control, Volume 95, 2020, 102949.
[2] Sands, C., Connelly, D.P. and Blackford, J.C., 2022. Introduction to the STEMM-CCS special issue. International Journal of Greenhouse Gas Control, 113, p.103553.

especially via abandoned wells, along fault surfaces or via gas chimneys. Very strict interpretation of regulatory requirements may impose very high costs or limit the number and size of storage site unnecessarily, thus potentially reducing the regional and global storage resources severely.

Given the important role that carbon capture and storage (CCS) plays, as a part of negative emission technologies (NETs) and emission reduction technologies, in most climate scenarios (IPCC, IEA and others), a balance between the merits of CCS on a global scale and the potential risks at a local scale, needs to be evaluated. A growing body of knowledge, gleaned over the past two decades into the environmental impact of leaked CO_2 have included studying the impact of CO_2 release in: natural settings, potable aquifers, via laboratory and controlled release experiments and modelling. It was desirable, therefore, that these learnings were summarised and evaluated in a clear and accessible document that would be of value to policymakers, project developers and regulators.

Key Messages

- Climate change is a global phenomenon and a threat. The benefits of the removal of significant volumes of greenhouse gas emissions to the atmosphere via carbon capture and storage (CCS) far outweigh the very low likelihood of material local environmental impacts associated with any leakage at a local scale.
- The probability of leakage via geological features when storing CO_2 at well-characterised sites is negligible for storage in depleted hydrocarbon fields and extremely low for saline aquifer storage. However, it is possible for compromised well or surface integrity issues to facilitate migration or release of CO_2 out of its storage reservoir and this could be material in individual cases. Well leakage can be easily detected, and mitigation and remediation are possible. Multiple barriers and partial migration into various intervening aquifers, buffering, dissolution and residual saturation will reduce the total volume ending up in groundwater, soils, the ocean or the atmosphere.
- Extremely high concentrations of CO_2 in the ocean, groundwater or the atmosphere are demonstrated in exceptional cases of natural CO_2 leakage and can cause material harm to the environment, but are improbable in the case of CO_2 geological storage.
- Multiple reviews of laboratory and field experiments on the remobilisation of other harmful substances as a result of CO_2 leakage concludes that material impacts are unlikely under CO_2 leakage conditions from a well-characterised and monitored geological storage project.
- In the absence of actual CO_2 leakage examples from CCS projects, leakage rates and risks are limited to synoptic studies and simulations often based on experience and data from the petroleum industry. Rates based on analogues can vary substantially and the probability of leakage also has a wide range.

- In the event of a material leak, consequences to the local environment could have direct environmental and health implications that should be used in environmental impact assessments using local knowledge and jurisdiction-specific regulatory thresholds. This study provides a non-site-specific and general framework.

Scope

The study was conducted by CSIRO and their approach was to bring the current state of knowledge around the risks of CO_2 leakage from a geological storage site and the potential health or environmental impacts together in an assessment framework, or Causal Network. This Causal Network allows for the identification of a series of steps that provide information on cause-and-effect relationships in relation to the challenge being addressed i.e. emissions reduction through the geological storage of CO_2.

By bringing together the potential environmental impacts with details on potential leakage pathways, leakage rates and probability of occurrence, the outcomes of the study give a clear understanding of the risks of leakage from CO_2 geological storage reservoirs, identifying where to focus monitoring and verification efforts, and suggesting mitigation strategies, should they be required.

Critical aspects for describing and quantifying consequences of CO_2 migration from geological storage that are critically reviewed in the project are:

- CO_2 leakage pathways, rates and volumes.
- Sensitivity to environmental receptors, animals and humans, and the climate in general, to increased CO_2 concentrations in groundwater, seawater and the atmosphere.
- Deployment constraints and detection limits of available monitoring technologies.
- Mitigation options.

Findings

The goal of CCS is to limit or reduce the concentration of CO_2 (a greenhouse gas) into the atmosphere, and thereby contribute to the reduction of global warming and climate change. Emissions reduction is the principal driver, and reduction targets at national levels are becoming more refined. CO_2 storage projects have accumulated many project years and wellbore years of experience without known examples of leakage. Geological storage of CO_2 is expected to be secure, but leakage cannot be guaranteed to be mathematically zero. By analogy with oil and gas operations, operators expect operational losses to be small, and use this experience in their risk management. Management of storage risk is a dynamic process, and monitoring will inform the updates and refinement to models during the lifespan of the project and beyond. Monitoring plans should ensure that leakage is detected early and mitigation strategies must be broad in scope[3]. Overall, a site operator's objective is to constantly drive the project risk (i.e., its probability x consequence) to ALARP (As Low As Reasonably Practicable)[4].

The impact of leakage of geological storage sites with the return of CO_2 to the atmosphere on targeted climate goals is not straightforward to calculate and requires full earth system (carbon cycle-climate) models, which depend on multiple assumptions. The scale of CCS may reduce emissions promptly and leaked CO_2 would represent a fraction of the stored volumes and occur at much slower rates. Several models in the literature with different assumptions all arrive at tolerable leakage rates of CCS (with a net benefit to the climate), at fractional rates around 0.001 to 0.0001 per year. This refers to a net benefit to the climate (atmospheric concentration of CO_2) but the environmental implications of a leak, such as impact on potable aquifers or acidification of the oceans, need to also be considered.

This study builds on the wealth of published material which has reviewed CO_2 environmental impacts combined with additional context and detail from the review of potential leakage pathways, leakage rates and probability of occurrence. The results are presented as a causal network (Figures 1 and 2) by illustrating activities (CO_2 geological storage), stressors (leakage pathways), processes (i.e. CO_2 migration into groundwater, ocean or atmosphere) and impact on endpoints (i.e. groundwater contamination) of CO_2 geological storage. This approach combines a vulnerability evaluation framework with a risk assessment component for each pathway. For this study, this is a general network description, but it would be possible to apply the approach to specific regions or geologic basins. Each of the building blocks (Figure 1) are underpinned by a literature review and a simple navigation tool (Figure 2) allows the reader to interactively access parts of the report of interest and return to the tool via clickable links.

Whether an impact is 'material' can be evaluated either qualitatively or quantitively (c.f. Victorian Environmental Protection Act, 2017[5]). For each link, this study examines what the relevant quantities are to consider in establishing materiality, and where available, provides an overview of quantitative estimates of thresholds for materiality. In the recently updated EU Directive Guidance Documents, the risk evaluation process encourages the characterisation of significant or insignificant risks, a function of likelihood and severity[6].

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[3] https://www.mirecol-co2.eu/

[4] Whether this is low enough, in a wider sense that the metrics of the project to hand, is a wider question that goes to the downside of not implementing the project at all.

[5] Victorian Environment Protection Act 2017. www.legislation.vic.gov.au/in-force/acts/environment-protection-act-2017/005.

[6] EC – Guidance document 1 – CO_2 storage life cycle and risk management framework (July 2024)

Node type	Description	Examples
 Driver	Major external driving forces (human or natural) that have large-scale influences on climate change	Industrial emissions
 Activity	A planned event associated with mitigating climate change	CO_2 geological storage
 Stressor	Physical or chemical condition, or external stimulus caused by activities	Compromised well integrity, Compromised subsurface integrity
 Process	A mechanism that could change a characteristic of an endpoint	CO_2 migration into the atmosphere, ocean, seabed, soil, surface water, or shallow aquifers
 Endpoint	A value pertaining to water, air and the environment that maybe impacted by processes due to activity	Climate, public health, marine or lake fauna & flora, plants growths, potable water, subsurface resources

Figure 1: Building blocks for the development of a causal network pathway[7]. See Figure 2 for the resulting causal network.

[7] Peeters, L.J.M., Holland, K. and Huddlestone-Holmes, C.R., 2021. Geological and Bioregional Assessments: assessing direct and indirect impacts using causal networks. The APPEA Journal 61 (2), 485-490.

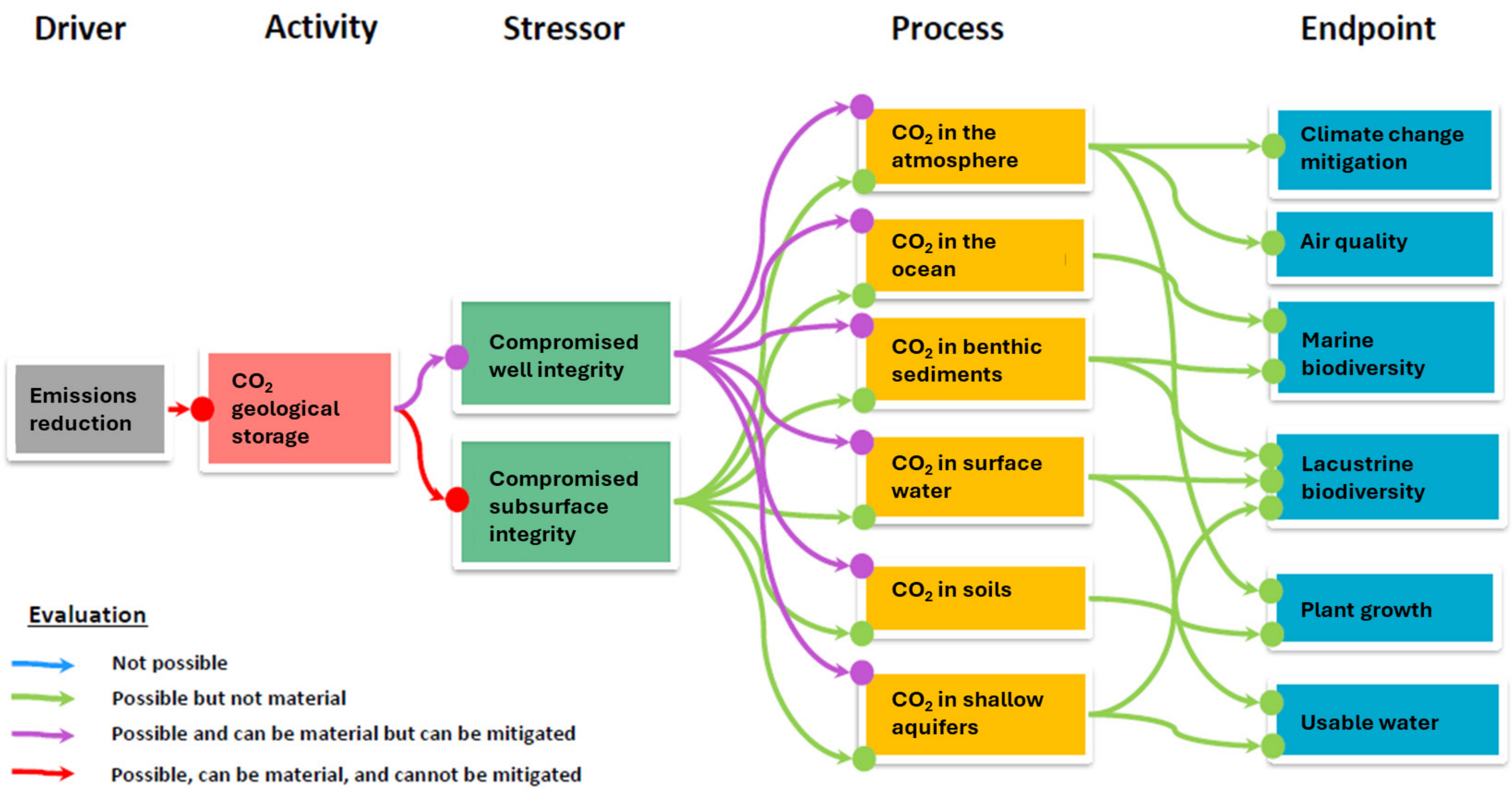

Figure 2: Causal Network as presented in this study. In the report, this is a live interactive navigation tool and you can click on any item (arrow endpoint or box) to take you to the related section in the report. Clicking the header line in the report section will take you back to the diagram.

Compromised subsurface integrity and well integrity as stressors

Following the framing of emissions reductions as a driver and geological CO_2 storage as an activity the report examines the stressors. These are divided into compromised subsurface integrity and compromised well integrity.

Compromised containment integrity resulting in unplanned migration of CO_2 or brine either laterally or vertically to shallower formations and the ground surface or seabed may be caused by low top seal capacity, hydraulic fractures, insufficient fault sealing potential or overpressure caused by injection. These themes are reviewed in a recent IEAGHG report[8] and contained in this report. Although leakage along, for example, faults and fracture zones can be material in individual cases, the probability of their occurrence at a well-characterised site is negligible for storage in depleted fields and extremely low in saline aquifers. In the case of wells, these might also present a material threat, with moderate probability in depleted fields and low for saline aquifers. Well mitigation and remediation technologies are well established.

Due to the absence of sufficient examples of leakage in industrial CO_2 storage, physical constraints on leakage mechanisms and rates are typically derived from natural analogues. Busch and Kampman (2019) provide an extensive review and assessment of leakage rates in natural systems[9].

Timescales for CO_2 leakage across seals of various thickness are on the order of 1-1000 years and on the order of 100,000 – 1 million years for migration from km-deep reservoirs across various formations to the surface. Diffusion of CO_2 through a non-fractured seal with effective permeability diffusion coefficients of the order of 10^{-10} to 10^{-12} m^2s^{-1} will take more than 100,000 years and it's therefore an unlikely leakage mechanism from deep CO_2 geological storage[9]. Generally, advection, dispersion, convection and dissolution processes will reduce the volume of free-phase CO_2 migrating to the surface. However, these processes are difficult to quantify at the basin-scale.

Kivi et al (2022) assessed basin-wide upward CO_2 migration over geological time scales through reservoir simulations and concluded that material vertical leakage of CO_2 through multiple sedimentary layers is unlikely to occur, even if intervening aquitards are strongly fractured, the consecutive layering of low permeability formations, residual trapping and CO_2 dissolution will greatly impede the migration of CO_2 to shallower formations[10]. Gilmore et al (2022) modelled leakage of a buoyant plume along a fault cutting through various reservoir and seal lithologies with the general conclusion that when the fault permeability is on the same order of, or less than the reservoir permeability, the majority of the CO_2

[8] IEAGHG, 2024, Geological Storage of CO2: Seal Integrity Review 2024-06 doi.org/10.62849/2024-06
[9] Busch, A. and Kampman, N., 2019. Migration and Leakage of CO. *Geological Carbon Storage*, p.285.
[10] Kivi, I.R., Makhnenko, R.Y., Oldenburg, C.M., Rutqvist, J. and Vilarrasa, V., 2022. Multi-Layered Systems for Permanent Geologic Storage of CO2 at the Gigatonne Scale. Geophysical Research Letters, 49(24): e2022GL100443.

remains trapped within the storage reservoir after a 1000-year time scale[11]. However, when fault permeability is larger than the reservoir permeability, there is significant CO_2 leakage all along the fault across multiple seals.

Statistical methods of leakage

Alcade et al (2018) developed a numerical program to evaluate CO_2 storage integrity and leakage over 10,000 years accounting for combined leakage through wells and geological features for three hypothetical scenarios (a well-regulated offshore scenario, a well-regulated onshore scenario, and a poorly regulated onshore scenario)[12]. They found that a moderate well density has a 50% probability that leakage remains below 0.0008% per year, with at least 98% of the injected CO_2 retained in the subsurface over 10,000 years. Hoydalsvik et al. (2021) developed assessments of leakage probability in the North Sea by means of: seepage up faults and fractures, leakage-up defective wells, and blowouts[13]. Ten scenarios for leakage were considered with the conclusions that 99.99% of the injected volume can be expected to remain securely underground for at least 500 years. Daniels et al (2023) modelled leakage probabilities due to geological and well leakage pathways for two representative UK offshore sites (designed to reflect features of depleted fields and saline aquifers) over 25 years of injection operations and 100 years of post-injection monitoring, suggesting that more than 99% of the injected CO_2 will be retained in the storage complex[14]. They extensively compiled and reviewed leakage data and probability assessments from the literature (Figures 3, 4 and 5). The most likely geological features that might contribute to seeps or minor leaks are sub-seismic fault/fracture zones, re-activated or newly initiated faults/fractures and gas chimneys.

The physics of leakage mechanisms in legacy wells are well understood, and models can be constructed of CO_2 plumes intersecting a leaky well and causing brine and then CO_2 to rise into overlying aquifers. Wellbore permeability is a crucial parameter to apply in these models and as wellbores are highly diverse this can prove challenging. Estimation of leakage rates and risks are limited to synoptic studies and simulations. Postma et al., (2019) modelled the CO_2 leakage flux into the atmosphere in a scenario representative of

[11] Gilmore, K.A., Sahu, C.K., Benham, G.P., Neufeld, J.A. and Bickle, M.J. 2022. Leakage dynamics of fault zones: experimental and analytical study with application to CO2 storage. Journal of Fluid Mechanics, 931: A31
[12] Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C.E., Scott, V., Gilfillan, S.M.V., Ogaya, X. and Haszeldine, R.S. 2018. Estimating geological CO2 storage security to deliver on climate mitigation. Nature Communications, 9(1): 2201.
[13] Hoydalsvik, H., Devaux, F., Zweigel, P., Gittins, C., Tucker, O., Seldon, L. and Neele, F. 2021. CO2 storage safety in the North Sea: Implications of the CO2 Storage Directive. Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021, Available at SSRN: https://ssrn.com/abstract=3811350).
[14] Daniels, S., Hardiman, L., D., H., Hunn, V., Jones, R. and Robertson, N. 2023. Deep Geological Storage of CO2 on the UK Continental Shelf: Containment Certainty, prepared for the UK Department of Business, Energy & Industrial Strategy (BEIS).

oil fields in North America (abandoned well density > 1 per km^2)[15]. They find that leakage is less than the 'climate threshold' of 0.1% per annum for any plausible combination of the density of abandoned wells and wellbore permeability, even under the conservative assumption that all the legacy wells reach the storage reservoir.

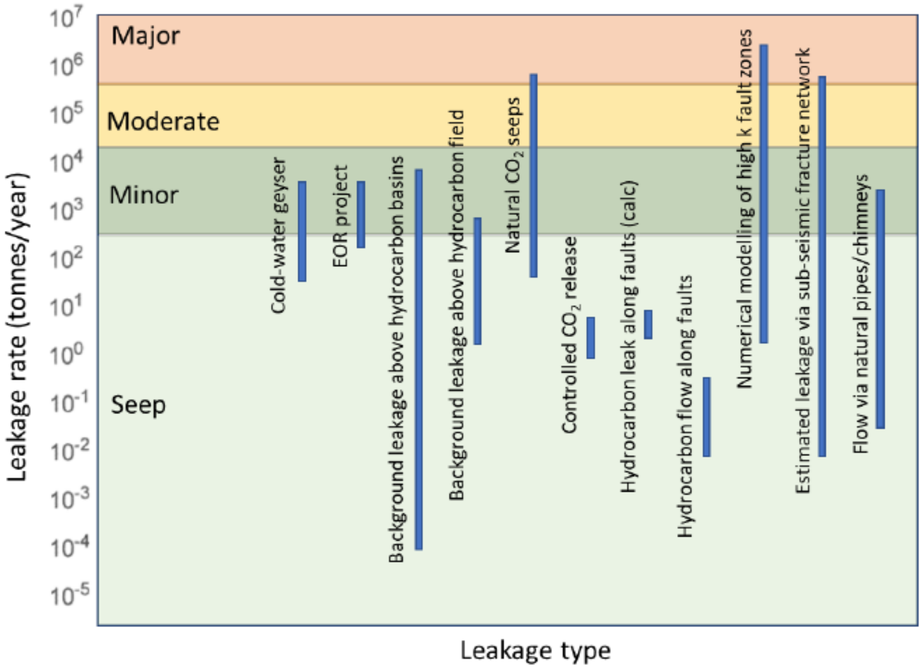

Figure 3: Representative CO_2 leakage rate data (log scale) reported in the literature for geological leakage pathways to the atmosphere (modified from Daniels et al, 2023), cold water geyser data from Watson. The severity of leakage is defined in the report (Table 6).

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15 Postma, T.J.W., Bandilla, K.W. and Celia, M.A., 2019. Estimates of CO2 leakage along abandoned wells constrained by new data. International Journal of Greenhouse Gas Control, 84: 164-179.

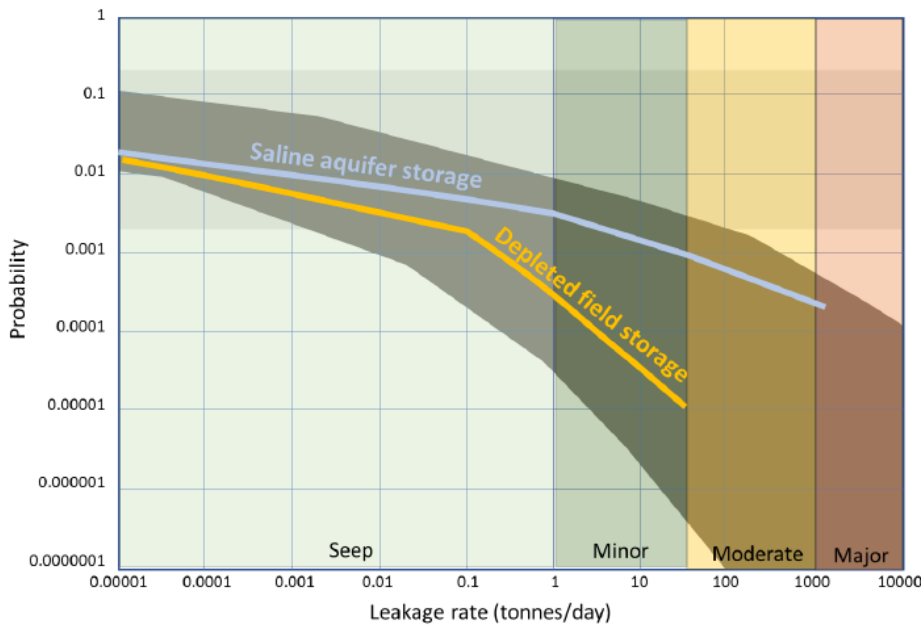

Figure 4: The probability of leakage through natural systems (modified from Daniels et al., 2023). The grey area represents the range of possibility estimates of leakage from the literature. The blue and orange lines approximately depict the probability estimates used in the assessment of CO_2 storage sites in the North Sea in saline aquifers and depleted fields.

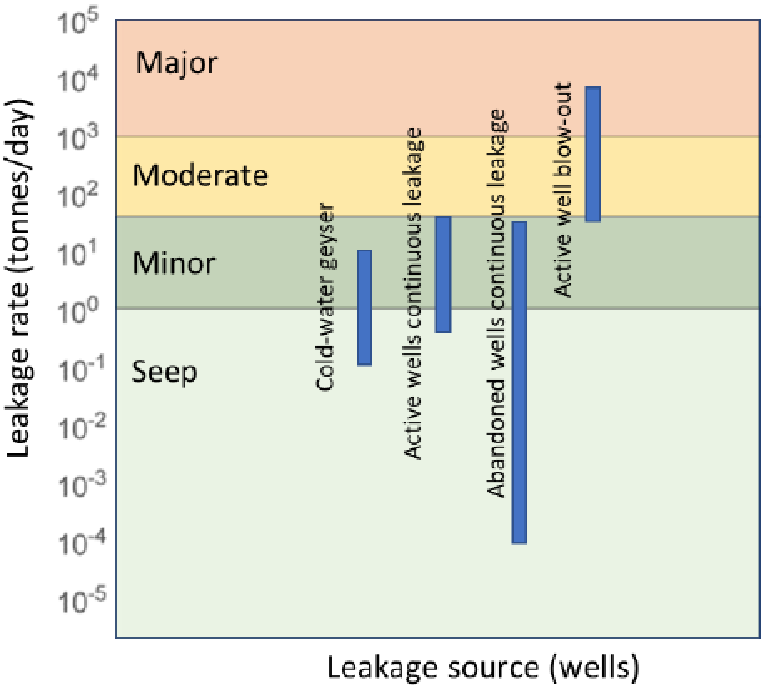

Figure 5: Representative CO_2 leakage rate data (log scale) reported in the literature for different types of well leakage (modified from Daniels et al., 2023 and references therein), Cold-water geyser data from Watson et al. (2014). The severity of leakage from Seep to Major is defined in the report. Note that impact severity may also be determined by the duration and flux-rate, an active well blowout may be major but over a short duration and could be remediated, whereas ambient

continual leakage may not be readily detected, occur over longer time frames and not be remediated.

Processes

CO_2 in shallow aquifers

Many studies on the potential impacts of CO_2 on groundwater resources have been conducted and been the focus of review papers over the past 20 years. Generally, the studies conclude that the environmental impacts of CO_2 leakage into groundwater appear to be low. The acidification of formation waters, by dissolution of CO_2, may result in mineral reactions, either the dissolution of certain minerals or the precipitation of other minerals as cements. Of specific concern are heavy metals that may be present within minerals and may dissolve due to pH changes, thereby increasing the heavy metal content of the groundwater. Cement precipitation may clog pore space and reduce the ability to extract groundwater. Of lesser potential is the dissolution and transport of organic material into groundwater due to CO_2 contacting organic-rich rocks. Groundwater monitoring and remediation technologies are well-established and widely applied in the environmental management of industrial subsurface developments.

Shallow release experiments, laboratory experiments, numerical simulations, and leakage from natural accumulations are all discussed. The intent of the majority of 41 different CO_2 release experiments undertaken at 14 sites was to investigate groundwater interactions and for the release of the injected CO_2 to remain in the shallow subsurface[16]. These experiments have shown the importance of establishing baseline conditions over an appropriate period for adequately determining CO_2 impacts, flux rates and total leakage volumes. Laboratory results have been recently reviewed[17], findings show that quantifying the impacts of mineral dissolution due to decreased pH at site scale is difficult due to differing pressures, the experiments were performed at atmospheric pressure not aquifer pressure. Higher pressures might increase CO_2 dissolution and pH decrease, further enhancing mobilisation of minerals. In contrast, experiments in unconsolidated sediments can overpredict the amount of metals released due to increased surface area. Varadharajan et al (2019) also conclude that reactive transport models can be used to predict the potential long-term changes in aquifer response to CO_2 leakage, to conduct uncertainty quantification, and to provide a basis for risk management and mitigation.

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[16] Roberts, J.J. and Stalker, L., 2020. What have we learnt about CO_2 leakage from CO_2 release field experiments, and what are the gaps for the future? Earth-Science Reviews, 209: 102939.
[17] Varadharajan, C., Tinnacher, R.M., Trautz, R.C., Zheng, L., Dafflon, B., Wu, Y., Reagan, M.T., Birkholzer, J.T. and Carey, J.W., 2019. A review of studies examining the potential for groundwater contamination from CO_2 sequestration. In: S. Vialle, J.B. Ajo-Franklin and J.W. Carey (Editors), Geological Carbon Storage - Subsurface Seals and Caprock Integrity, Wiley, pp. 305-326.

CO_2 in soils

There are many dynamic sources and sinks of CO_2 in soil due to plant and microbial processes, and this can make it challenging to differentiate between CO_2 arising from these natural processes and CO_2 that might arise from a deep subsurface storage, where the greatest risk is likely to be surrounding legacy well bores. Soil gas in CCS is extensively covered in the literature and soil gas monitoring has been tested for over two decades and baselines deployed at potential CCS sites and operational projects including Weyburn, Otway, Lacq and Decatur. Control release experiments all show a patchy surface expression of CO_2 leakage that is also observed in natural analogues i.e. volcanic CO_2 degassing, where small patches of altered or dead vegetation can be observed. Natural analogues, laboratory and field experiments indicate that high concentrations of CO_2 in the root zone are harmful to plants through oxygen depletion and could cause plant stress responses such as changes in leaf area and chlorophyll content, microbial communities can also be impacted. Methods of monitoring and mitigation are discussed, including methods to differentiate natural CO_2 from exogenic CO_2, the use of tracers, and case studies from Weyburn and Otway.

CO_2 in surface waters

Lakes, rivers, wetlands, estuaries, coastal or marine environments may overlie storage areas, therefore it is important to understand the passage of leaked gas for the purpose of determining environmental impacts and identifying appropriate monitoring methods to identify and quantify the leaked gas. Similar to soil gas, there are a variety of sources and sinks within water. Oldenberg and Lewicki, 2006, summarised the processes by which gases (including CO_2) might migrate into surface waters (not including volcanic lakes). Analogues are well studied into water bodies e.g. Italy; Mammoth Mountain, California; Paradox Basin, Utah, and Daylesford, Victoria, whereas high energy fluvial systems are harder to quantify and observe – although gas bubbles in line with fault traces are observed at the Green River, Utah. Lakes can become highly temperature stratified and this can lead to enhanced concentrations of CO_2 at depth. Volcanic lakes are an extreme and atypical analogue, in temperate regions these overturn seasonally mitigating large-scale build-up of CO_2, whereas in the tropics seasonal surface forcing is limited and in areas with large CO_2 inputs, saturation of bottom waters can occur. The oft-cited Lake Nyos tragedy is explored and reasons are given why it is unrealistic to equate this example to a potential leakage of CO_2 from CO_2 storage activities. Monitoring within aqueous environments is more complex and expensive relative to onshore monitoring techniques, however surface waters may not be as deep as the marine environment which brings the cost down. These options are discussed including the QICS (Quantifying and Monitoring Potential

Ecosystem Impacts of Geological Carbon Storage) controlled release experiment[18] and experiments using tracers to quantify and attribute leakage[19]

CO_2 in the atmosphere

Changes to atmospheric concentrations of CO_2 are the key focus of emissions reduction to avoid environmental impacts such as climate change. Leakage would be expected to be detected by the monitoring methods that are tailored to detect CO_2 in the various barriers between the storage complex and the atmosphere – leakage to the atmosphere comprises two distinct risks:

- Leakage from subsurface equipment is usually the main concern of operators, however examining monitoring and verification plans submitted to the US Environmental Protection Agency (EPA), CO_2 losses into the atmosphere are minimal and have negligible consequences.
- Leakage up wellbores and into the atmosphere, and leakage at the wellhead would be quickly detected. The key conclusion from statistical studies of wellbore leakage suggest CO_2 leakage up a wellbore annulus will be felt in the overlying aquifers that intervene between the storage complex and the surface and act as thief zones to absorb the CO_2.

In volcanic areas where naturally occurring CO_2 reaches the surface, there are occasional fatalities of livestock or (rarely) humans, typically caused by seeped CO_2 pooled overnight in low-lying areas. Direct leakage into the atmosphere is improbable, and should it occur it can be monitored and managed.

CO_2 in the ocean

CO_2 in the world's oceans and seas is constrained by air-sea exchange driven by natural processes. Concentrations of CO_2 in the oceans tend to be in equilibrium with the atmosphere over long periods. When CO_2 dissolves into seawater it forms carbonic acid (H_2CO_3) and carbonate and bicarbonate ions, increasing seawater acidity. Therefore, the CO_2 concentration is often considered in terms of changes in pH of waters. Atmospheric emissions of CO_2 from human activities have generated an imbalance resulting in increasing amounts of CO_2 being absorbed into the oceans, effectively buffering the build-up of CO_2 in the atmosphere. The increased amount of CO_2 in the atmosphere is causing ocean acidification associated with decreasing pH. The process of point source CO_2 leakage into the water column is a well-understood phenomenon. Globally numerous natural (volcanic) submarine CO_2 seeps have been studied to understand the impacts of

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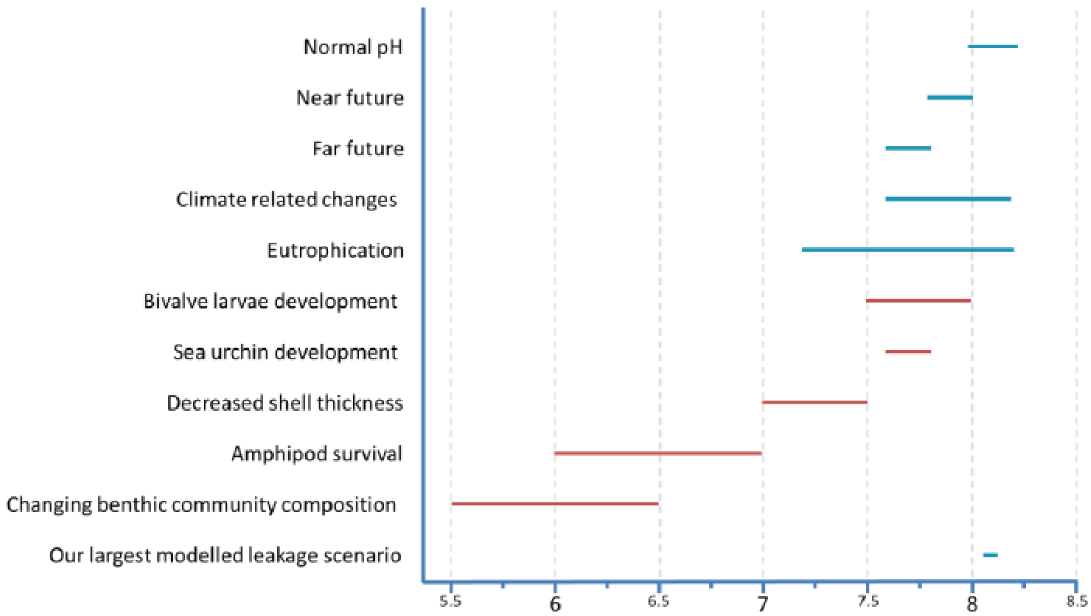
[18] CCS and the Marine Environment Special Issue, 2015. International Journal of Greenhouse Gas Control, 38, 1-230.
[19] Myers, M., Roberts, J.J., White, C. and Stalker, L., 2019. An experimental investigation into quantifying CO2 leakage in aqueous environments using chemical tracers. Chemical Geology, 511, 91-99.

ocean acidification and the impact of CO_2 release from subsurface CO_2 storage[20]. CO_2 seeps typically manifest as a number of discrete bubble plumes which rapidly dissolve in the water, and bubble plumes may not reach the sea surface, especially in deep water. The dissolution of CO_2 will change the pH of the nearby waters.

For CCS projects, considerable effort has been made over the last decade to developing time evolving, 3D coupled hydrodynamic-biogeochemical simulations which describe physical flows and biogeochemical fluxes. The primary purpose is to simulate chemical changes in the water column, these provide a viable option to characterise the morphology of hypothetical release events, quantify detection targets and devise the most cost-efficient deployment of sensors. To understand the effects of CO_2 leakage in the water column the 'detection footprint' needs to be established. Blackford et al, 2020, has evaluated a range of simulations to determine detection footprints[21] across a range of leakage scenarios c.f Ross et al (2022)[22].

Setting the change in pH associated with CO_2 leakage in context with pH variability of the environment, and its likely change over time, is critical to understanding its overall impact. When compared to the natural variation within pH and the medium-term changes in pH



[20] Aiuppa, A., Hall-Spencer, J.M., Milazzo, M., Turco, G., Caliro, S. and Di Napoli, R. 2021. Volcanic CO_2 seep geochemistry and use in understanding ocean acidification. Biogeochemistry 152, 93–115. https://doi.org/10.1007/s10533-020-00737-9.
[21] Blackford, J., Alendal, G., Avlesen, H., Bereton, A., Cazenave, P.W., Chen, B., Dewar, M., Holt, J. and Phelps, J. (2020) Impact and detectability of hypothetical CCS offshore seep scenarios as an aid to storage assurance and risk assessment. International Journal of Greenhouse Gas Control, 95, 102949.
[22] Ross, A., Myers, J., Van Ooijen, E., Greenwood, J., Ryan, T., Hughes, D., Marouchos, A., Keesing, J. Scoulding, B. and Jenkins, C. 2022. Methodology to deploy shallow-focused subsea CCS technologies: M8 Synthesis Report on network designs for CCS site marine Measurement, Monitoring and Verification – Volume 1. EP2021-1974 CSIRO, Australia.

associated with ocean acidification, changes of ~0.1 pH units over impact length scales of metres to tens of metres associated with 45 t CO_2 leakage in a well-mixed coastal environment is unlikely to significantly impact marine biodiversity (Figure 6).

Figure 6: Summary of current variability in ocean pH and future predicted pH associated with ocean acidification due to climate change (blue bars at top of graph). pH range over which there are potential impacts to various biota (red bars), 0.1 pH change associated with 30 m in the longshore direction and 6 m in the cross-shore direction 45 t CO_2 d-1 modelled leakage scenario pH change of Greenwood and Mongin, 2020, Ross et al. 2020 (blue bar bottom of graph).

CO_2 in benthic sediments

The term benthic sediment has broad applicability and can in principle include the entire submarine sedimentary sequence. However, for the purpose of understanding CO_2 in benthic sediments it is limited here to near seabed, typically unconsolidated sediments, characterised by a series of redox zones in which diverse microbial and infaunal communities are present. Redox zonation is determined by factors including but not limited to, sediment grain size, deposition, overlying and pore water chemistries, organic and inorganic carbon and bioturbation. Understanding the effect of CO_2 and pH on these zones allows understanding of the impact of the CO_2 on sediment infaunal biodiversity. Many benthic faunas are sessile or have limited mobility, have reduced dispersal potential, and slow generation times, making them potentially more vulnerable than pelagic species to exposure from a leak. CO_2 leakage is anticipated to have two pathways for effects on benthic sediments; one where CO_2 enters benthic sediments from deeper geological intervals, and another mediated by CO_2 rich plumes in the water column. The latter is expected to have limited impact due to high degree of localisation and mixing. Whereas CO_2 from deeper intervals may be expected to have a more pronounced effect.

Laboratory and field CO_2 injection experiments into shallow benthic sediments have shown that sediments retain significant volumes of CO_2 and therefore reduce leakage volumes into the water column (e.g. QICS ~35% retained and STEMM-CCS ~39-27% retained).

Many factors impact the capacity to trap CO_2 prior to leakage into the ocean waters (stratigraphy, composition, grain size etc), and also the magnitude and spatial extent of chemical perturbation (leakage pathway, rate of leakage, duration etc). In addition, porewater pH is complex, and the increase in pCO_2 in sediment porewater could be greater than those in the overlying water. Monitoring options for benthic sediments and limiting factors are also discussed.

Endpoints

The final section of the report details the potential endpoint of the processes described, climate change has already been introduced and the following are other potential impacts.

Lacustrine biodiversity

Whilst CO_2 is not considered a contaminant in surface water, an increase in CO_2 due to leakage would result in a decrease in pH, i.e. an increase in acidity. pH is one of the most important environmental factors limiting species distributions in aquatic habitats because it affects most chemical and biological processes in water. Acceptable ranges of pH are between 6.5-9 for aquatic life. A sustained pH outside this range can result in decreased reproduction, decreased growth, disease or death of lacustrine species. A description of potential impacts is given and a table of potential biological changes due to surface water acidification[23].

Marine biodiversity

A thorough exploration of the impact of a CO_2 leakage and consequent reduction in acidity on marine biodiversity is given, which includes infauna (organisms living in the sediments), benthic communities (organisms living on or attached to the seafloor), planktonic organisms, and fish. The impacts of a CO_2 leak will not be felt uniformly, with infauna and benthic communities at greater risk as they are sessile, in direct contact with the sediment and often lack planktonic level dispersal. Pelagic (organisms living in the water column) may not be affected by CO_2 release, because pH changes may be of small magnitude and disperse quickly. Coastal organisms may be least sensitive to changes in pH as they are frequently exposed to low alkalinity water from terrestrial run-off.

Plant growth

A CO_2 leak could accumulate in the root zones of plants and cause plant death, with some evidence from natural analogues on the nature and scale of the impact. Early studies in volcanic areas confirmed that soil gas >20-40% CO_2 resulted in plant stress and eventual death. In volcanic areas the emissions are spatially small but have lasted a long time and vegetation has adapted with more CO_2-tolerant plants around a seep. This evidence was later corroborated by controlled release experiments showing that the volcanic model provided good parallels to CO_2 leakage. Further research into a broader number of plants show that no plants can survive without O_2 being available in the root zone. A full range of these experiments is reviewed by Roberts and Stalker (2017) who confirmed the spatially patchy nature of the impact – essentially leakage will overwhelmingly favour the highest permeable path[24].

Groundwater use

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[23] Baker, J.P., Bernard, D.P., Christensen, S.W. and Sale, M.J., 1990. Biological effects of changes in surface water acid-base chemistry. National Acid Precipitation Assessment Program, Washington DC. NAPAP Report 13.

[24] Roberts, J.J. and Stalker, L., 2017. What have we learned about CO_2 leakage from field injection tests?." Energy Procedia 114: 5711-5731.

Groundwater is used for a range of purposes including drinking water, irrigation, stock watering and industrial water use. Water quality limits apply and are set by environmental regulators at state, province or country level. The US EPA through their Underground Injection Control (UIC) program requires the protection of underground sources of drinking water (USDWs). As many parts of the world rely on groundwater as potable (drinking) water there is a concern that migration of CO_2 from a geological storage complex could contaminate potable water and constitute a risk to human health.

CO_2 occurs naturally in groundwater, and is not regarded as a pollutant or contaminant, and while pH is considered an important operational water quality parameter, there is no guideline water quality value for pH because it is not deemed to be of health concern at levels found in drinking water[25]. However secondary standards have been set in several jurisdictions (e.g. US EPA the acceptable range of pH are between 6.5-8.5 for human consumption of water). Water-rock interaction due to an increase in CO_2 concentrations may result in the mobilisation of metal concentrations considered harmful for human consumption (examples from US EPA are given).

As mentioned in the processes section on shallow subsurface, many controlled release experiments and modelling studies have been undertaken over the past 20 years, these are discussed and the general conclusion is that the environmental impact of CO_2 leakage into groundwater is low.

Air quality

There is a nuanced debate to be had on the impacts of global climate change (driven by rising greenhouse gas concentrations) and the impact on public health, through rising temperatures and more extreme weather events. Climate anxiety is an additional stress that increases overall impact to the health of individuals and community groups. Therefore, doing nothing to mitigate emissions may have a major impact on public health. However, mitigation technologies also present risks to public health and these need to be balanced – especially against public perception as local stresses can also arise from areas that support facilities that aim to mitigate emissions. The specific risks of physical, chemical and psychosocial handling of CO_2 and remediation technologies are discussed, with the key risks in handling CO_2 summarised in a table. While oxygen depletion is often cited as a major risk factor for human health, cold burns due to the Joule-Thomson effect are a more frequent risk. Two case studies from Weyburn, Canada, and Barendrecht, The Netherlands, are used to give some context around public health concerns over a suspected leak and also gaining public trust over a proposed project.

[25] WHO, 2022. Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. World Health Organization, Geneva, 614 p. www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/water-safety-and-quality/drinking-water-quality-guidelines.

Conclusions

This report uses a causal network framework to interactively and systematically explore the potential environmental and public health implications of CO_2 migration or leakage to the surface or shallow subsurface from a CO_2 storage project and balance these against the overarching broader risk of a 'do nothing' approach to meeting reductions in emissions to meet climate goals.

The geological storage of CO_2 is a form of waste disposal, but CO_2 itself is not regarded as a pollutant in ground or surface water. The lack of cases of leakage from commercial operations to date makes it challenging to characterise what a leak might look like, determine the rates of leakage, or quantify the leakage impacts. Leakage rates are expected to be small and diffuse or patchy in nature, and it's expected that multiple barriers and migration within intervening aquifers, chemical buffering, dissolution and residual saturation will retard CO_2 migration and reduce volumes ending up in the shallow subsurface or atmosphere. Leakage along wells or faults and fractures represent the greatest area of risk, and monitoring and mediation techniques are discussed.

Natural analogues, controlled release experiments and modelling are our best methods of studying impacts on the range of scenarios from subsurface aquifers, bodies of water, soils, and the atmosphere and are explored herein. With these results coupled with estimates of leakage probability, the general conclusion is that CO_2 migration from geological storage to the surface or shallow subsurface has a low risk to having material adverse effects on the environment and public health.

Although considered rare, a material leak can still have severe consequences to the local environment, it's noted that detailed specific risk assessment for a specific site is far beyond the scope of the project.

Climate mitigation is the only Endpoint (in the causal network) for which the impact from CO_2 leakage can be assessed at a global level because it needs to consider the combined potential CO_2 leakage from storage projects worldwide. Recent studies agree that the rare case of a single project experiencing material leakage would not have material impacts on climate mitigation efforts. The biggest risk is not doing it at all.

Expert Review

The report was reviewed by seven reviewers from six organisations and was well received, especially in meeting the aims of being an easy-to-follow and interactive body of work with useful summary tables at the end of each chapter. Although long, the interactive nature means you do not have to read it all in one sitting to reach meaningful conclusions.

One reviewer noted that the combination of a holistic approach including probability and process of leakage and severity which complemented the recent work by Daniels et al.

2023 created a nice pair of reports to help assess leakage risks (in terms of consequences and their likelihood).

The reviewers provided many helpful comments and suggestions in the text that were incorporated into the final report and the reviewers are thanked for their time.

Recommendations

This work has compiled the results of over 20 years of detailed studies into the impacts of both localised elevated concentrations of CO_2 on habitats and human health that might be caused by a CO_2 leakage framed against the growing evidence and impacts of increasing concentrations of CO_2 as a greenhouse gas in the atmosphere and oceans.

Against this backdrop, it's recommended that there is more quantified research into the public health impacts of climate anxiety (real or perceived threats) versus the psychosocial effects of deploying industrial mitigation technologies. Gaining public trust and communicating risks in a clear fashion is a key factor to project success.

Australia's National
Science Agency

Reviewing the implications of unlikely but potential CO_2 migration to the surface or shallow subsurface

Document navigation is provided through an interactive Causal Network tool.

IEA/CON/22/287

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Executive Summary

Recent modelling by the International Panel of Climate Change (IPCC) and by the International Energy Agency (IEA) suggest that some form of carbon capture and storage (CCS) is needed as part of an emissions reduction portfolio for achieving net-zero greenhouse gas emissions by 2050 and thereby limiting the impacts of climate change. There is some concern that CO_2 stored in the subsurface could migrate back to shallow aquifers, the ocean or the atmosphere with adverse consequences for the environment and, at least partly, negate climate mitigation efforts. It is important to note that while CO_2 geological storage is considered to be a form of waste disposal, CO_2 itself is not regarded as a pollutant in ground or surface waters. This study has used an assessment framework to systematically step through the key issues and risks associated with the geological storage of CO_2 and to assess the potential environmental and public health implications of CO_2 migration to the surface or shallow subsurface, while illustrating the low likelihood of this occurring.

The assessment framework used is a Causal Network (Figure 1) which allows for the identification of a series of steps that provide information on cause-and-effect relationships in relation to the challenge being addressed; that is climate change/emissions reduction through the geological storage of carbon dioxide.

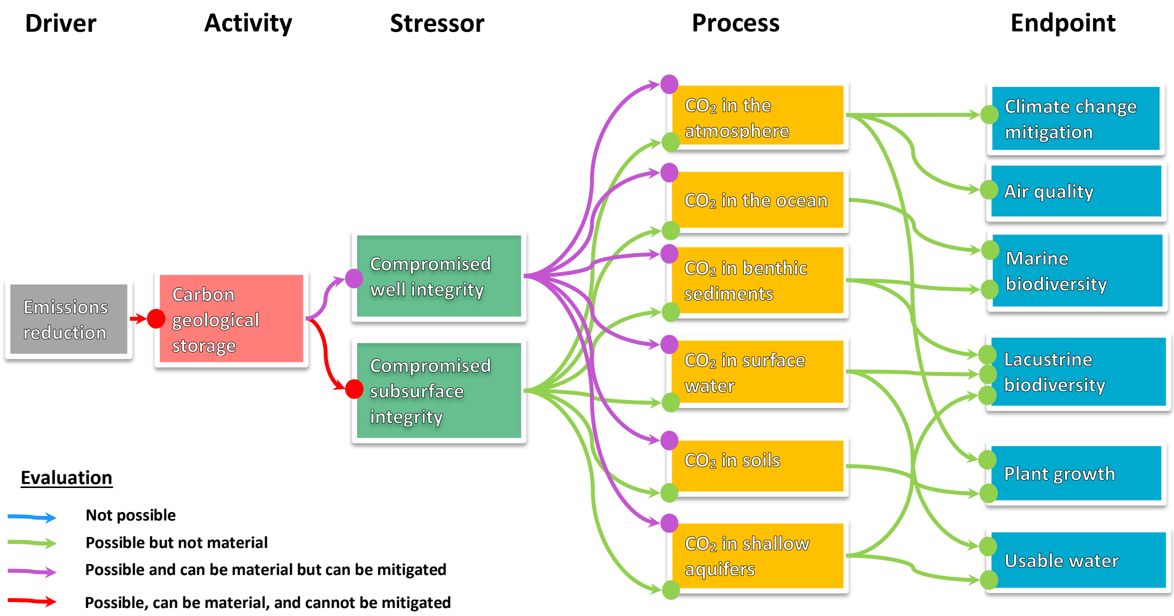

Figure 1. Causal Network flow path for assessing environmental and health impacts of CO_2 leakage for CCS. See Page 36 for the interactive navigation tool.

The Causal Network provides a series of descriptors as a graphical presentation using nodes with descriptions, link evaluations and an overall assessment summary. These are based on literature reviews of the driver, activity, stressors, processes and resultant endpoints that discuss the environmental and public health impacts that may result from leakage in different general environments. Each heading can be clicked on to navigate through the document.

The application of this approach has primarily been at a GENERAL perspective and provides general information on whether events may be possible, material, avoidable or able to be mitigated or remediated. From that general perspective, we conclude that it is possible for compromised well or subsurface integrity issues to facilitate the migration or release of CO_2 out of its primary storage container and leakage volumes can be material in individual cases. However, the probability of leakage via geological features when storing CO_2 at well-characterised sites is negligible for storage in depleted fields and extremely low for saline aquifer storage. While the probability of compromised well integrity occurrence based on petroleum industry experience is extremely low, the probability of well leakage increases with the number of active and inactive wells within the area of the injected CO_2 plume. However, well leakage is easily detected and well mitigation and remediation technologies are well-established. As the CO_2 migrates upwards, each of the processes described in the nodes can occur, and are possible at a global scale, but only material at a local scale in some instances, which are noted in the assessment tables and discussed in more detail in the topic descriptions where relevant. Multiple barriers and partial migration into various intervening aquifers, as well as buffering, dissolution and residual saturation will reduce the total volume ending up in groundwater, soils, the ocean or the atmosphere.

The endpoints highlight what those risks might be and their environmental and human health impacts. Again, at a global scale, these are possible, but not material. Extremely high concentrations of CO_2 in the ocean, groundwater or the atmosphere would be required to cause material harm to the environment as demonstrated in exceptional cases of *natural* CO_2 leakage. Such conditions are improbable in the case of CO_2 geological storage. Also, the remobilisation of other harmful substance as result of CO_2 leakage has been investigated in laboratory and field experiments, which have been reviewed multiple time (e.g., Lemieux, 2011; Harvey et al., 2013; Lions et al., 2014; Jones et al., 2015; Fischer et al., 2016; Varadharajan et al., 2019) concluding that material impacts are deemed unlikely under CO_2 leakage conditions from a well-characterised and monitored geological storage project. It is acknowledged that the CO_2 continues to be the largest volumetric impact over and above any secondary reactions that mobilise other materials.

The assessment is based largely on CO_2 leakage rates and volumes from storage, which are challenging to estimate in general terms. Due to the lack of actual CO_2 leakage examples from CCS projects, estimation of leakage rates and risks has been limited to synoptic studies and simulations (e.g. Alcade et al., 2018; Postma et al., 2019; Hoydalsvik et al., 2021; Daniels et al., 2023), which often are based on experience and data from the petroleum industry. Leakage rates based on analogues can vary substantially (Figure 2) and the probability of leakage occurrence also has a wide range (Figure 3). Any of the rates and probabilities presented in the graphs will need to be constrained by actual data when there is more experience with CO_2 geological storage projects.

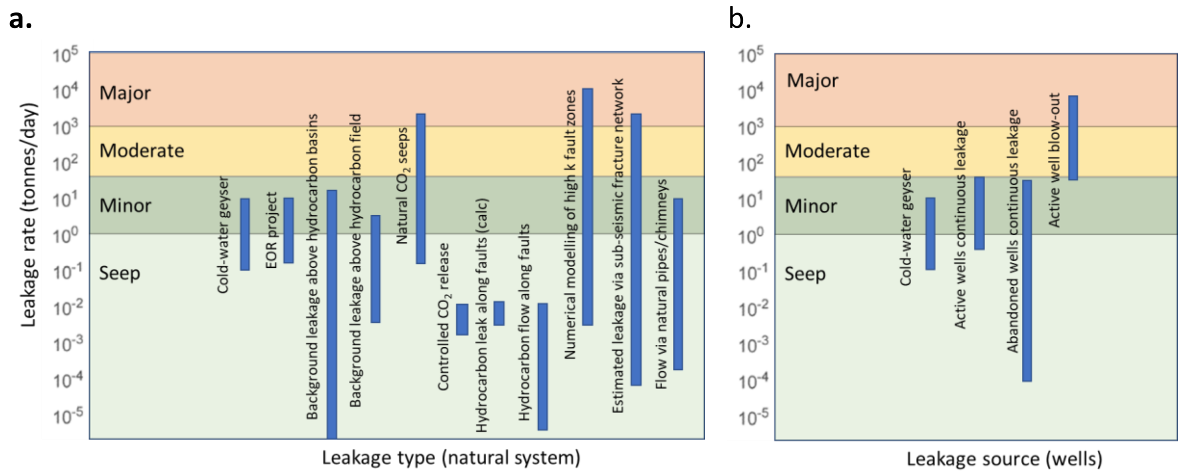

Figure 2. Representative CO_2 leakage rate data (log scale) reported in the literature for a) geological leakage pathways and b) different types of well leakage (modified from Daniels et al., 2023 and references therein).

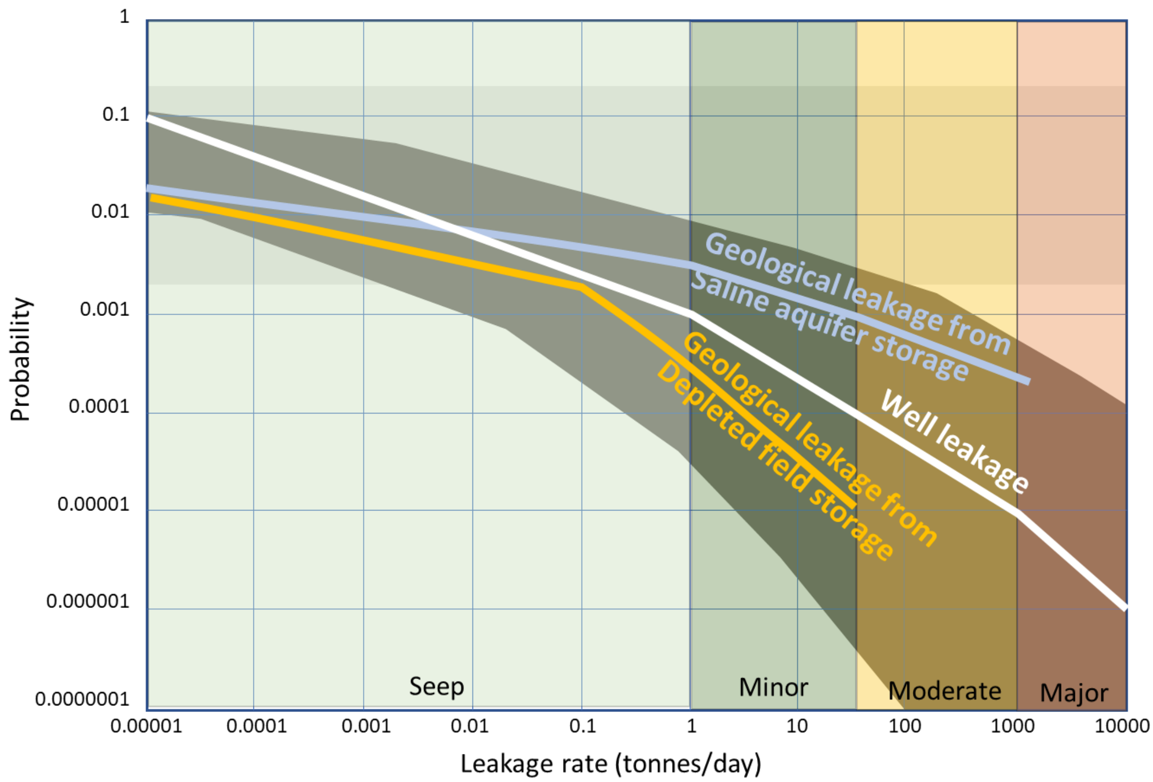

Figure 3. The probability of leakage through natural systems and active and inactive wells (summarised from Daniels et al., 2023 and references therein). Note: In the case of continuous leakage (i.e. non-detectable or not fixable), probability refers to the occurrence of a leak per well (seeps) or leak per geological feature. In the case of minor to major well leakage which should be only temporary (detectable and possible to fix), probability refers to the occurrence of a leak per well per year. The grey area represents the range of probability estimates of leakage from the literature. The white, orange and blue lines approximately depict the probability ranges of leakage used by Daniels et al. (2023) in their assessment of CO_2 storage sites in the North Sea.

Although considered a rare occurrence, a material leak may still have severe consequences to the local environment and leakage thresholds (i.e., water quality limits and toxicity levels in groundwater and surface water, and for human health limits for CO_2 in the air) that have direct environmental and health implications that should be used in environmental impact assessments. However, local knowledge and jurisdiction-specific regulatory thresholds are required to adequately quantify leakage and specific environmental risks, which was beyond the scope of the general (i.e., non-site specific) assessments of this study. Local causal networks can be built from the global causal network to include spatial information, local thresholds, and nodes and data relevant to a specific storage project. While maintaining some of the general descriptions from the global causal network, the structure of the local network would contain different nodes and a more detailed assessment of links. For example, an offshore storage project would not require any nodes or links involving lacustrine biodiversity or plant growth. On the other hand, the local network would need to be extended by including 'assets' that are important to a specific region, for example specific endangered fish species or marine mammals. For further information review a complete study such as the GBA Explorer (https://gba-explorer.bioregionalassessments.gov.au/)

Climate change is a global phenomenon and, given the very low likelihood of material local environmental impacts, the benefits of CCS, i.e. the removal of significant volumes of greenhouse gas emissions to the atmosphere, far outweigh the environmental risks associated with any leakage at a local scale.

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Introduction

Background and objectives

The objective of this study is to review the progress made over the past 20 years in assessing the consequences and risks of CO_2 leakage from geological storage to the environment, human health, and to the mitigation of climate change.

CO_2 environmental impacts have been reviewed repeatedly over the last 15 years (i.e. Lemieux, 2011; Harvey et al., 2013; Lions et al., 2014; Jones et al., 2015; Fischer et al., 2016; Varadharajan et al., 2019), and these form an important base for the current study. By adding more details with respect to the review of potential leakage pathways, leakage rates and probability of occurrence, the outcomes of this study are presented in a manner that can provide policy makers, regulators and project developers with a clear understanding of the risks of leakage from CO_2 geological storage reservoirs, identifying where to focus monitoring and verification efforts, and suggesting mitigation strategies, if required. The results are presented as a CAUSAL NETWORK by illustrating activities (CO_2 geological storage), stressors (leakage pathways), processes (i.e., CO_2 migration into groundwater, ocean or atmosphere) and impact on endpoints (i.e. groundwater contamination) of CO_2 geological storage. This involves the mapping and assessment of logical connections between development activities and how they may impact things we have concerns for, such as social, environmental and economic impacts in regions where development might take place (Figure 4).

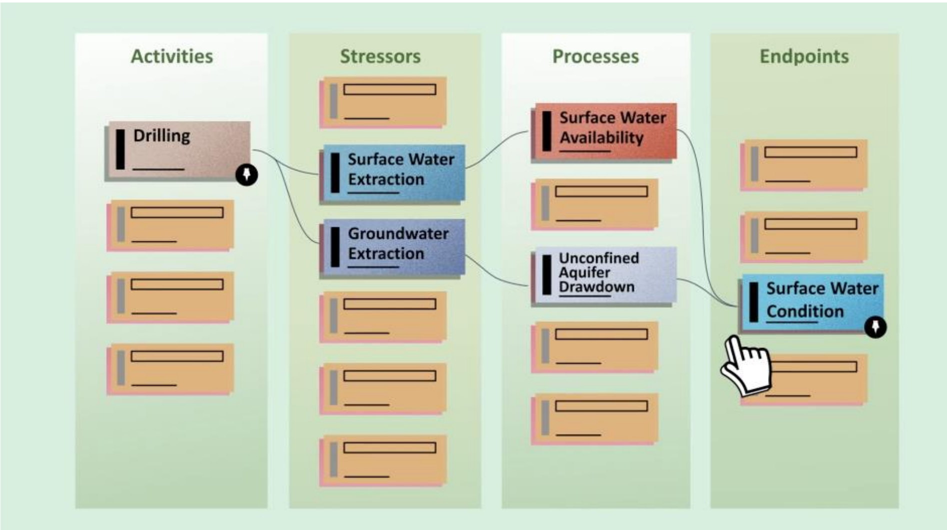


Figure 4. Illustration of how a Causal Network is developed and nodes identified. https://gba-explorer.bioregionalassessments.gov.au/ for further information.

Conceivable CO_2 leakage pathways and impacts are broad and can have a range of consequences and a comprehensive compilation of features, events and processes (FEPs) related to CO_2 geological storage are provided by Quintessa (2014) in a Generic CO_2 Geological Storage FEP Database. Version 2.0.0 (quintessa.org). However, CO_2 leakage from geological storage is considered unlikely from properly selected sites and the potential impacts are anticipated to be small when compared to other anthropogenic and natural stressors (Blackford et al., 2020). Still, it is important to predict and understand potential environmental impacts and risks to human health for realistic leakage scenarios in order to perform appropriate monitoring and mitigation necessary to meet both regulatory and societal expectations (Sands et al., 2022). These expectations are partly reflected in the work by Hepple and Benson (2005) where they refer to the following:

"An annual seepage rate of 0.01% or 10^{-4}/year would ensure the effectiveness of geologic carbon storage for any of the projected sequestration scenarios explored herein, even those with the largest amounts of storage (1,000 s of gigatonnes of carbon-GtC), and still provide some safety margin. Storing smaller amounts of carbon (10 s to 100 s of GtC) may allow for a slightly higher seepage rate on the order of 0.1% or 10^{-3}/year".

Subsequent reviews of controlled and shallow release experiments e.g., Roberts et al. (2017) and Roberts and Stalker (2020) have attempted to harmonise data sufficiently to draw a comparison and use those experiments to highlight environmental impacts if CO_2 were to be released in the volumes indicated in Hepple and Benson (2005). Jenkins et al (2021) consider the role of leakage versus storage and have reviewed more recent publications following the Hepple and Benson (2005) assessments and what range of leakage is referred to in more recent times.

Critical aspects for describing and quantifying consequences of CO_2 migration from geological storage that will be critically reviewed in the project are:

1. CO_2 leakage pathways, rates and volumes.
2. Sensitivity of environmental receptors, animals and humans, and the climate in general, to increased CO_2 concentrations in groundwater, seawater and the atmosphere.
3. Deployment constraints and detection limits of available monitoring technologies.
4. Mitigation options.

These aspects can be presented as a pathway from the initial driver i.e., the need for emissions reduction by geological carbon storage, through to stressors such as containment failure. The process causing impact can be described, for example, migration of CO_2 into soil horizons, and describe potential consequences. This logical narrative approach can enable policy makers, regulators and other interested (but lay) parties to follow the full chain of effects and impacts, and see the source materials (peer reviewed publications, government reports etc.,) that have been used in the assessment of environmental and human health impacts.

Project scope

The current project provides a review of the generalised consequences, impacts and likelihood of potential leakage scenarios, both in the onshore and offshore environment. A range of leakage pathways, rates, volumes and duration were considered based on published observations from:

- natural seeps (i.e., Jones et al., 2015; Roberts et al., 2015),
- controlled-release experiments (i.e., Roberts and Stalker, 2020; Dean et al., 2020; and references therein),
- leakage quantification assessments (i.e., Alcade et al., 2018; Busch and Kampman, 2018; Blackford et al., 2020; Hoydalsvik et al., 2021; Daniels et al., 2023;),
- industrial analogues (i.e., oil and gas operation, natural gas storage, deep waste disposal),
- IEAGHG reports on 'Caprock Systems for CO_2 Geological Storage' (IEAHG, 2011), 'Quantification Techniques for CO_2 Leakage' (IEAHG, 2012), and 'CO_2 migration in the overburden' (IEAHG, 2017),
- compiled reviews in books and reports (i.e., Michael et al., 2013; Vialle et al., 2019).

For a representative range of leakage scenarios, the severity of potential impacts on environmental receptors and their risk profiles are discussed, including the following environments as examples:

- shallow groundwater
- soil and vegetation
- seabed and marine sea life
- atmosphere

The two main consequences being assessed are:

- impacts on human, plant and animal health
- impacts on climate mitigation effectiveness

This also includes a review of the effectiveness of various monitoring technologies to detect potential CO_2 leaks in groundwater, soil and the atmosphere (Figure 5), as well as monitoring schemes in the marine environment (Figure 6).

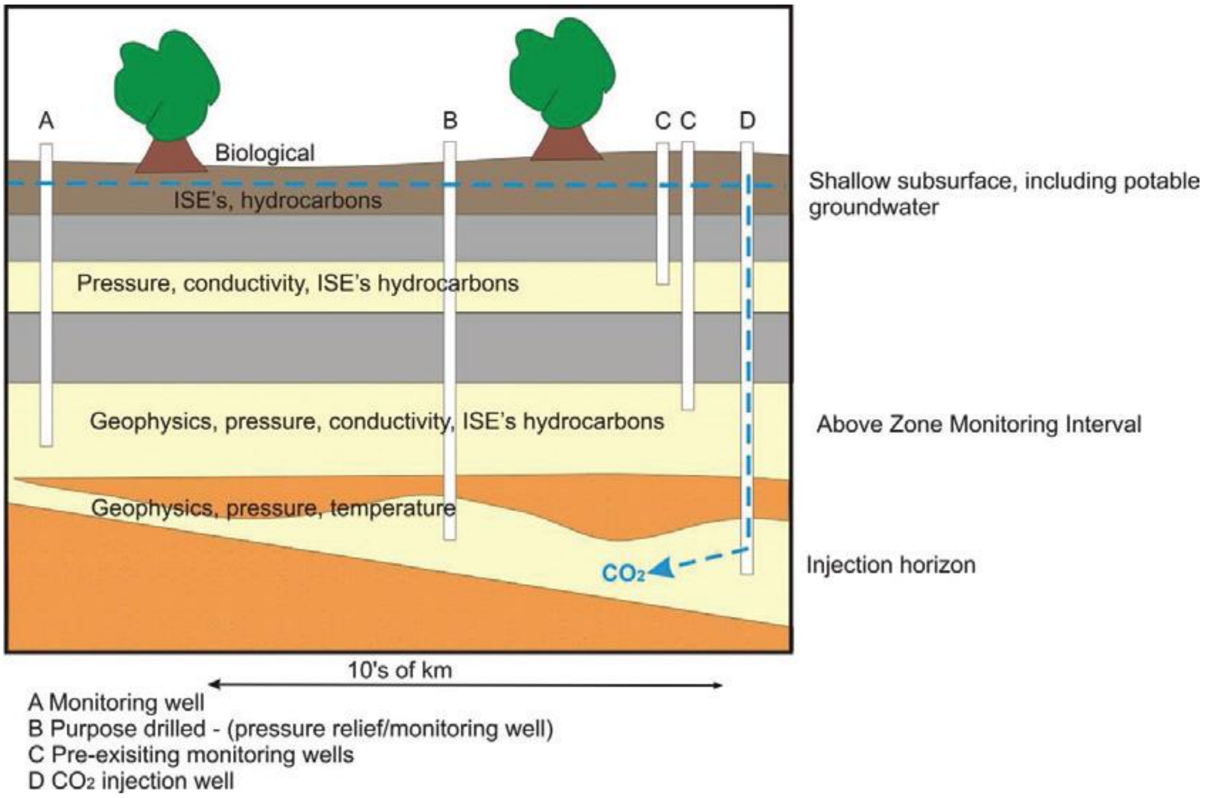


Figure 5. Schematic of different subsurface monitoring domains and applicable monitoring tools for CO_2 storage sites (Stalker et al., 2012). ISE stands for ion-selective electrode measurements. Not to scale.

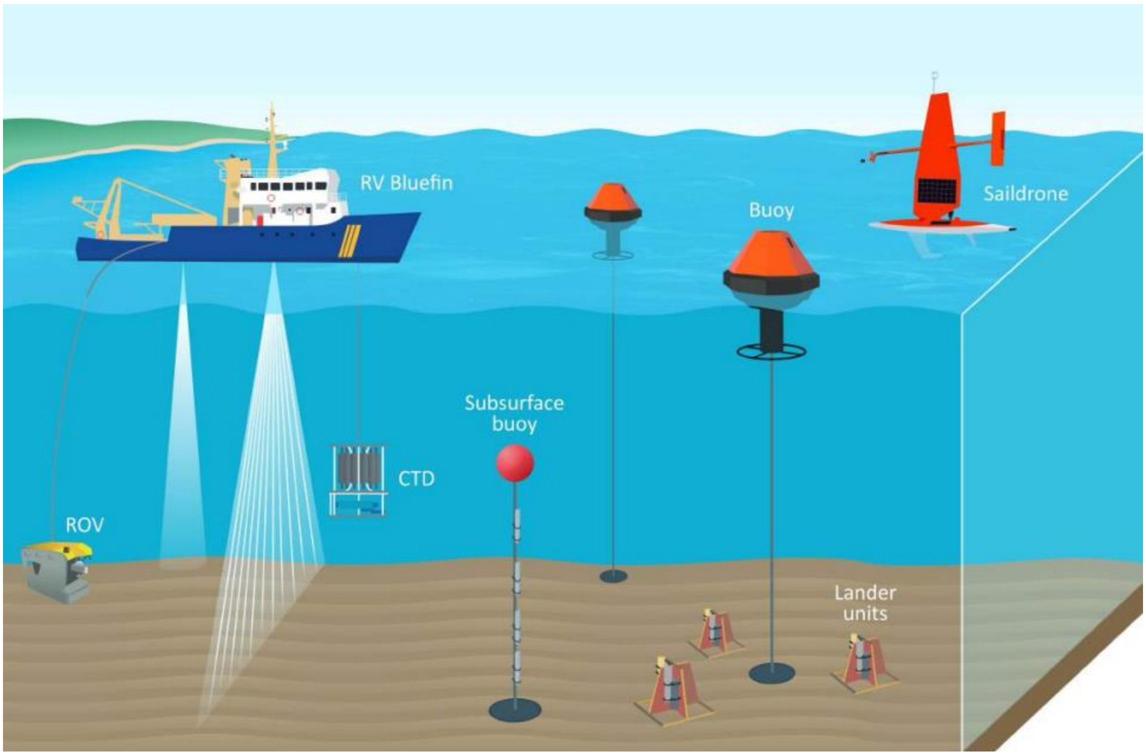


Figure 6. Schematic of marine monitoring technologies tested in the Gippsland Basin, Australia (see Ross et al., 2022; https://anlecrd.com.au/projects/methodology-to-deploy-shallow-focused-subsea-ccs-technologies/). Not to scale.

Migration of CO_2 to the atmosphere will not only be detrimental to the mitigation of climate change but would also reduce the amount of carbon credits a CCS operator could claim for the volume of CO_2 reported to be stored in the subsurface (Jenkins et al., 2021). In this context, the project considered leakage limits to the atmosphere as cited by Hepple and Benson (2005) and others as a lens with which to consider overall global versus local impacts.

Assessment framework for risks associated with geological carbon storage

Vulnerability evaluation framework for geological carbon storage

A geological carbon storage operation, like any industrial facility, needs to be assessed and permitted by the responsible regulator and, in most jurisdictions, will require some form of environmental impact assessment (EIA). An example of a vulnerability evaluation framework (VEF) specifically for CO_2 geological storage was introduced by the US Environmental Protection Agency (USEPA, 2008) (Figure 7) and the underlying concepts are applicable to the regulation of storage operations globally, and reflect conclusions reached in other assessments (e.g., Oldenburg et al., 2002a, 2002b; Friedman and Nummedal, 2003; Maul et al., 2005; Celia and Radonjic, 2004; Celia et al., 2004; Le Gallo et al., 2004; Walton et al., 2004; Zhang et al., 2006; Price and Oldenburg, 2009).

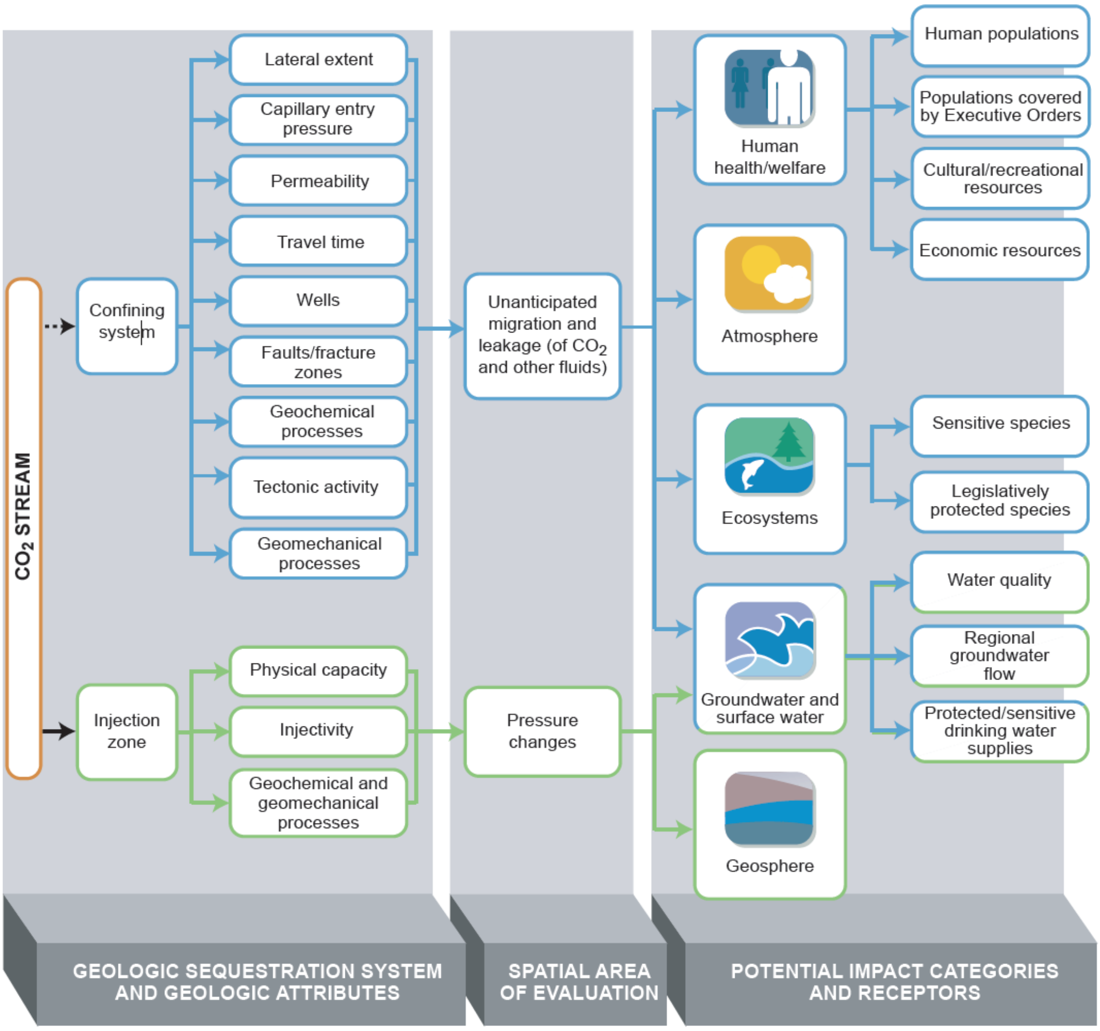


Figure 7. Conceptual schematic of the vulnerability evaluation framework (VEF) for geologic sequestration from the USEPA (2008).

The VEF in Figure 7 consists of three main components (USEPA, 2008):

- Characterisation of the confining system, the injection zone, and a series of geologic attributes that could influence the vulnerability of the storage system to unanticipated migration and leakage of CO_2 and brine, and increased formation pressure.
- Definition of the spatial area of evaluation for assessing adverse impacts due to unanticipated migration, leakage CO_2 and brine, or increased formation pressure.
- Identification of potential impact categories and receptors, including human health, the atmosphere, ecosystems, groundwater and surface water, and the geosphere.

The VEF was designed as a conceptual framework to support regulators, operators and other stakeholders, in developing key site-specific considerations and in identifying main aspects of project design, site-specific risk assessment, monitoring, and operational management (USEPA, 2008). The framework assesses conditions that affect the susceptibility, positively or negatively, to consequences, as opposed to a quantitative, probabilistic risk assessment that measures the probability and severity of consequences.

Risk management of geological carbon storage

The risks of the geological storage of CO_2 are managed through rigorous and well-established methods. The assessment steps are captured in the “safety and security” pyramid (Figure 8) and are also covered by the international standard “ISO 27914:2017 - Carbon dioxide capture, transportation and geological storage — Geological storage”.

The aim of risk management of CO_2 geological storage is driving down the risk level and includes site selection, monitoring and verification, operational management, and mitigation methods.

In standard terminology, harmful events (“hazards”) are thought to occur within a specific probability (risk). More commonly, the risk usually refers to some combination of the things that can go wrong and the probabilities that they will. Risk management is the process of identifying hazards, assessing likelihood and consequence AND establishing strategies to mitigate these risks.

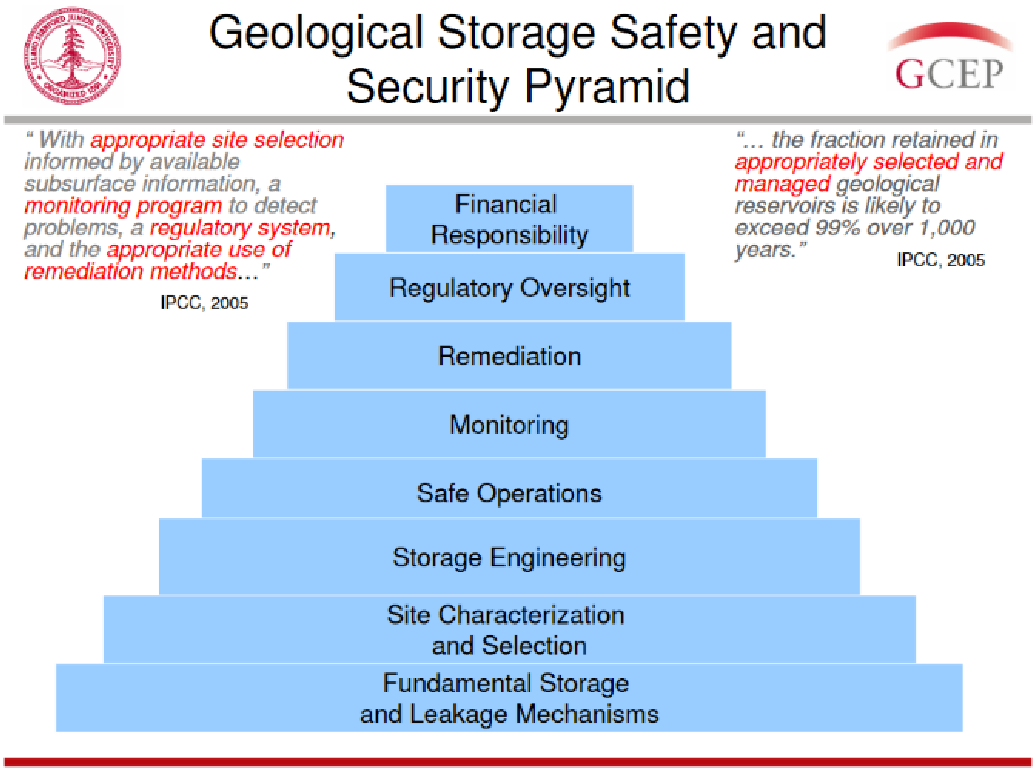


Figure 8. The "safety pyramid" for geological storage, from a presentation by Benson (2007). The combination of all these steps is essential to keeping risks low.

There are many formal methods of risk management, but they all have four fundamental steps.

1. Identify the hazards
2. Assign a probability to the occurrence of the hazard
3. Identify the consequences of the hazard eventuating
4. Eliminate the hazard, reduce its probability, or reduce the consequences.

The objective of risk management is to minimize the expected harm, the probability of a hazard eventuating multiplied by the probability that it does. The target is often stated as ALARP, or "As Low As Reasonably Practicable". Whether this is low enough, in a wider sense than the metrics of the project to hand, is a wider question that goes to the downside of not implementing the project at all.

The notion of risk, meaning the probability of failure, is not a transparent concept in CCS, because of the imperfect analogies with other examples, the unique and highly selected specific nature of sites, and the inherent "unknown unknowns" of the deep subsurface. Nonetheless, experts have a clear sense of the ranking of various risks and, when they attempt to assign numerical probabilities, all arrive at very small numbers. Estimated risks are low because the risk assessment is on sites that have already undergone a filtering and selection process and have monitoring plans in place. These estimates of low risk frame the risk management strategy.

The Quest (Bourne et al., 2014), Goldeneye (Dean and Tucker, 2017) and Gorgon (Trupp et al., 2021) projects made familiar one risk management method, which illustrates the concepts clearly. In the "bow tie" method the unwanted "top event", the occurrence of the hazard, is placed at the centre of the diagram (Figure 9). Leading to it from the left are lines indicating the various ways ("threats") that the top event might occur; on these lines are "barriers", aspects of natural barriers, engineering or monitoring that should block those routes. These barriers are themselves analysed for failure. On the outgoing side from the top event, "consequences" are reached by lines which are also blocked by engineered barriers.

As a simple example, the "top event" might be the failure of the cement in the wellbore's annulus. "Threats" leading to cement failure might include inadequate removal of drill fluid prior to the cement job; "barriers" might then be a meticulous well clean-up routine, followed by a cement bond log to check for damage or imperfections. On the outgoing side, a "consequence" might be that CO_2 would reach an overlying geological layer; barriers would include monitoring for this, and possibly running a cement squeeze to fix the well imperfections.

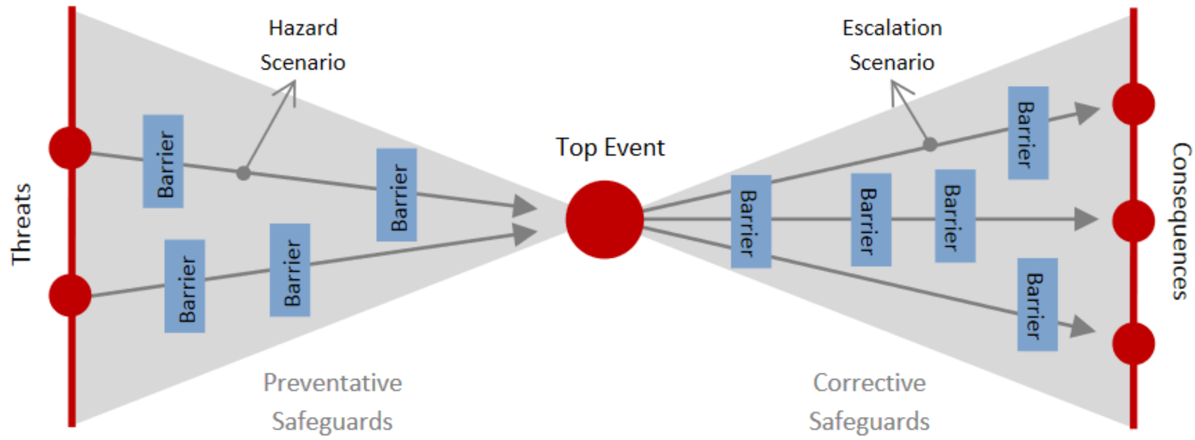


Figure 9. A simplified bow tie diagram, from Tucker and Tinios (2017).

Other methods of risk management make more explicit use of probability. Hazards are ranked according to likelihood and matched against consequences should the hazard occur. The consequences are ranked according to their seriousness. This procedure places the hazard in the familiar risk management matrix, a diagram that indicates via traffic light colour code where management should be focused (Figure 10).

Managers of risk rely on their past experience, as well as expert judgement and subject matter advice to assess threats, consequence and assign likelihoods. CCS is a younger industry than oil and gas extraction, its main analogue. However, oil and gas is a global, well-established, and large industry using many of the same processes and expertise used in geological storage of CO_2.

		Consequence				
		Negligible 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
Likelihood	5 Almost certain	Moderate 5	High 10	Extreme 15	Extreme 20	Extreme 25
	4 Likely	Moderate 4	High 8	High 12	Extreme 16	Extreme 20
	3 Possible	Low 3	Moderate 6	High 9	High 12	Extreme 15
	2 Unlikely	Low 2	Moderate 4	Moderate 6	High 8	High 10
	1 Rare	Low 1	Low 2	Low 3	Moderate 4	Moderate 5

Figure 10. A typical risk management matrix; each hazard is assigned a likelihood and a consequence in some structured way, hence placing it somewhere in the diagram.

CO_2 storage projects have accumulated many project-years and wellbore-years of experience without known examples of leakage. Useful analogues of geological CO_2 storage are the disposal of hazardous waste (Apps, 2005), "sour gas" (hydrogen sulphide (H_2S) + CO_2, Carroll et al., 2009), brine produced as an unwanted by-product of oil and gas production, and natural gas storage for domestic use and to even out seasonal fluctuations in demand (Perry, 2005). Together these activities currently greatly outstrip the activity in pure CCS. If one were to include EOR in which CO_2 is used to sweep trapped oil out of reservoirs, the large amount of relevant experience is even more apparent. These analogies do need to be approached with insight – for example, the wells used for underground natural gas storage typically encounter large cyclic changes in pressure, something that would not occur in CCS and which increases the risk for natural gas storage in a unique way.

Geological storage of CO_2 is expected to be secure, but leakage cannot be guaranteed to be mathematically zero. By analogy with oil and gas operations, operators expect operational losses to be small, and use this experience in their risk management. For example, Alcalde et al. (2018, Supplementary Material) analysed data from the UK Health & Safety Executive, covering uncontrolled fluid losses during drilling and production in the North Sea's oil and gas operations. Both operations are far riskier in terms of consequences than CO_2 storage. The North Sea data indicates one gas release per well per fourteen years, with an average loss of about 4 tonnes CO_2 equivalent. Only two of the 1,597 recorded gas release incidents have exceeded 500 tonnes CO_2 equivalent.

These numbers are not a prediction for CO_2 storage, but they indicate that the industry can manage a much more hazardous, and more volumetrically significant, set of processes to levels where uncontrolled losses are very small indeed. As quoted by the IPCC (2005):

"With appropriate site selection based on available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geologic storage would be comparable to risks of current activities such as natural gas storage, [enhanced oil recovery], and deep underground disposal of acid gas."

Just as importantly, the management of storage risk is a dynamic process. As CO_2 injection proceeds, comprehensive monitoring data will be collected that allow the geologist and reservoir engineer to update and refine their models in a dynamic and evolutionary process. It has often been said that "the CO_2 illuminates the geology" in the case of acquiring repeat seismic survey data. As the injection project moves to completion, the understanding of the fate of the CO_2 will become better and better. A site will be "closed" (liability handed to state or Crown) when the regulators are satisfied that its long-term behaviour is predictable and safe with sufficient certainty. This may be because the CO_2 is proven to be trapped beneath the seal, or it may be moving slowly, or even stabilised, in an aquifer in which it will dissolve long before reaching any assets of importance.

It is worth noting that a hazard may be rated as more severe because very little is known about its theoretical magnitude compared to risks that can be estimated numerically with some confidence. Risk assessments for geological carbon storage appear to go beyond experience because they look ahead over long periods of time. However, the underlying disciplines (mainly geology, physics and chemistry) provide a strong underpinning to extrapolate current experience. Also, experience across many projects give information about the likelihood of rare events. An element of expert judgement is essential in deciding which analogous industries are relevant, or to assign a range to the probabilities of relevant unknowns.

A final element in the expert assessment of the risk management for CO_2 storage is understanding how unforeseen and detrimental incidents can be mitigated. The monitoring plan should ensure that leakage is detected early. As noted, any loss of CO_2 from the storage reservoir will be an unplanned event, so mitigation strategies must be broad in scope (e.g. Manceau et al., 2014; the MiReCOL project https://www.mirecol-CO2.eu). Simply stopping injection is effective in many scenarios, or reservoir pressure can be reduced by removing formation water through other existing or specially drilled wells. The pattern of CO_2 injection and the removal of brine by pressure relief wells can be adjusted to "steer" the CO_2 plume away from hazards. Remediating a failed wellbore is well-established technology, although expensive. Methods are under development to seal leaky wells by novel geochemical or biological methods (Castaneda-Herrera et al., 2018). In general, the crucial steps of proper site characterisation and selection will greatly reduce the likely need and scope of possible mitigations.

Overall, a site operators' objective is constantly to drive the project risk (i.e., its probability x consequence) to ALARP, As Low As Reasonably Practicable. Reflecting the unknowns, probability x consequence is not the only metric – "bookend" cases, the worst and best that can plausibly happen, are an important output of modelling to inform decisions about whether the risks are significant.

Returning to risk management steps, the itemization and assessment of hazards is a sophisticated and complex process, using established tools to gather information in a structured way. (The bow-tie method presented earlier is an example; Figure 9). The information comes from a wide range of experience in related industries and frames these data within detailed geological, physical and chemical models of the storage site. The strong understanding of the relevant processes means that knowledge and experience can be extrapolated with confidence into areas where CO_2 poses novel challenges. Finally, operating a storage site is a *continuing* process, where many of the barriers in the bow-tie model will be methods of monitoring the progress of the storage, so that the conceptual models of the site can be updated continuously. Typically, regulators will review these data every few years and may agree on an updated operational plan.

Site-specific assessment – area of review

Imposed by the regulator, a CO_2 geological storage project requires monitoring within the Area of Review (AOR), Spatial Area of Evaluation (USEPA, 2008) or Area of Potential Impact (Bandilla et al., 2012). The AOR includes the surface projections of the CO_2 plume and the portion of the reservoir affected by the pressure increase and brine (Michael et al., 2013; 2016; Figure 11). The impact assessment and the monitoring and verification efforts should follow a tiered approach based on the likelihood of impact occurrence and its severity (Birkholzer et al., 2014).

Pressure changes within the storage reservoir induced by CO_2 injection may extend across an area several orders of magnitude larger than that of the actual CO_2 plume. The increase in pressure declines rapidly outward from the injection well pressure propagation is governed by the reservoir thickness, porosity and permeability, and the presence of any faults or low-permeability baffles.

The extent of the AOR is defined differently between jurisdictions but is generally constrained by the degree of pressure increase that potentially results in measurable geomechanical impacts or changes to water quality. Generally, thresholds are limits of acceptable change, for example to water or air quality, biophysical parameters, or social/cultural values. Thresholds can be tiered (i.e., cautionary, target, critical) or could represent tipping points (i.e., environmental conditions that cause a rapid change to an ecosystem that cannot be reversed).

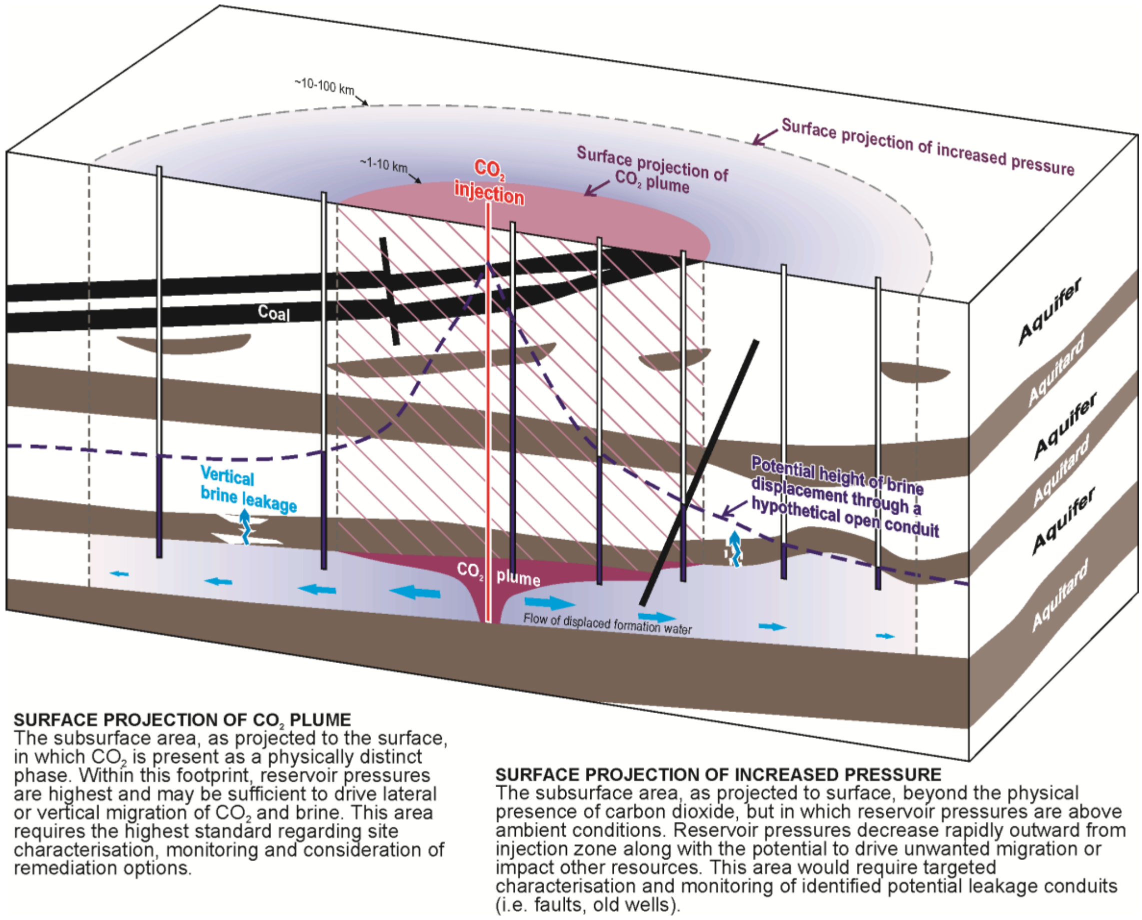


Figure 11. Schematic representation of the potential extent of impacts related to CO_2 injection (Michael et al., 2016). The subsurface volumes possibly impacted by CO_2 leakage or pressure increase have approximately cylindric shape. The Area of Review (AOR) at the surface follows the surface projection of increased pressure, whereby the degree of monitoring and characterisation requirements would depend on the radial distance from the injection centre. Not to scale.

Typical thresholds with respect to pressure impacts are the pressure required to re-activate faults or to induce fractures in the seal, which are largely near-well impacts. In the far-field, the United States Environmental Protection Agency (USEPA, 2008) has proposed to limit the extent of the AOR by “the minimum pressure increase at which a sustained flow of brine upward through a hypothetical conduit into an overlying drinking water aquifer occurs”. Other jurisdiction uses explicit thresholds. For example, for constraining the effects of coal seam gas production in Queensland, Australia a 5 m hydraulic-head drop in confined aquifers is set as a trigger threshold (Queensland Water Act, 2000). Similarly, White et al. (2020) propose a risk-based approach in relation to water quality and constrain the AOR to the area where CO_2 or brine leakage from a hypothetical open and uncemented well connecting the storage reservoir to the shallow drinking water aquifer would result in drinking water quality parameters that exceed “no-net degradation” threshold values (i.e., pH = 6.6 and salinity = 420 mg/l). Accounting for the potential of the mobilisation of heavy metals, this risk-based approach can be extended to general potable water quality thresholds.

Site characterisation and monitoring of CO_2 geological storage should identify site specific risks and should assess the severity and likelihood of potential injection impacts. Pressure increases will be greatest and the potential for unplanned migration of carbon dioxide is highest in the vicinity of the injection well and within area of the CO_2 plume, where geological characterisation and monitoring should be most comprehensive (Michael et al., 2013; 2016). Beyond the plume footprint, site characterisation and monitoring should focus on features that could provide a potential leakage pathway for CO_2 or displaced brine. Depending on the level of degree of vulnerability, different site characterisation requirements, M&V and mitigation strategies would be recommended, which may require substantial data collection, interpretation and expert risk assessment. An example of the process for evaluating a CO_2 storage project is shown in Figure 12 (Michael et al., 2012).

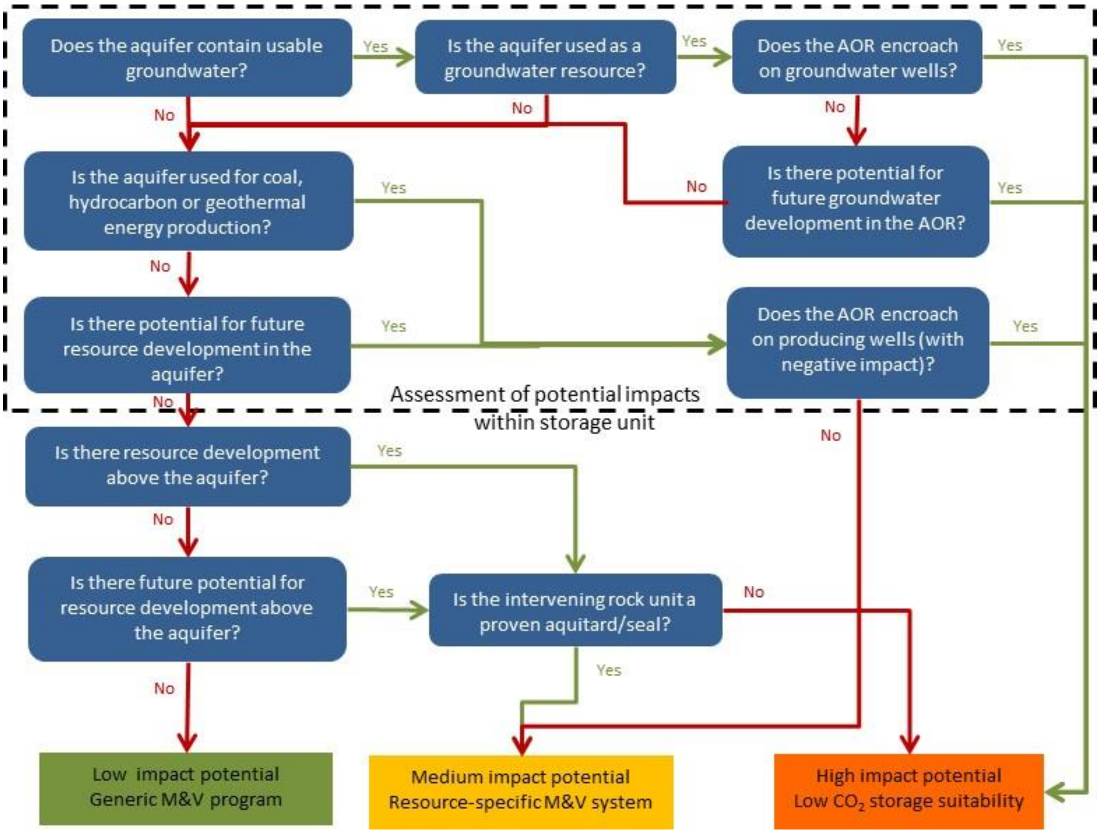


Figure 12. Quick assessment workflow for evaluating a CO_2 aquifer storage site with respect to potential resource interactions within its Area of Review (modified from Michael et al., 2012).

Assessment approach of this study

We use a causal network approach to evaluate activities and risks of CO_2 leakage in relation to CO_2 geological storage operations. It combines a vulnerability evaluation framework with a risk assessment component for each pathway. The current work only provides a general network description, but it would also be possible to apply the approach to specific regions or geologic basins. We believe that this approach can be a clear way in which to demonstrate or rebut any environmental and public health implications of CO_2 migration to the surface or shallow subsurface.

Causal Network Methodology

The causal network methodology is used to evaluate potential impacts of development activities and visualise both direct and indirect impacts on ecological, economic and/or social values that are to be protected. Causal networks are graphical models that describe the cause-and-effect relationships linking development activities with endpoints, and the representation provides a logical and transparent pathway of understanding (i.e., Perdicoulis and Glasson, 2006). The building blocks for developing the input materials are illustrated in Table 1. A literature review of each of the parameters provides the input materials and the underpinning information. It is anticipated that this approach will provide an interactive method of evaluating the relationship between environmental and public health implications of CO_2 migration to the surface or shallow subsurface, risk of leakage pathways, environmental impacts and mitigation methods so that those less familiar with CO_2 geological storage can use it in determining risks in their jurisdictions.

Table 1. Building blocks for development of a causal network pathway (from Peeters et al., 2021).

Node type	Description	Examples
Driver	Major external driving forces (human or natural) that have large-scale influences on climate change	Industrial emissions
Activity	A planned event associated with mitigating climate change	CO_2 geological storage
Stressor	Physical or chemical condition, or external stimulus caused by activities	Compromised well integrity, Compromised subsurface integrity
Process	A mechanism that could change a characteristic of an endpoint	CO_2 migration into the atmosphere, ocean, seabed, soil, surface water, or shallow aquifers
Endpoint	A value pertaining to water, air and the environment that maybe impacted by processes due to activity	Climate, public health, marine or lake fauna & flora, plants growths, potable water, subsurface resources

The framework of the causal network developed in this project is shown on Page 36 and can be used as an interactive tool for accessing the material in the report. The potential impact of one node on another node from Table 1 is depicted by a connecting arrow. Each impact is assessed individually by answering the questions in the table below and by assigning a risk (Table 2).

Table 2. Example of the process of developing the assessment tables and how they are structured.

Question 1. Can activity/stressor/process lead to stressor/process/ degradation of an endpoint? Successive examples from left to right: can carbon geological storage lead to compromised well integrity? Can compromised well integrity lead to an increase of CO_2 in the atmosphere? Can an increase of CO_2 in the atmosphere lead to a degradation of climate mitigation efforts?				
Key Questions	Answers			
Is it possible?	Yes/No			
Is it material?	No (negligible, minor) or Yes (moderate, major, catastrophic)			
Can it be monitored?	Yes/No. List monitoring technologies and measurable value or condition beyond which change due to impact requires mitigation/remediation.			
Could it be mitigated?	Yes/No; list mitigation options			
Could it be remediated?	Yes/No; list remediation options			
SUMMARY	**Not Possible**	**Possible but not material**	**Possible and can be mitigated**	**Possible, material and cannot be mitigated**

For example, the leakage pathway, such as "compromised subsurface integrity" could result in a range of processes, where CO_2 could migrate to the atmosphere, the oceans, the seabed etc. The endpoint or consequence of each of these processes can have a range of effects. For example, CO_2 migration to the atmosphere could result in adverse effects on climate change mitigation efforts and/or pose a risk to public health through air pollution. The causal network descriptors and background information are presented and connected so that each pathway can be followed and the level of impact on stressors, processes and endpoints can be clearly identified, qualified and mitigation/remediation strategies proposed.

Whether an impact is 'material' can be evaluated either qualitatively or quantitively. For example, the Victorian Environment Protection Act 2017 defines "material harm", in relation to human health or the environment as harm that is caused by pollution https://classic.austlii.edu.au/au/legis/vic/consol_act/epa2017284/s3.htmlor waste that:

(a) involves an actual adverse effect on human health or the environment that is not negligible; or

(b) involves an actual adverse effect on an area of high conservation value or of special significance; or

(c) results in, or is likely to result in, costs in excess of the threshold amount being incurred in order to take appropriate action to prevent or minimise the harm or to rehabilitate or restore the environment to the state it was in before the harm.

Such a definition of material harm can be quantified into specific measurable quantities and associated thresholds, similar to 'No Adverse Effect Limits' (NAEL). Quantifying such materiality threshold is often project and location specific. This study examines for every link what the relevant quantities are to consider in establishing materiality, and, where available, provide an overview of quantitative estimates of thresholds for materiality. Identifying these relevant quantities further informs monitoring strategies. The evaluation of materiality for each link presented here is not project or region-specific and therefore often qualitative and generic. The information and reasoning provided for the materiality assessment can be used as a starting point for a local, project specific assessment.

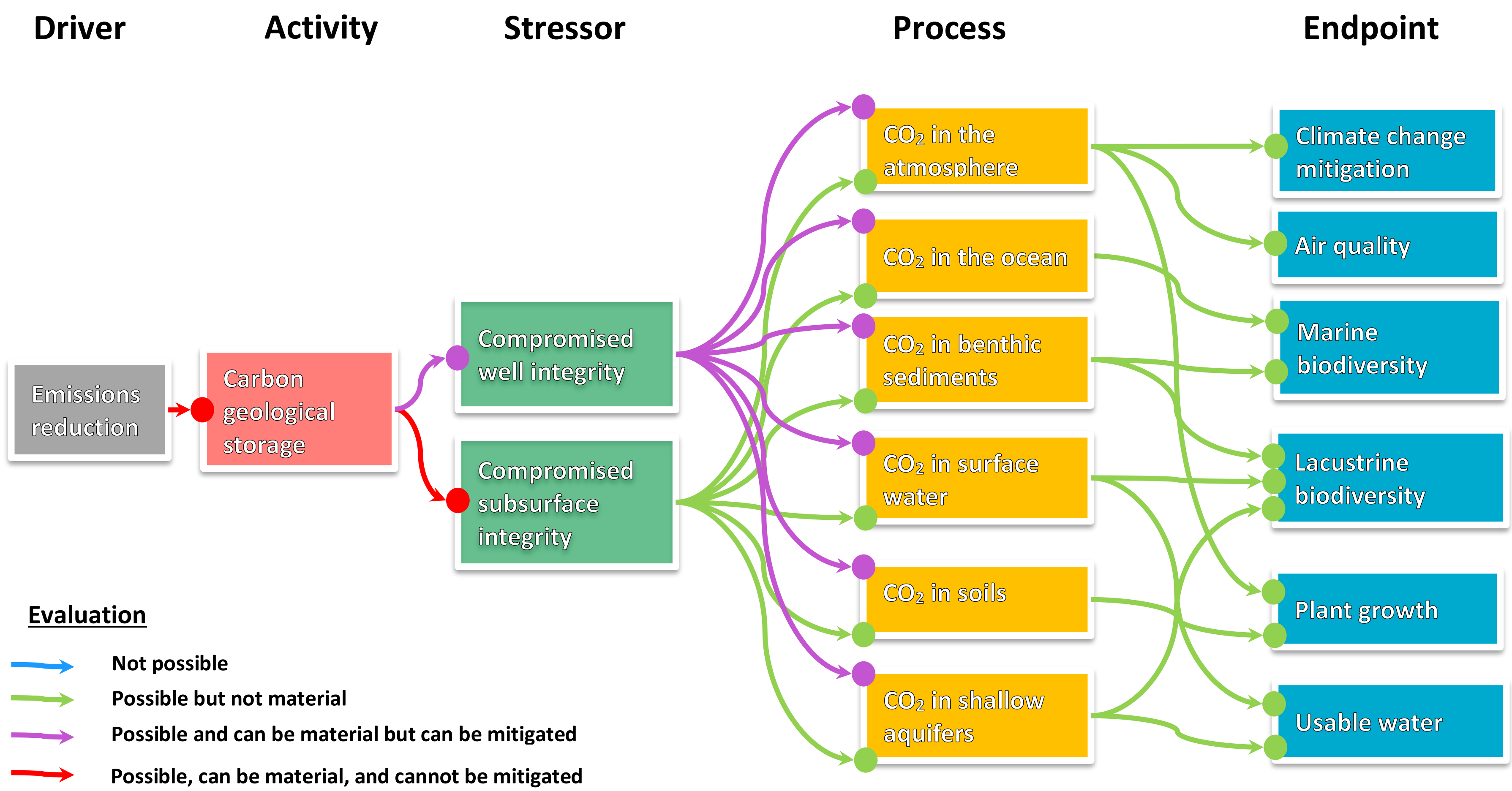
Obviously, for an onshore CCS project, the pathway from 'Compromised well or subsurface integrity' via 'CO_2 in Oceans' to 'Marine biodiversity' would be assessed as 'Not possible'. Similarly, in the case of offshore storage (unless nearshore), the pathway from 'Compromised well or subsurface integrity' via 'CO_2 in Soils' to 'Plant growth' would be 'Not possible'. Also, the likelihood of well leakage in a mature petroleum province (i.e., brownfield site) with hundreds of producing and abandoned wells would be larger than at a storage location without any neighbouring wells (e.g., greenfield site) and the impact could be quantified based on the number, distance, age and condition of the wells. Also, our assessment assumes that storage operators and regulators follow and enforce standard practices (for example ISO 27914) with respect to site characterisation, modelling, storage operation and monitoring.

With respect to mitigation options, the evaluation considers options that can 'avoid' or 'minimise' an event to occur, i.e., using best practice well completion and cementing technologies to minimise the risk of leakage along a well. For cases in which an event cannot be avoided or minimised, remediation options are listed, if available, i.e., a leaky well can be remediated by installing cement plugs. **Note:** The stop of injection is always possible and the obvious initial mitigation measure in case of a material leak. Back production of injected CO_2 may also be possible to further reduce reservoir pressure and potentially reverse the flow of CO_2 in the reservoir.

Notwithstanding the level of assessment in this report, the same assessment framework could be applied at the basin- or site -scale, in which case more detailed basin- or site-scale information would be provided for the respective nodes, which then could be used for more quantitative impact assessments that could address specific and sensitive to region risks (e.g., regional at-risk fauna https://gba-explorer.bioregionalassessments.gov.au/bee/9/67/0).

To use the causal network tool, click on any node in the diagram to be taken to the detailed review section of that node. Clicking the arrow between nodes will take the reader to the respective impact assessment table. Click the colour bar in the header to return to the process diagram.

Navigation tool



Click on any item (arrow endpoint or box) to take you to the related section in the report. Clicking the header line in the report section will take you back to the diagram.

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1 Driver

1.1 Emissions reduction

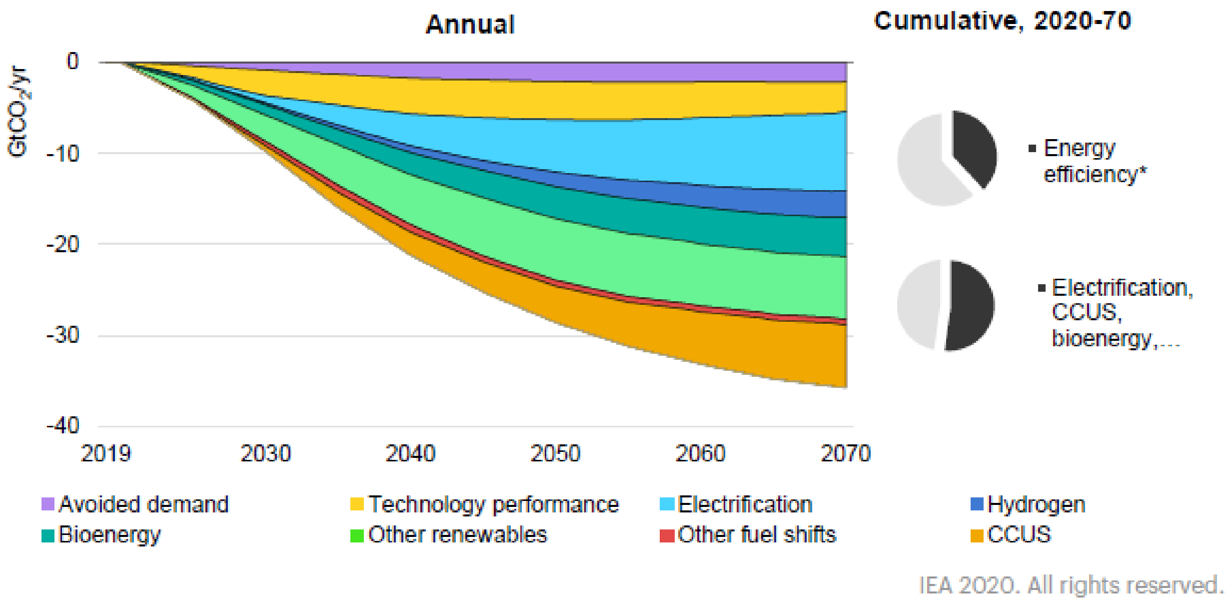
1.1.1 Definition

The act or process of limiting or restricting greenhouse gas emissions, including through the permanent storage of carbon dioxide in geological formations.

1.1.2 Description

Emissions reduction activities aim to eliminate, limit or restrict the generation of a group of gases (known as greenhouse gases or GHGs (Table 3) that have an adverse impact on the climate. Technologies are evolving that aim to reduce emissions through a range of activities that address energy generation, optimisation and consumption, industrial and agricultural processes and transport. As such the mitigation options being researched, developed and deployed are both technical and nature based. IEA's Energy Technologies Perspectives Report (2020) identify the need for a range of activities to occur to meet international targets for emissions reduction through the following activities (Figure 13):

- Avoided demand – caused by improved processes and increased efficiencies
- Bioenergy – e.g., biomass, BECCS, biofuels, and potentially waste-to-energy, ethanol production etc.
- Technology performance – enhanced technical solutions reducing overall energy use and material substitution that has a lower carbon footprint
- Other renewables – e.g., wind, solar, geothermal, green hydrogen, hydro
- Electrification – the conversion of a range of existing energy sources to being transmitted as electricity, e.g., trucks and rail transportation where emissions would be hard to abate otherwise
- Other fuel shifts – substitution of high emissions intensity energy to lower alternatives (e.g., from coal to natural gas, sustainable aviation fuels)
- Hydrogen – conversion of hydrocarbons or other hydrogen-rich materials to H_2 for use in a range of industrial, energy generation and transport activities
- CCUS – Carbon capture, utilisation and storage removes CO_2 generated via energy generation or industrial processes for purification and re-use, or for geologically permanent storage deep underground in aquifers or depleted oil and gas fields



* Energy efficiency includes enhanced technology performance as well as shifts in end-use sectors from more energy-intensive to less energy-intensive products (including through fuel shifts).

Notes: CCUS = carbon capture, utilisation and storage. See IEA (2020a) and the ETP model documentation for the definition of each abatement measure. Hydrogen includes low-carbon hydrogen and hydrogen-derived fuels such as ammonia.

Figure 13. IEA projections of emissions reduction by each of the main potential methods for mitigation to meet current sustainable development goals. IEA, 2020.

Table 3. Major greenhouse gases (GHG) and their global warming potential (GWP). From IPCC, 2014. and Centre for Climate and Energy Solutions (https://www.c2es.org/content/main-greenhouse-gases/).

Greenhouse Gas	Chemical Formula	GWP 100 yr	Atmospheric lifetime (yr)
Carbon dioxide	CO_2	1	100
Methane	CH_4	25	12
Nitrous oxide	NO	265	121
Chlorofluorocarbon-12 (CFC-12)	CCl_2F_2	10,200	100
Hydrofluorocarbon-23 HFC-23)	CHF_3	12,400	222
Sulfur hexafluoride	SF_6	23,500	3,200
Nitrogen trifluoride	NF_3	16,100	500

Table 4. from page 1017 of IPCC Climate change 2021 The Physical Science Basis WG 1 contribution to Sixth Assessment report of IPCC.

Table 7.15 | Emissions metrics for selected species: global warming potential (GWP), global temperature-change potential (GTP). All values include carbon cycle responses as described in Section 7.6.1.3. Combined GTPs (CGTPs) are shown only for species with a lifetime less than 20 years (Section 7.6.1.4). Note CGTP has units of years and is applied to a change in emissions rate rather than a change in emissions amount. The radiative efficiencies are as described in Section 7.3.2 and include tropospheric adjustments where assessed to be non-zero in Section 7.6.1.1. The climate response function is from Supplementary Material 7.SM.5.2. Uncertainty calculations are presented in Supplementary Tables 7.SM.8 to 7.SM.13. Chemical effects of CH_4 and N_2O are included (Section 7.6.1.3). Contributions from stratospheric ozone depletion to halogenated species metrics are not included. Supplementary Table 7.SM.7 presents the full table.

Species	Lifetime (Years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100	CGTP-50 (years)	CGTP-100 (years)
CO_2	Multiple	$1.33 \pm 0.16 \times 10^{-5}$	1.	1.000	1.000	1.000	1.000		
CH_4-fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8	13.2 ± 6.1	7.5 ± 2.9	2823 ± 1060	3531 ± 1385
CH_4-non fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8	10.4 ± 6.1	4.7 ± 2.9	2675 ± 1057	3228 ± 1364
N_2O	109 ± 10	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 118	273 ± 130	130 ± 64	290 ± 140	233 ± 110		
HFC-32	5.4 ± 1.1	$1.1 \pm 0.2 \times 10^{-1}$	2693 ± 842	771 ± 292	220 ± 87	181 ± 83	142 ± 51	78,175 ± 29,402	92,888 ± 36,534
HFC-134a	14.0 ± 2.8	$1.67 \pm 0.32 \times 10^{-1}$	4144 ± 1160	1526 ± 577	436 ± 173	733 ± 410	306 ± 119	146,670 ± 53,318	181,408 ± 71,365
CFC-11	52.0 ± 10.4	$2.91 \pm 0.65 \times 10^{-1}$	8321 ± 2419	6226 ± 2297	2093 ± 865	6351 ± 2342	3536 ± 1511		
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5301 ± 1395	7380 ± 2430	10,587 ± 3692	7660 ± 2464	9055 ± 3128		

Emissions reduction targets have firmed up in terms of amounts of reductions and have become increasingly time-bound (i.e., “net zero by 2050”). This is in keeping with the evolution of international discussions, actions and agreements from the Kyoto Protocol in 1997 (international treaty committing state parties to reduce greenhouse gas emissions because of anthropogenic production) to the Paris Agreement in 2015 (international treaty on mitigation, adaptation and financial imperatives of emissions reduction and climate change). At the time of development, 196 countries adopted the Paris Agreement to reduce global impacts on climate change with the ambition to limit warming to no more than 1.5°C.

These treaties have provided platforms for states and territories to be able to develop their own emissions reduction, or net zero emissions targets, many of which have become enshrined in law by governments. Climate Action Tracker (https://climateactiontracker.org/global/cat-net-zero-target-evaluations/) state that around 140 countries have announced, or are in the process of considering net zero targets. This would encompass action on approximately 90% of current emissions.

Examples of international pledges for emissions reduction (information from Climate Action Tracker accessed 9/12/2022):

- USA – Inflation Reduction Act (IRA) signed into law in 2022 to half emissions by 2030 (based on 2005 emissions).
- Australia – Passed legislation to reduce emissions by (at least) 43% by 2030 (based on 2005 emissions).
- EU – submitted as a single entity to a target of at least 55% reduction below 1990 levels by 2030.
- Japan – aims for 46% emissions reduction by 2030 below the 2013 levels, with stretch target of 50%.

- UK – has stated that their target is to reduce emission to 68% below 1990 levels by 2030.
- China – aims to have carbon neutrality before 2060.

Emissions reduction by Geological Carbon Storage of CO_2

In terms of the range of methods for mitigating emissions, carbon capture and storage is one in which large-scale emissions reduction is possible at a practicable financial, environmental and social cost.

Other methods of removing CO_2 from the atmosphere are available but have different rates, levels of permanence, cost and acceptability. These might include utilisation of CO_2 to make other products (e.g., anything from bricks to synthetic aviation fuels; see CSIRO's Carbon Utilisation Roadmap (Srinivasan et al., 2021) or nature-based solutions where CO_2 from the atmosphere is withdrawn by biological (trees) or chemical (mine tailings) processes, which are less well quantified and constrained.

There are environmental impacts and consequences, some positive and some negative, associated with any approach to reduce emissions, but the largest risk to climate is not doing anything.

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2 Activity

2.1 Carbon geological storage

2.1.1 Definition

Carbon geological storage is the process of storing carbon dioxide (CO_2) extracted from a capture process such as pre- or post-combustion on a geologic timescale in deep geologic reservoirs. The activity includes processes necessary for injection of CO_2 into the subsurface, as well as the monitoring of CO_2 storage.

The carbon capture and storage activity only includes storage through geological sequestration, not through other process, like for instance biological sequestration.

2.1.2 Description

Carbon geological storage requires a series of operations (Figure 14) that includes the injection of CO_2 through a well into a geological formation at a depth at which the CO_2 is stored as a supercritical fluid (Figure 15). The CO_2 is delivered as supercritical fluid via pipeline to the wellhead, where additional compression and heating may be required to ensure continuous injection of supercritical CO_2 (Figure 14). While it is becoming increasingly acceptable to re-use existing infrastructure, it is important that pipelines and well casing/tubing/cement exposed to CO_2 are resistant to acid-gas corrosion.

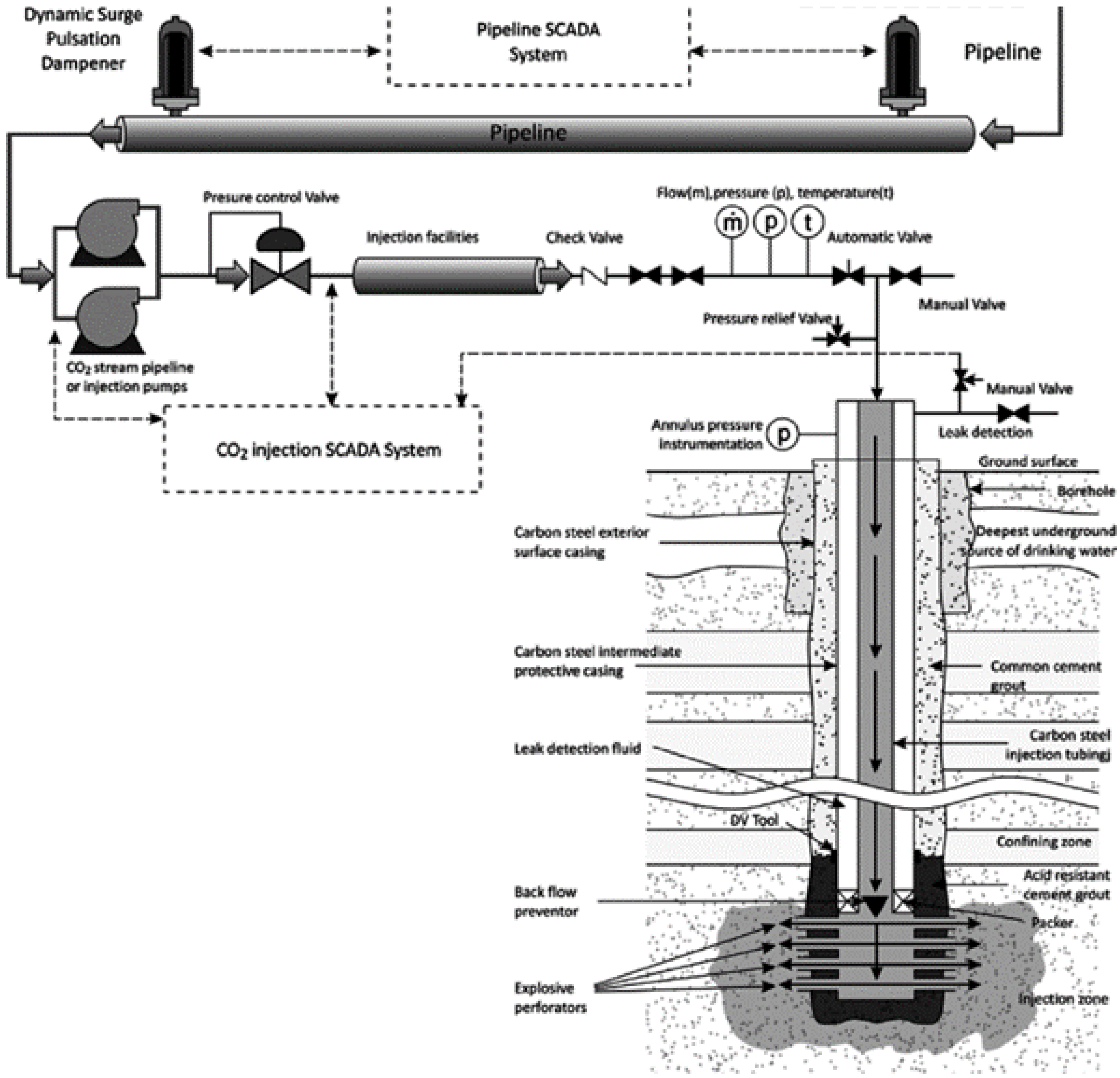

Figure 14. Compression, transportation and injection of CO_2 (Witkowski et al., 2014). Not to scale.

The relatively high density of supercritical CO_2 optimises storage volumes (Figure 15) and reduces buoyancy-driven migration potential. The critical temperature and pressure of CO_2 are 31.1 °C and 7.39 MPa, respectively, which generally corresponds to a depth of approximately 800 m depending on the local geothermal and pressure gradients.

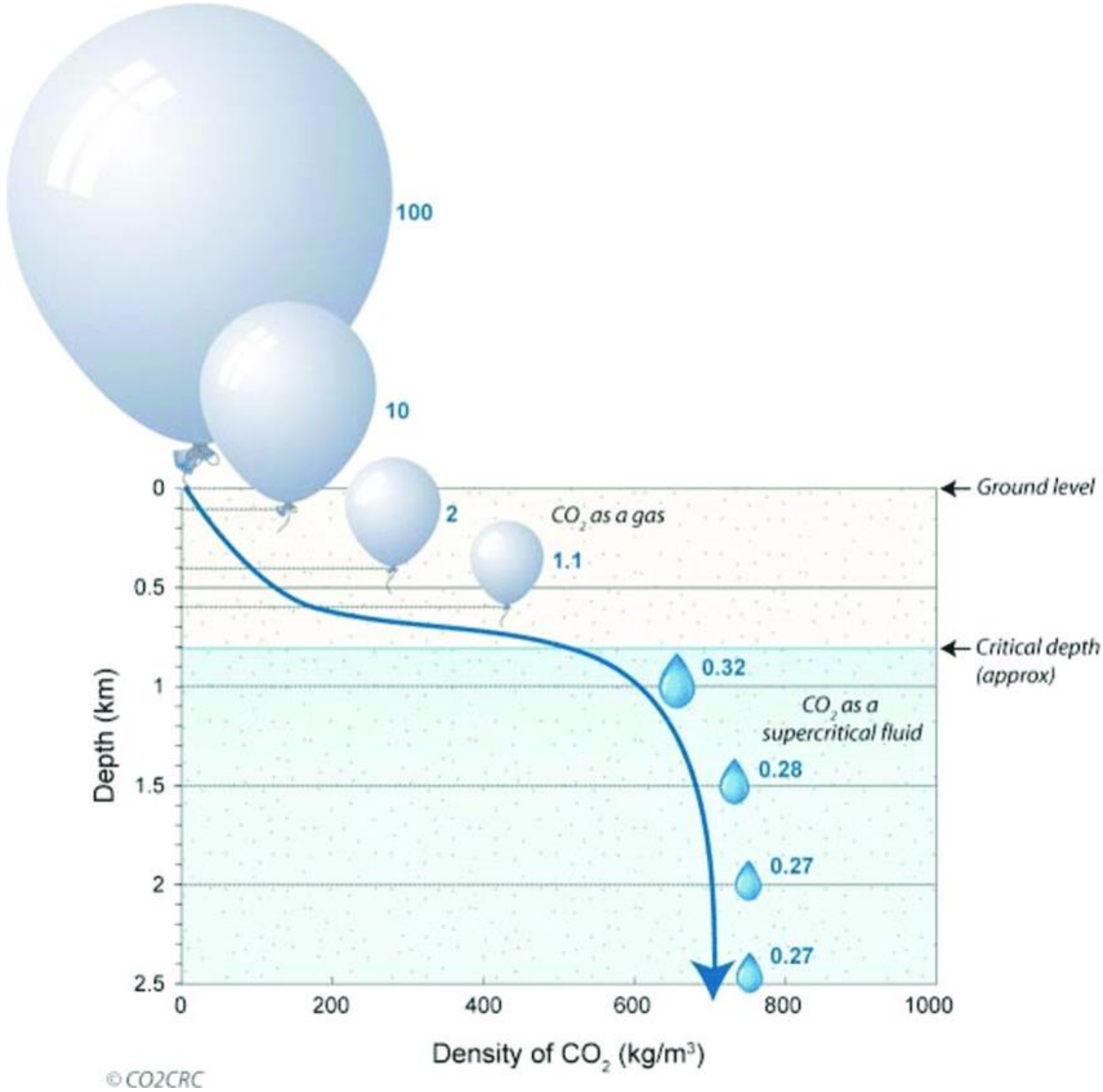

Figure 15. Schematic diagram showing change of CO_2 density and volume with depth of storage (CO2CRC).

Storage mechanisms

Containment of the CO_2 can occur in various ways and over various time scales, with storage security generally increasing over time (see Figure 16). Structural trapping is the process of trapping free-phase CO_2 by buoyancy in a closed structure below an impervious seal in a manner similar to naturally occurring oil, gas, and other gases (e.g., natural carbon dioxide) accumulations. As the supercritical CO_2 moves through the reservoir rock, capillary forces occur between the CO_2 as a nonwetting phase and the saline formation water as the wetting phase. Once the main CO_2 plume has passed through the rock, small droplets of the CO_2 will remain trapped in the centre of each of the pores and become immobilized by imbibition of formation water; a process termed residual trapping.

When CO_2 is injected into a saline aquifer, it will gradually dissolve into the formation water resulting in a CO_2-enriched water. As such a solution is slightly denser than CO_2-free water, buoyancy forces will induce the CO_2-saturated water to migrate downwards. This process may occur when the CO_2 is contained within a structural trap or when it is migrating through the pores of the reservoir rock as it rises by buoyancy from the injection point. The process occurs over slightly longer time periods and is referred to as solubility trapping. CO_2 dissolved in water is also available to react with the rock framework in the form of mineral dissolution or precipitation. Some of these geochemical processes (i.e. dissolution and precipitation of calcite) can occur early in the injection process and impact on injectivity. However, trapping large volumes of carbon permanently via mineral trapping of CO_2, will take hundreds to thousands of years, depending on the mineralogy of the reservoir rock.

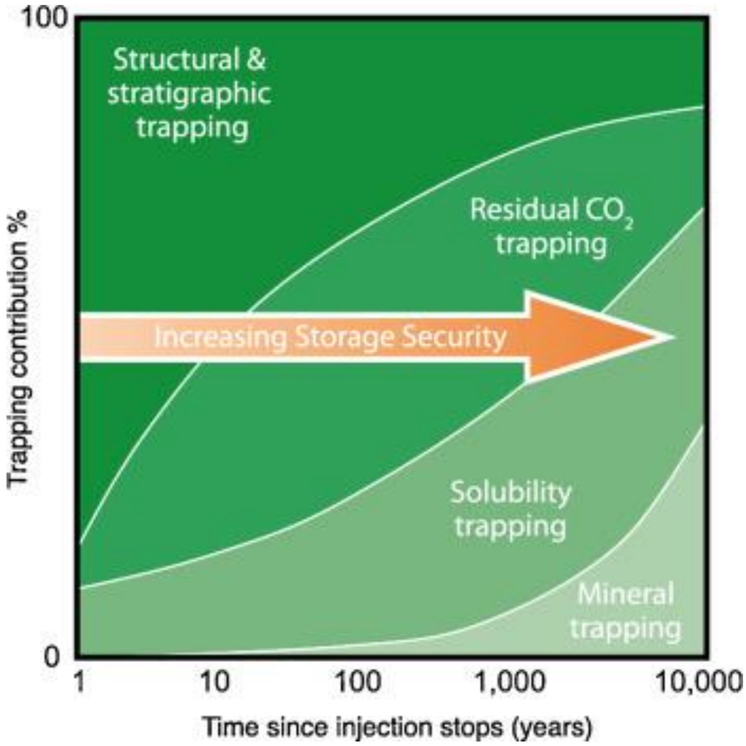

Figure 16. Schematic showing the relative importance of CO_2 trapping mechanisms over time (IPCC, 2005).

A CO_2 storage complex consists of a porous reservoir formation (e.g., sandstone, carbonate) and a low permeability sealing formation (e.g., shale, evaporite) with the following requirements to avoid atmospheric emissions:

1. The reservoir formation needs to have sufficient storage capacity for storing the anticipated volume of CO_2.
2. The reservoir formation needs to have adequate injectivity (as defined by permeability and thickness of the reservoir rock) for accepting CO_2 at the desired injection rate. The most important constraint is that the bottomhole injection pressure should remain below the formation fracture pressure, which may require additional water production wells for controlling reservoir pressure and re-injection of the produced water (aquifer reinjection).

3. The sealing formation and geological structure of the reservoir complex need to ensure the containment of the injected CO_2.

Storage options

The most feasible options for industrial-scale CO_2 geological storage based on existing experience are depleted oil and gas reservoir and deep saline aquifers (Figure 17). Less promising options, either due to the lack of successful demonstration projects or low prospective storage volumes, include storage in coal seams, or surface dissolution of CO_2 in water and injection into basalts or shallow aquifers.

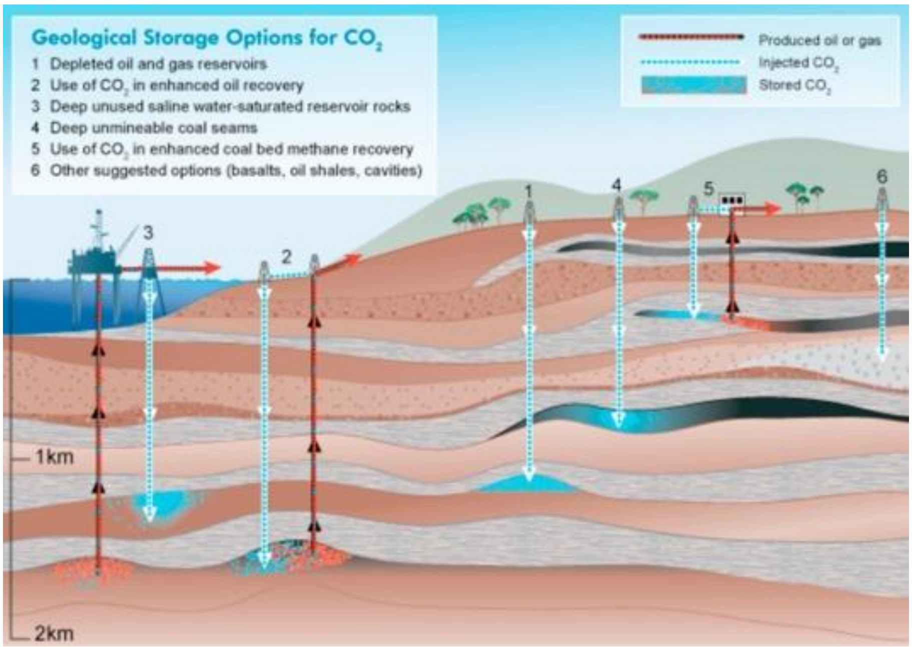

Figure 17. Geological storage options (CO2CRC).

Depleted oil and gas reservoirs have the advantages that the previous accumulation of hydrocarbons demonstrates successful containment characteristics, there is abundant geological and operational data for site characterisation, and existing infrastructure (wells, pipelines) may be repurposed for CO_2 injection. Saline aquifers, on the other hand, would require more effort with respect to data collection and interpretation and development of new injection facilities. However, prospective storage capacity, although more uncertain, is generally significantly larger.

The Global CCS Institute publishes an annual report on the Global Status of CCS, and in 2023 a total number of 41 CCS facilities were in operation with a capture capacity of 49 $MtCO_2$/year (Global CCS Institute, 2023). In some parts of the world a portion is used for enhanced oil recovery (EOR) projects and while approximately 20% was stored in saline aquifers in 2021 (Global CCS Institute, 2021). The CO_2 Storage Resource Catalogue (CSRC) is assessing global CO_2 storage resources using the SPE Storage Resources Management System (SRMS) In 2021, a total storage resource of 96.6 $GtCO_2$ is held within defined storage projects, representing 0.7% of the total 13,954 Gt aggregated storage resource. Of this global total, only 4.1% are classed as Discovered (577 Gt) with less than 0.002% assessed as Commercial (211 Mt).

Impacts of CO_2 geological storage

Impacts from CO_2 geological storage (Figure 18) fall into two categories: a) impacts in response to injection pressures and b) impacts in response to CO_2 and/or brine leakage. Geological characterisation should be most comprehensive within the region of the reservoir containing the carbon dioxide plume and should consider potential leakage pathways like faults and fracture zones (compromised aquitard integrity) and wells (compromised well integrity). Risk- and performance-based monitoring should be focussed on this region, where increases in reservoir pressure and the potential for unplanned migration of CO_2 are highest (Michael et al., 2013; 2016). In the far-field of the projected CO_2 plume, geological characterisation and monitoring should concentrate on identifying potential leakage pathways for CO_2 or displaced formation water.

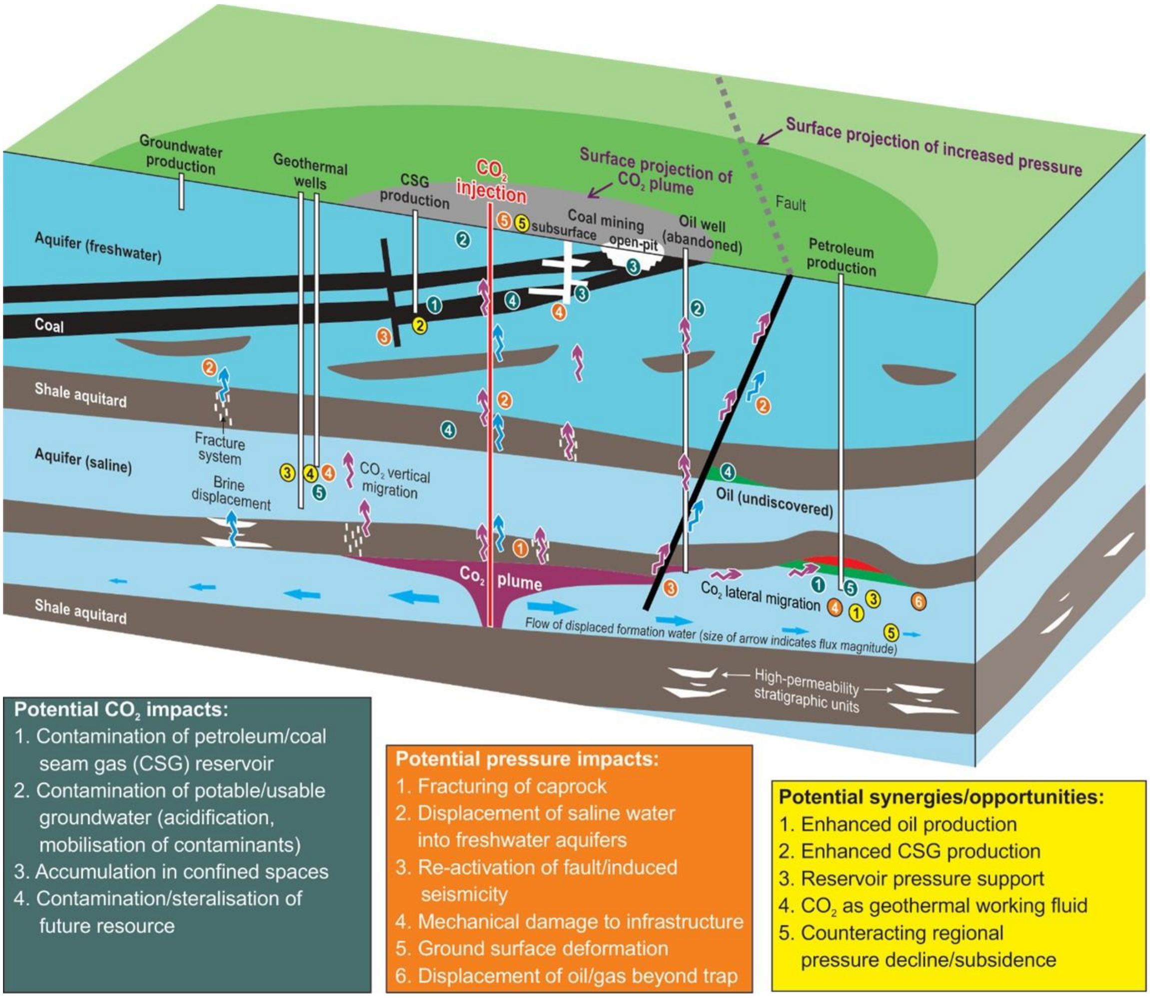

Figure 18. Potential impacts of CO_2 geological storage on other basin resources (Michael et al., 2016). Not to scale.

Monitoring of storage projects

Monitoring and verification (M&V) practices for onshore CO_2 geological storage projects focus on atmospheric emissions, soil and groundwater (seabed and water column for offshore projects) and are dictated by the different project phases (site selection and development, operations, site closure, post-closure). The choice of technologies depends on the monitoring domain (Figure 19) and the role it plays in managing project risk and reporting to the various stakeholders. During site selection, the emphasis is on the monitoring of baseline conditions. Monitoring during the operational phase allows for model calibration and validation, and for the identification of key identifiable events such as deviations from expectations. This is then used to update the risk analysis (as well as various models) and provide performance indicators. M&V is crucial for establishing storage stability and demonstrating key performance criteria are met for site closure and post-closure requirements before the liability can be transferred back to the nation or state.

Monitoring the borehole conditions (e.g., pressure and temperature) and CO_2 distribution (e.g., with seismic) in the storage complex provides the means to confirm storage confinement, whereas the role of M&V in the overburden is to verify non-seepage of the injected CO_2 above the seal (Figure 19).

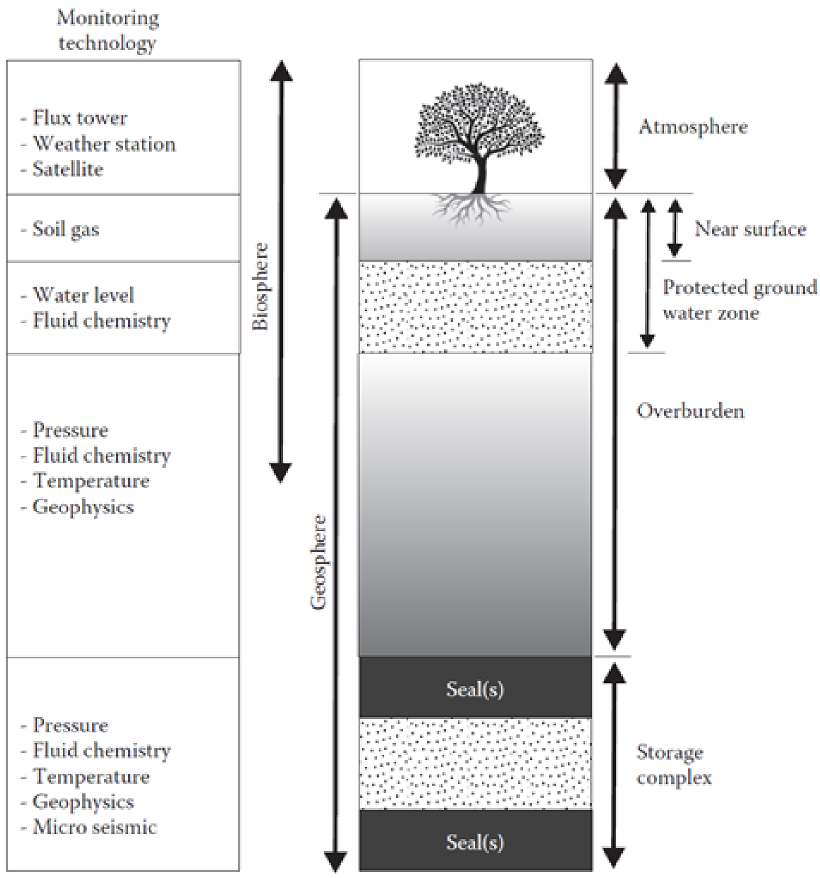

Figure 19. Monitoring domains and technologies for carbon geological storage (Underschultz et al., 2016).

Onshore, the near-surface and atmospheric domain can be achieved by a diverse range of geochemical and gas sensing technologies deployed in grids, down shallow boreholes, and through soil gas accumulators and atmospheric sensing towers. Offshore (Figure 20), high-risk areas such as pockmarks or poorly abandoned wells can be continuously monitored using landers or subsurface moorings with chemical sensors and acoustic sensors (Dean et al., 2020). In supplement to this, areal surveys could be performed at the seabed using autonomous underwater vehicles (AUVs) or remotely operated vehicles (ROVs) for gas bubble detection (Dean et al., 2020).

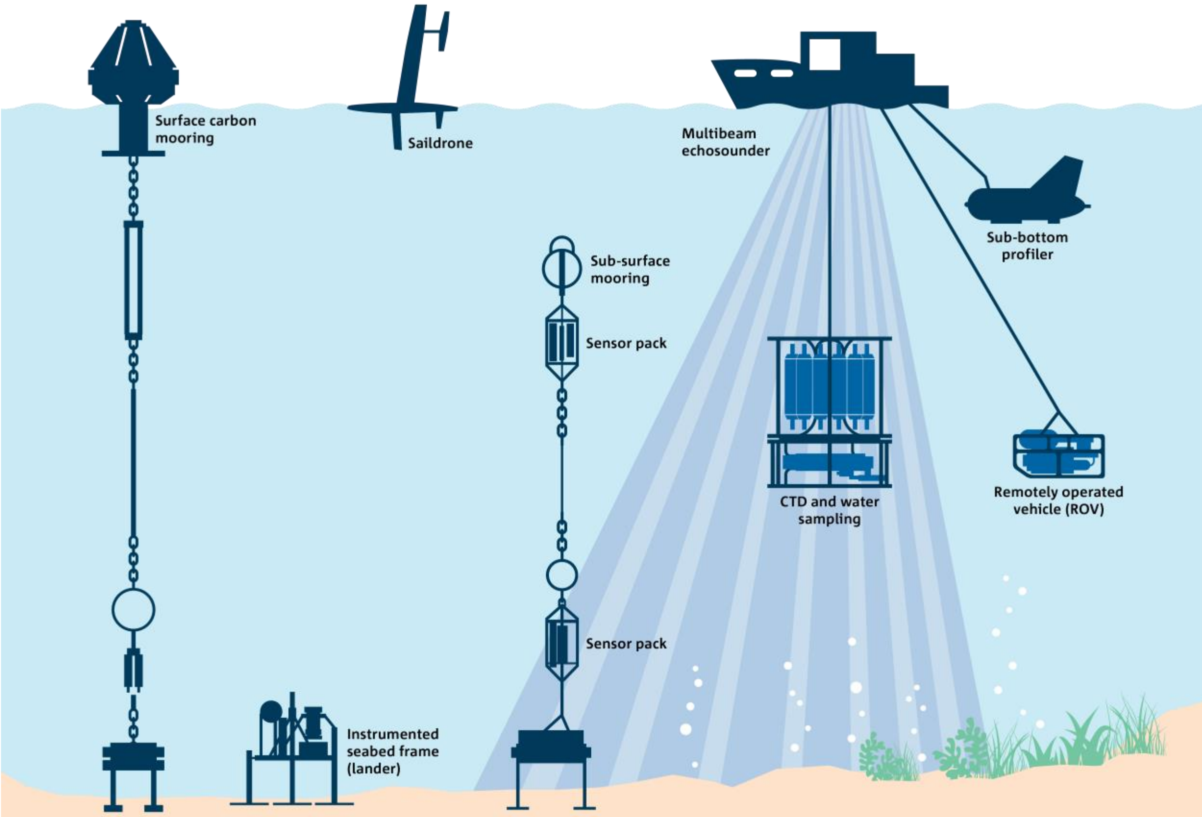

Figure 20. Marine monitoring technologies for CCS projects. www.csiro.au/en/research/natural-environment/oceans/Validating-monitoring-technologies-for-carbon-storage.

Although leakage of CO_2 to this domain is unlikely for a well-designed storage site, it is needed to assure the regulator and public that there are no environmental impacts from the storage operation. The role of M&V also provides the means to verify storage of CO_2 to meet the regulatory conditions and for recovery of carbon credits assigned to emissions abatement (Jenkins et al., 2021).

2.1.3 Assessment

Will the need for Emissions Reductions result in an increase in Carbon Geological Storage?

Key Questions	ANSWERS
Is it possible?	***Yes.*** Carbon capture and geological storage is a viable option for mitigating greenhouse gas emissions as part of an emissions reduction portfolio.
Is it material?	***Yes.*** In the IPCC Special Report "Global warming of 1.5°C" (https://www.ipcc.ch/sr15/), three of the four modelled pathways involve major use of CCS and between 350 and 1200 Gt of CO_2 will need to be captured and stored until 2100. According to the International Energy Agency's Net-Zero Roadmap (https://www.iea.org/reports/net-zero-by-2050), globally around 7.6 Gt/year will need to be captured by 2050.
Can it be monitored	**Yes.** CO_2 injection volumes can be accurately measured at the well head.
Could it be mitigated?	**No**. The only IPCC modelling scenario for achieving the 1.5 °C goal without CCS, requires a significant reduction in global energy demand and the timely installation of sufficient capacity of renewable energy generation. Also, CCS is the only option for mitigating emissions from some of the hard-to-abate industries like steel and cement.
Could it be remediated?	N/A
SUMMARY	**Possible, material and cannot be mitigated.** CCS is an important option for mitigating greenhouse gas emissions as part of an emissions reduction portfolio.

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3 Stressor

3.1 Compromised subsurface integrity

3.1.1 Definition

High-permeability pathways through the confining geological layers/boundaries of a CO_2 storage complex can result in unplanned migration of CO_2 or brine, either laterally, or vertically to shallower formations and the ground surface/seabed.

3.1.2 Description

The main geological reasons for compromised containment integrity and potential CO_2 migration to the overburden include (IEAGHG, 2011; Kaldi et al., 2013; Michael et al., 2013):

- Low top seal capacity = insufficient threshold capillary entry pressure of the caprock to resist the pressure build-up in the CO_2 column.
- Hydraulic fractures – induced by pore pressure increases due to injection exceeding the minimum horizontal stress plus the tensile strength of the rock.
- Insufficient fault sealing potential –
    - insufficient threshold capillary entry pressure of the fault zone material allowing across-fault migration (lateral)
    - high-permeability fault zone material allowing up-fault flow and top seal bypass
- Overpressure due to injection may reduce the effective stress and re-activate faults.

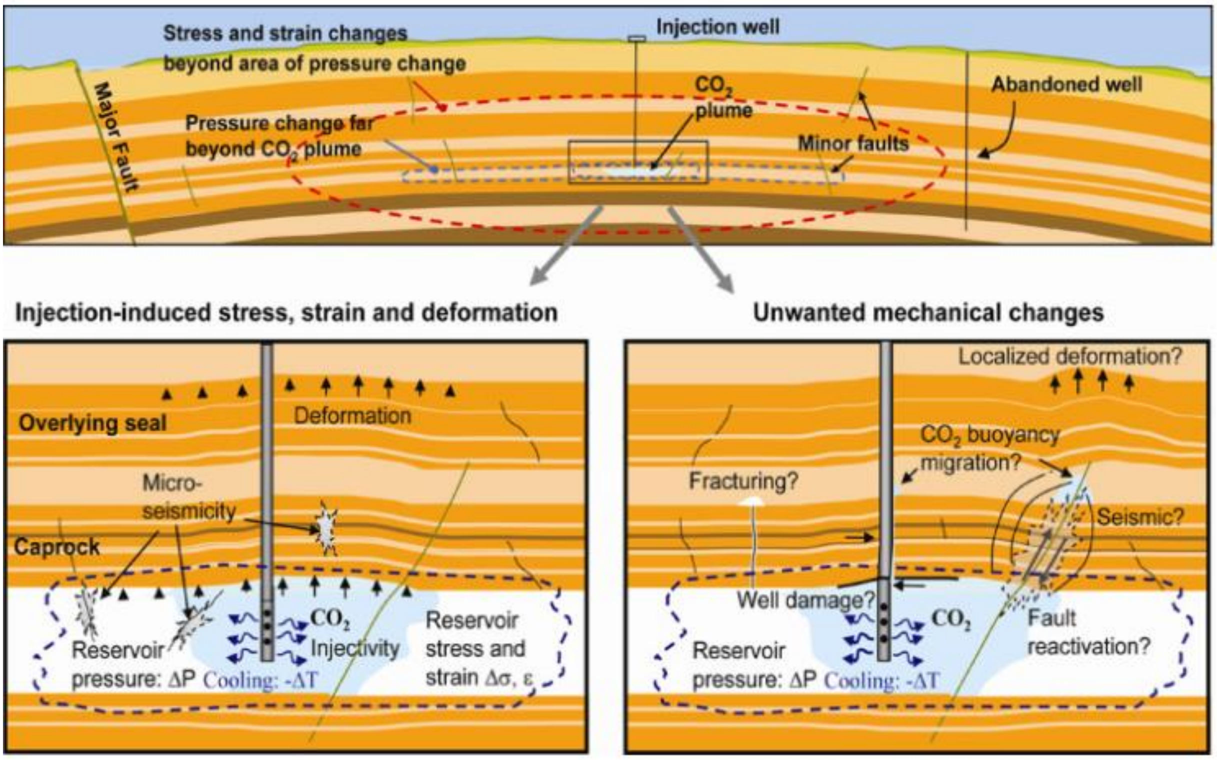

Figure 21. Geomechanical processes and key technical issues associated with CCS in deep sedimentary formations (from Rutqvist, 2012). Top: the different regions of influence for CO_2 plume, reservoir pressure changes, and geomechanical changes in a multilayered system with minor and major faults. Bottom left: injection-induced stress, strain, deformations and potential microseismic events. Bottom right: potential geomechanical damage processes. Not to scale.

Top seal capacity

Seal capacity is defined by the CO_2 column height that the caprock can retain before capillary forces allow the migration of the CO_2 through the caprock. As a non-wetting phase, CO_2 can only pass through a porous material when its phase pressure exceeds that of the wetting phase (formation water) by the capillary threshold pressure. If CO_2 buoyancy pressure exceeds the capillary entry pressure of the top seal, CO_2 can enter the sealing formation and continue to migrate via Darcy-type flow (Rutqvist, 2012; Figure 21).

Natural hydraulic fractures in a top seal may form pathways for CO_2 to leak into overlying formations. Hydraulic fractures form when the pore pressure exceeds the minimum horizontal stress plus the tensile strength of the rock, moving the rock towards the Mohr-Coulomb and/or the composite Griffith-Coulomb failure envelops. This stress state allows the development of shear fractures or hybrid shear-tensile fractures.

Role of faults in CO_2 containment

Faults can act as barriers or pathways for fluid flow depending on their hydraulic properties and stress regime, thereby impacting on the trapping efficiency of buoyant fluids like CO_2. The following two sections on fault leakage are based on IEAGHG (2011), Kaldi et al. (2013) and Michael et al. (2013) and references therein.

Across-fault leakage

Across fault leakage is the lateral migration of CO_2 into aquifers or hydrocarbon reservoirs due to buoyancy and pressure build-up in the storage reservoir. This involves the juxtaposition of permeable reservoirs by faulting, where flow between the reservoirs is restricted by low permeability in the fault. Leakage occurs when fluid pressure is larger than the capillary entry pressure of the fault zone. The assessment of across-fault leakage requires evaluation of the permeability properties of the fault-gouge, which is routinely performed in faulted hydrocarbon field studies.

Along-fault leakage

Along fault leakage involves the vertical migration of CO_2 to an overlying formation or the ground surface due to a breach of the top seal by large-scale faulting, during fault reactivation or by fracture permeability associated with large-scale faulting. In this case, the fault acts as a conductive pathway through the top seal, thereby hydraulically connecting the storage reservoir with overlying aquifers. Possible mechanisms for the creation of a conduit are intimately linked to the build-up and release of geopressured fluids (e.g. Sibson, 1992, 1996; Sleep and Blanpied, 1992), which can result in critical stressing of faults or fault zone fractures (Barton et al., 1995), or slip-induced dilation (Wilkins and Naruk, 2007). Therefore, active, newly formed or reactivated faults intersecting the cap rock are often identified as potential conduits, whereas inactive or non-critically stressed faults are thought to act as barriers (e.g., Sibson, 1987; Muir-Wood and King, 1993; Anderson et al., 1994; Barton et al., 1995; O'Brien et al., 1999; Sanderson and Zhang, 1999; Wiprut and Zoback, 2000; Revil and Cathles, 2002; Chanchani et al., 2003; Ligtenberg, 2005; Wilkins and Naruk, 2007. Along-fault leakage requires the geomechanical determination of the stress state of the fault plane.

Diffusive and advective leakage rates in natural systems

Busch and Kampman (2019) provide an extensive review and assessment of leakage rates in natural systems, which is summarised in this section. Leakage of CO_2 through the caprock can occur through the rock matrix, or via fractures or faults (Figure 22). Leakage rates depend on the thickness of the caprock, (relative) permeability of the caprock/fracture system, capillary entry pressures and whether CO_2 migration is advective or diffusive (Figure 22). Diffusion will be the dominant transport mechanism if the pressure imposed by the CO_2 column does not exceed the capillary entry pressure of the seal matrix (Figure 22f), or that of the fractures and faults (Figure 22a) if present. Mechanisms that will retard CO_2 migration include dispersion, convective mixing, dissolution and trapping (residual, capillary).

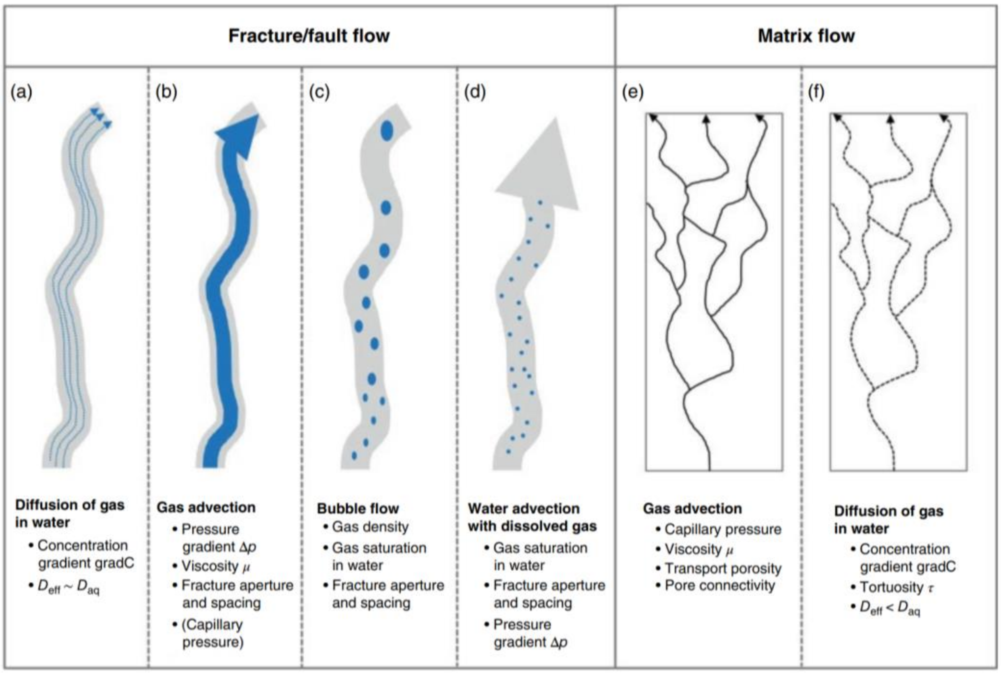

Figure 22. Schematic diagram of leakage mechanisms along faults/fractures (a-d) and through the caprock matrix (e-f) (Busch and Kampman, 2019).

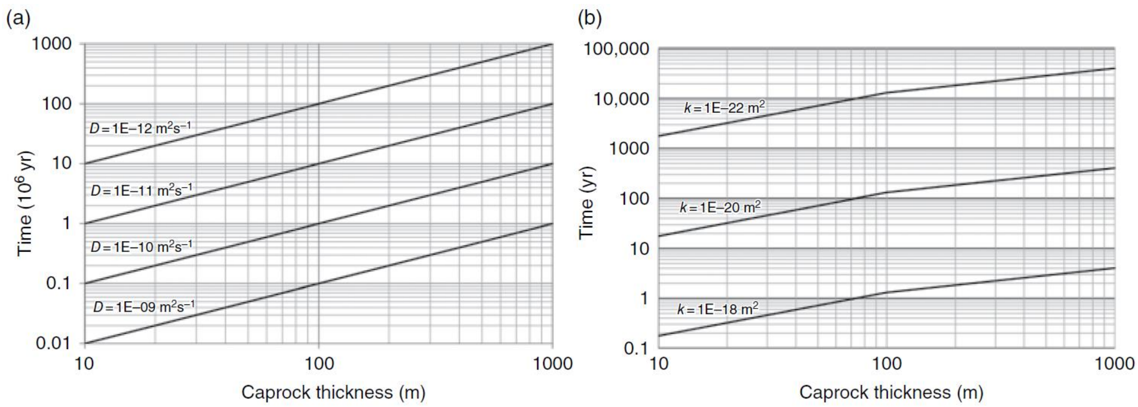

Figure 23.Diffusive (a) and advective (b) travel times through a caprock of varying thickness and permeability. Assumptions and calculation steps given in Busch et al. (2010). The depth of the reservoir-caprock interface is at 2000 m; note that in (a) the time axis is in millions of years. Busch and Kampman (2019).

Fracture flow

Effective diffusion coefficients in fractures (with apertures of the order of 10^{-3}–10^{-5}m) for any gas in brine can be considered close to aqueous diffusion coefficients of the order of 10^{-9} m^2s^{-1}, which is one to three orders of magnitude higher than diffusion coefficients in tortuous pore (nm-sized) system pathways. For example, diffusive leakage across a 10m seal will take 100,000 years, and proportionally longer in the case of larger seal thickness.

In the presence of fractures, leakage via advective flow is likely to occur under reservoir pressure conditions because CO_2 column heights of a few meters would exceed fracture entry pressure of 0.1 –1000 kPa for fracture apertures of the order of 10^{-3}–10^{-5}m (Figure 22b).

The risk of advective leakage through a fractured seal in a depleted hydrocarbon reservoir is relatively small because, as opposed to the seal, reservoir pressures are below original hydrostatic pressures at least at the beginning of injection. In a saline aquifer, however, where reservoir pressure due to CO_2 injection is above hydrostatic, advective flow becomes more likely for open or connected fault and fracture networks with an effective gas permeability that is considered lower than the single-phase brine permeability (Busch and Kampman, 2019).

Matrix flow

The effective gas permeability of seals is up to two orders of magnitude lower compared to their single-phase permeability of typically ranging between $10^{-19} – 10^{-21}$ m^2 (0.01–1 nD) (Busch and Amann-Hildenbrand, 2013; Hildenbrand et al., 2004). Time-scales for CO_2 leakage across seals of various thickness are on the order of 1 –1000 years and on the order of 100,000 – 1 million years for migration from kilometre deep reservoirs across various formations to the surface (Figure 23b, Busch and Amann-Hildenbrand, 2013).

Diffusion of CO_2 through a non-fractured seal with effective permeability diffusion coefficients of the order of $10^{-10} – 10^{-12}$ m^{2}s^{-1} will take more than 100,000 years and is therefore an unlikely leakage mechanism from deep CO_2 geological storage (Busch and Kampman, 2019).

Leakage retarding mechanisms

Flow and mixing processes will enhance rates of CO_2 dissolution when coming into contact with formation water during migration, which involves a) large-scale dispersive mixing of fluids in fracture networks, b) mixing of brine and CO_2 with freshwater in aquifers penetrated by the fracture networks, and c) gravity-driven convective mixing of dense CO_2-saturated water with low-density low-salinity water in overlying aquifers (Busch and Kampman, 2019). The dense CO_2-saturated brines will tend to sink relative to the background formation waters, and then flow laterally along the base of the aquifer driven by the density contrast and regional groundwater flow.

Generally, advection, dispersion, convection and dissolution processes will reduce the volume of free-phase CO_2 migrating to the surface. However, these processes are difficult to quantify at the basin-scale because it is not trivial to adequately account for these multi-scale and interrelated processes in numerical simulations (Busch and Kampman, 2019).

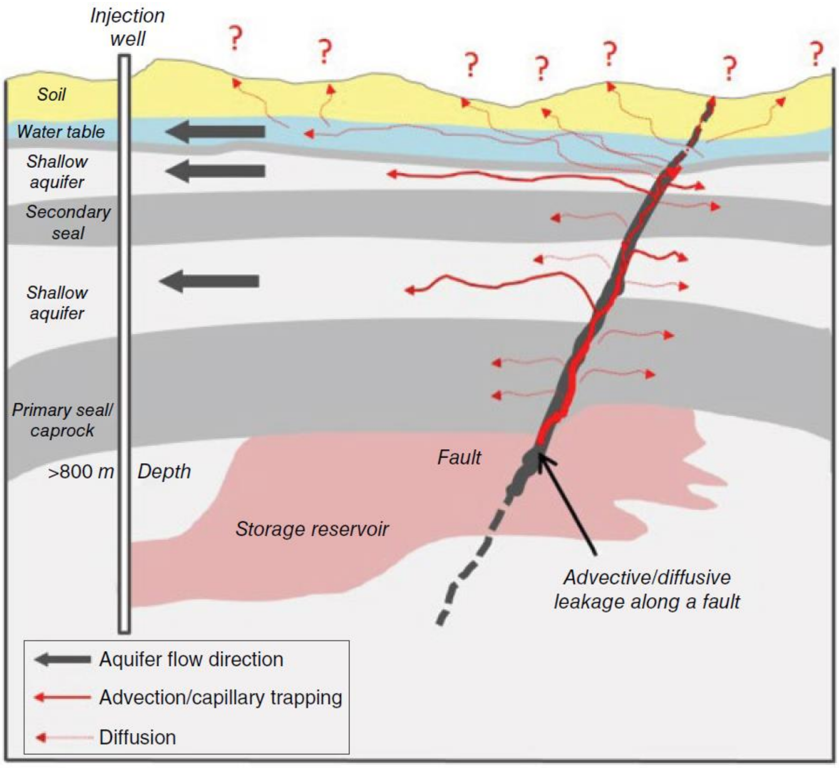

Figure 24. Conceptual model for potential fault leakage by CO_2 advection and diffusion to the surface (Busch and Kampman, 2019).

Mitigation and remediation options

The immediate response to the detection of a CO_2 leak would be to stop injection to relieve reservoir pressure and reduce the driving force for leakage, followed by investigating the nature of the leak. Depending on the location and type of leak, well-related or geological, suitable mitigation can be investigated. Castaneda-Herrera et al. (2019) reviewed different possibilities of materials and techniques that may seal or avoid leakage of CO_2 and categorized these into two main groups in Table 5. Examples of hydraulic barrier and chemical barrier formation are shown schematically in Figure 25.

Table 5. Technologies for mitigation and remediation of CO_2 leakage (Castaneda-Herrera et al., 2019).

Barrier formation group	Material/ technology	Leakage pathway	Chemical resistance to CO_2	Stage of research for CO_2 storage	Disadvantages
High-viscosity fluid based	Cements	Engineered	Low	Applied in the field	Degradation under CO_2 conditions
	Geopolymers	Engineered	High	Ongoing lab research	Manufacture needs development procedures
	Gels	Engineered/natural	Medium	Ongoing lab research	Not suitable for sealing at high pressures
	Nanoparticles	Engineered/natural	High	Ongoing lab research	Immobilization of CO_2 will not occur with difference in viscosity
Low-viscosity fluid based	Biomineralisation	Natural	Medium	Ongoing lab research	Growth of microbial communities
	Hydraulic barrier	Natural	N/a	Ongoing simulation research	Requires certain geological conditions and brine availability
	Chemical reactive barrier	Natural	Medium	Ongoing lab research	Depends on precipitation rates and fluid mixing

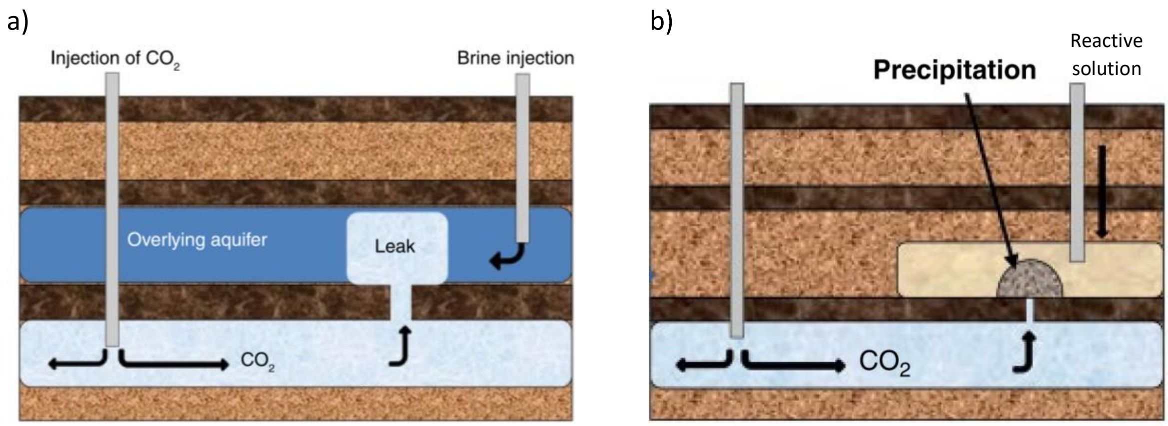

Figure 25. Schematic scenarios of a) hydraulic barrier and b) reactive barrier formation (from Castaneda-Herrera et al., 2019).

Quantification of CO_2 leakage due to compromised subsurface integrity

Natural analogues

Due to the absence of sufficient examples of leakage in man-made CO_2 storage reservoirs, physical constraints on leakage mechanisms and rates are typically derived from natural analogues. Busch and Kampman (2019) conclude that most analogues reviewed and discussed in the literature (i.e., Lewicki et al., 2007; IEAGHG, 2011 and references therein; Roberts et al., 2015; Roberts and Stalker, 2020) for CO_2 storage are shallow reservoirs of CO_2-charged fluids or gas in tectonic or volcanically active areas, which are not directly analogous to CO_2 leakage from an industrial storage operation. No quantifiable CO_2 fluxes from deep natural geological sedimentary reservoirs (> ~1000m) have been reported, which suggests that the risk and probability of significant CO_2 leakage from an industrial CO_2 storage reservoir to the atmosphere is small.

Generic models

Kivi et al. (2022) assessed basin-wide upward CO_2 migration over geological time scales through reservoir simulations and concluded that material vertical leakage of CO_2 through multiple sedimentary layers is unlikely to occur. Even if intervening aquitards are strongly fractured, the consecutive layering of low-permeability formations, residual trapping and CO_2 dissolution will greatly impede the migration of CO_2 to shallow formations (Figure 28).

Gilmore et al. (2022) developed an analytical model for leakage of a buoyant plume along a fault cutting through various reservoir and seal lithologies. The model accounts for increased pressure gradients within the fault due to an increase in Darcy velocity directly above the fault and was applied to natural CO_2 seeps at Green River (Figure 27). The general conclusions are that when the fault permeability is on the same order of, or less than the reservoir permeability, the majority of the CO_2 remains trapped within the storage reservoir after a 1000-year time scale (Gilmore et al., 2022). However, when the fault permeability is larger than the reservoir permeability, there is significant CO_2 leakage all along the fault across multiple seals.

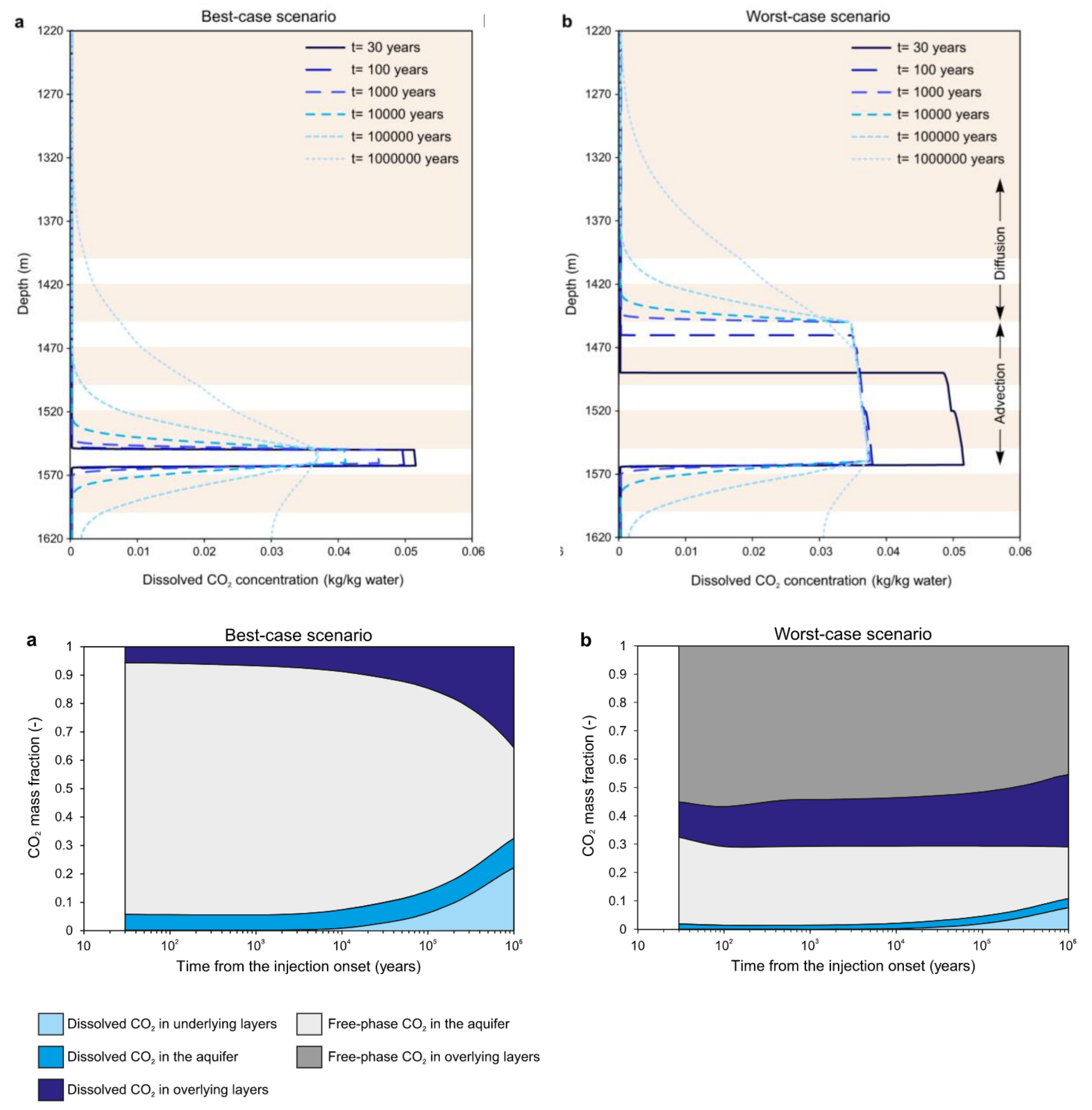

Figure 26. Top: Temporal evolution of the CO_2 concentration along a sequence of aquifers and caprocks for the (a) best-case and (b) worst-case leakage assessment scenarios. Bottom: Temporal evolution of the CO_2 mass fractions for (a) the best-case and (b) the worst-case leakage assessment scenarios. Kivi et al. (2022).

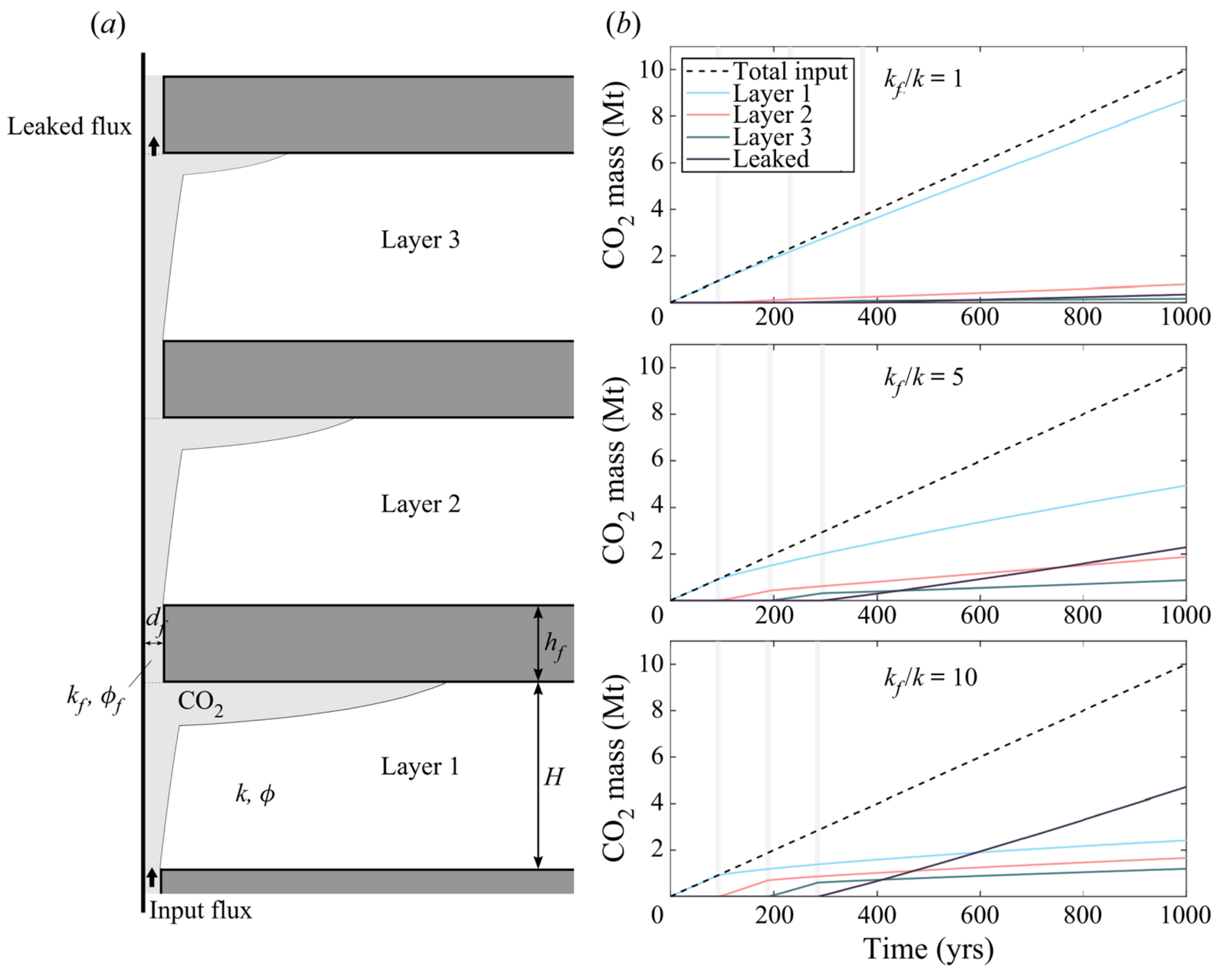

Figure 27. a) Schematic diagrams showing injection of CO_2 into a system with multiple stacked aquifers and seals with a fault cutting through the layers. (b) The total CO_2 mass in each layer and the total leaked CO_2 (leakage from Layer 3 plotted as a function of time for three different values of the fault permeability. The breakthrough time into each layer is marked with a grey vertical line. Gilmore et al. (2022).

Statistical methods

Alcade et al. (2018) developed a numerical program to evaluate CO_2 storage integrity and leakage over 10,000 years accounting for combined leakage through wells and geological features. They reported that a moderate well density has a 50% probability that leakage remains below 0.0008% per year, with at least 98% of the injected CO_2 retained in the subsurface over 10,000 years.

Hoydalsvik et al. (2021), relying on expert judgment from years of experience in operations, was concerned with storage risk in the North Sea, and so developed assessments of leakage probability by various mechanisms. The work built on extensive operators' experience in the North Sea to develop estimates of probabilities (total over 500 years) of the usual key risks; seepage up faults and fractures, leakage up defective wells, and blowouts. The study examined a hypothetical case of storing 100 Mt CO_2 over 50 years. Ten scenarios for leakage were considered with one injection well and one abandoned well, with the conclusion that 99.99 % of the injected volumes can be expected to remain securely underground for at least 500 years. Combined leakage via geological features (i.e., faults, fractures) in their modelling scenarios added up to about 56% of the total risked leakage.

Daniels et al. (2023) modelled leakage probabilities due to geological and well leakage pathways for two representative UK offshore sites over 25 years of injection operations and 100 years of post-injection monitoring, suggesting that more than 99.9% of the injected CO_2 will be retained within the storage complex. For their study, Daniels et al. (2023) compiled and reviewed extensively leakage data and probability assessments associated with subsurface storage from the literature (Figure 28).

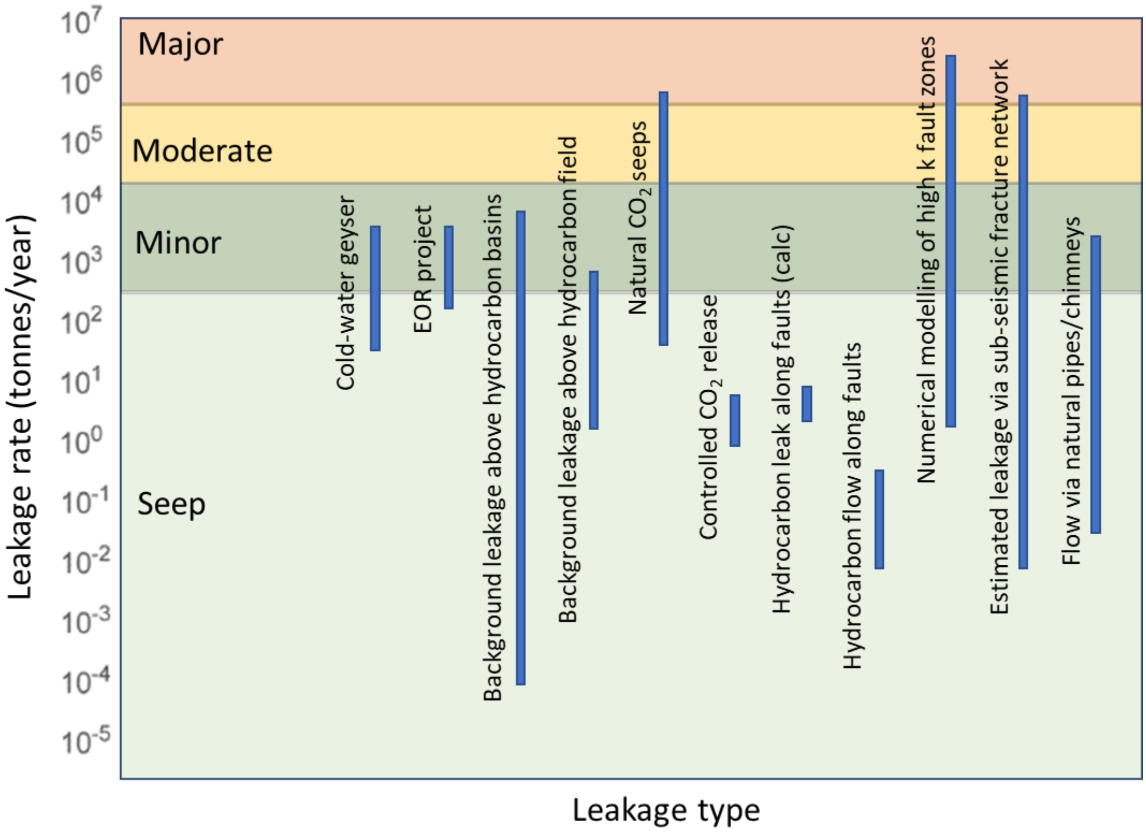

Figure 28. Representative CO_2 leakage rate data (log scale) reported in the literature for geological leakage pathways to the atmosphere (modified from Daniels et al., 2023 and references therein), cold-water geyser data from Watson et al. (2014). The severity of leakage from Seep to Major is defined in Table 6.

The overall leakage risk depends on the severity of the leak (Table 6) and the probability that this type of leak can occur (Figure 29). For two modelled sites designed to reflect the features of storage in depleted fields and saline aquifers, Daniels et al. (2023) estimate overall leakage volumes to be small (less than 0.1 %), with leakage from geological feature deemed to be comparatively higher in the saline aquifer case.

Table 6. Severity of geological leakage rates and pathways (Daniels et al., 2023).

Leak Category	Leak Rate	Description
Seep	< 1 t/d (< 365 t/year)	Possible geological leakage pathways include pre-existing pathways (fault & fractures, induced fractures, gas chimneys /pipes including combined pathways with lateral migration) and induced faults or fracture networks. Leaks are easily dispersed or absorbed into sea water. Detected through testing and targeted monitoring. If they occur, they are expected to be continuous and difficult to remediate.
Minor Leak	1 – 50 t/d	Possible geological leakage pathways include pre-existing pathways in a depleted field (up to ~3 t/d) or saline aquifer (up to 50 t/d) and induced faults or fracture networks (up to ~30 t/d). Detected on repeat seismic survey (once accumulated at sufficient concentration), or seabed / water column monitoring if the leak has extended to surface.
Moderate Leak	50 – 1000 t/d	Possible geological pathways include leakage along a large fault. Sites along a large fault are unlikely to be viable CO_2 storage sites, they would require significant regulatory scrutiny to prove they were sealing (for example, evidence of different fluid regimes across the caprock). Detection by seismic survey, or seabed / water column monitoring.
Major Leak	> 1000 t/d (> 365,000 t/year)	Possible geological pathways include leakage along a large fault. Sites along a large fault are extremely unlikely to be viable CO_2 storage sites, they would require significant regulatory scrutiny to prove they were sealing (for example, evidence of different fluid regimes across the caprock). Detection by seismic survey, or seabed / water column monitoring.

Two modelled sites were designed to reflect the features of depleted fields and saline aquifer stores within permitted storage complexes. Worst-case leakage volumes from geological features in depleted fields and saline aquifers were estimated to be 0.002% and 0.024%, respectively compared to respective well leakage volumes of 0.07% and 0.06%. Overall leakage volumes are estimated to be less than 0.1 % of the total storage volume. In other words, leakage via geological features is more likely for saline aquifer storage than for storage in depleted fields, but less probable than well leakage in general. The most likely geological features potentially contributing to seeps or minor leaks are sub-seismic fault/fracture zones, re-activated or newly initiated faults/fractures and gas chimneys. Moderate to major leaks would be associated with major tectonically active fault zones or large block bounding faults, which would be largely avoided when following the appropriate site selection and characterisation processes.

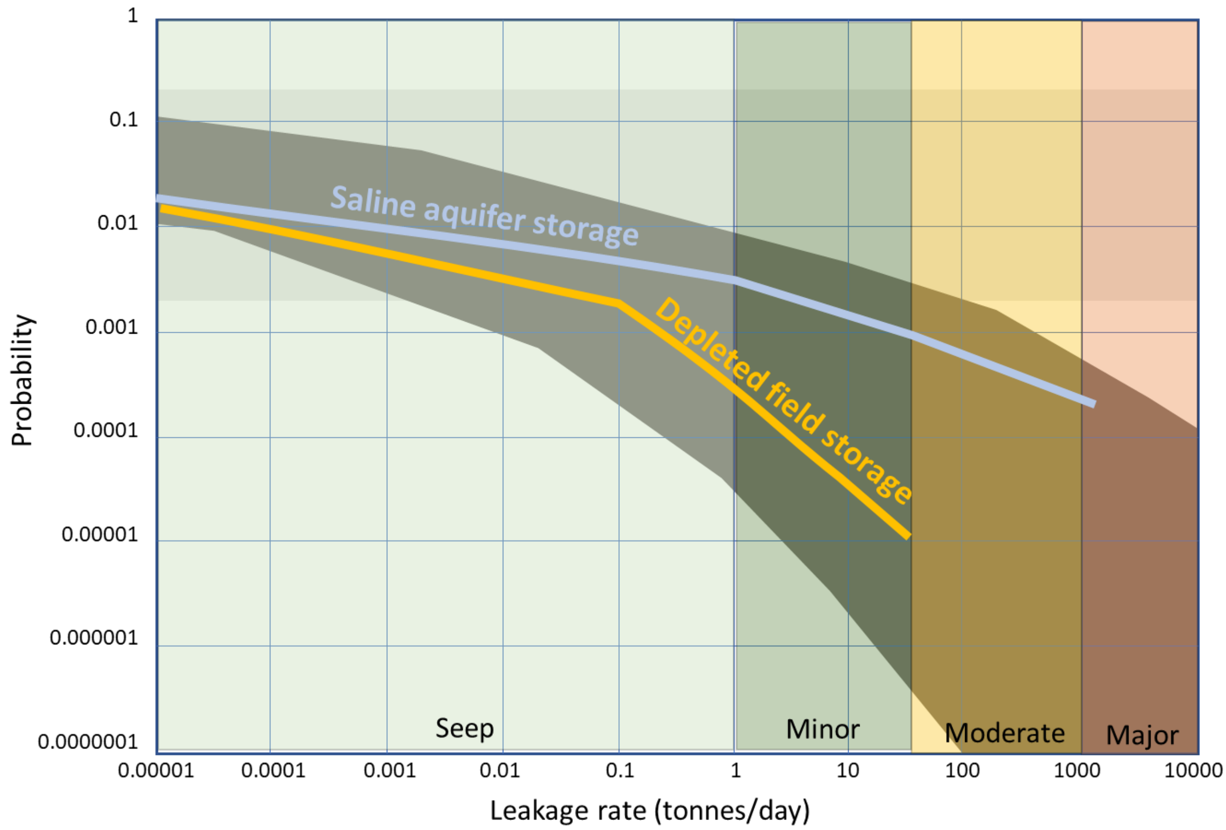

Figure 29. The probability of leakage through natural systems (modified from Daniels et al., 2023). The grey area represents the range of probability estimates of leakage from the literature. The blue and orange lines approximately depict the probability ranges of leakage used by Daniels et al. (2023) in their assessment of CO_2 storage sites in the North Sea in saline aquifers and depleted fields, respectively. Leakage severity from Seep to Major are defined in Table 6.

3.1.3 Assessment

Will carbon geological storage result in or encounter compromised subsurface integrity?

Key Questions	ANSWERS
Is it possible?	***Yes.*** Subsurface geology is inherently heterogenous and can only be directly assessed through the drilling of wells, or indirectly through geophysical methods like seismic. Therefore, any geological characterisation of a storage complex and inferred containment integrity will have some degree of uncertainty depending on the available data. Depleted oil and gas reservoirs have demonstrated the containment of hydrocarbons for millions of years and generally have abundant well and geophysical data available to suggest adequate containment of injected CO_2. Still, there are examples of 'leaky' hydrocarbon reservoirs, some of which would have been discovered due to surface leakage indicators in the first place. In comparison, saline aquifers are generally less well characterised initially and may require the drilling of wells and geophysical surveys to adequately assess containment security. The increase in reservoir pressure can also enhance or create flow paths, i.e., • if the bottomhole injection pressure exceeds the fracture pressure of the reservoir formation, fractures can be formed that enhance fluid flow within the reservoir or, if propagating into the sealing formation, create vertical leakage pathways. See In Salah example (Stork et al., 2015). • The reactivation pressure of a fault within or in the vicinity of the storage complex, the fault may be reactivated, i.e., induced movement along the fault plane may displace sealing formations or create increased permeability pathways that enhance fluid flow.

<table>
<tr><td>Is it material?</td><td>No. The literature review by Daniels et al. (2023) suggests following probability ranges for different leak types and summarised for all geological features:
<table>
<tr><td rowspan="2">Leak category</td><td rowspan="2"></td><td colspan="2">Probability of defined leak rate occurrence/well</td></tr>
<tr><td>Maximum</td><td>Minimum</td></tr>
<tr><td colspan="4">Depleted fields</td></tr>
<tr><td>Seep (<1 t/day)</td><td></td><td>1 in 400</td><td>1 in 5000</td></tr>
<tr><td>Minor (1-50 t/day)</td><td></td><td>1 in 2000</td><td>1 in 100,000</td></tr>
<tr><td>Moderate (50-1000 t/day)</td><td></td><td>negligible</td><td>negligible</td></tr>
<tr><td>Major (>1000 t/day)</td><td></td><td>negligible</td><td>negligible</td></tr>
<tr><td colspan="4">Saline aquifers</td></tr>
<tr><td>Seep (<1 t/day)</td><td></td><td>1 in 80</td><td>1 in 333</td></tr>
<tr><td>Minor (1-50 t/day)</td><td></td><td>1 in 200</td><td>1 in 1,000</td></tr>
<tr><td>Moderate (50-1000 t/day)</td><td></td><td>1 in 1,100</td><td>1 in 2000</td></tr>
<tr><td>Major (>1000 t/day)</td><td></td><td>negligible</td><td>negligible</td></tr>
</table>
To date, there is only one reported incident of compromised subsurface integrity, In Salah, from a small number of existing CO_2 storage operations. The In Salah incident occurred due to erroneously injecting above fracture pressure in a relatively low-permeability reservoir, where CO_2 migrated at unquantified rates outside the specified storage complex but not to the atmosphere.
The table by Daniels et al. (2023) and the case studies show that compromised subsurface integrity due to carbon geological storage operations can locally be material. However, the probability of its occurrence when storing CO_2 at a well-characterised sites is negligible for storage in depleted fields and extremely low for saline aquifer storage.</td></tr>
<tr><td>Can it be monitored?</td><td>Yes. Multiple monitoring technologies are available for detecting:
Cautionary: Micro-seismic events
Critical: Wellhead injection pressure = fracture pressure of the reservoir rock or = fault re-activation pressure</td></tr>
<tr><td>Could it be mitigated?</td><td>No. There will always be some uncertainty with respect to the geology. However, encountering compromised subsurface integrity can be minimised by:

Following best practise site selection and characterisation (i.e., ISO/TC 265, various national guidelines);
Adhering to maximum injection pressures below the fracture pressure/fault reactivation pressure
Early leakage detection and timely stop of injection
</td></tr>
<tr><td>Could it be remediated ?</td><td>No. Remediation of geological leakage pathways is challenging because these are generally difficult to locate, can be of a diffuse nature and are therefore difficult or expensive to access, for example by drilling new wells for creating hydraulic barriers or injecting sealing material.</td></tr>
<tr><td>SUMMARY</td><td>Possible, can be material, and cannot be mitigated. Although leakage from geological leakage pathways like fault or fracture zones can be material in individual cases, the probability of its occurrence when storing CO_2 at a well-characterised site is negligible for storage in depleted fields and extremely low for saline aquifer storage.</td></tr>
</table>

3.1.4 References

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3.2 Compromised well integrity

3.2.1 Definition

The compromised well integrity refers to breaches of a well system that allows the unintended movement of fluids (in this case CO_2) within or along a well.

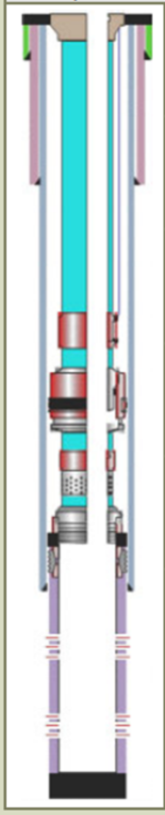
3.2.2 Description

If the hydraulic integrity of wells is compromised, this can lead to leakage of injected CO_2 or brine from the storage complex into shallower geological formations (including potable aquifers) or the ground surface/atmosphere. As wellbores can potentially form direct conduits between geological layers and to the surface, they are usually seen as an important subsurface risk (e.g. Zhang and Bachu, 2011). Wells that may potentially form leakage pathways include the CO_2 injection well(s), monitoring or pressure management wells, other production/injection wells, or abandoned wells (legacy wells) in the assessment area.

Wells injecting CO_2 must have effective technical or engineered barriers that prevent hydraulic communication between the storage reservoir and overlying aquifers. This includes proper isolation between the well annuli, and between the well casing and the external environment. The design of a CO_2 injection well typically involves at least two strings of casing, including surface casing to isolate the well from the potable groundwater aquifers (Tsang et al., 2008) and production casing. Inside the casing string, the CO_2 is injected through a separate tubing string with a corrosion resistant liner. Figure 30 shows the downhole assembly and specifications of a typical injection well. To prevent corrosion inside the well, the injected CO_2 should be sufficiently dehydrated and in a supercritical state.

Cements between the well casing and the formation are used to prevent vertical leakage along the borehole (Rutqvist, 2012). Adequate cement placement and tight bonding between borehole and casing are the primary requirements for achieving good isolation (Cooper, 2009 and references therein). Protecting against cement degradation in an acidic environment can be ensured by using specific CO_2 resistant cements (Barlet-Gouedard et al., 2006;2009; Benge and Dew, 2005; Yang et al., 2016). There is a large amount of literature that assesses geochemical interactions between well cements and CO_2 (e.g., Carey et al., 2007; Jacquemet et al., 2007; Kutchko et al., 2007; Connell et al, 2015).

Cement plugs in combination with other materials are used for abandoning wells, to form a vertical flow barrier inside the borehole after injection has ceased (Cooper, 2009; Figure 31). However, old, abandoned wells that may lack or have an incomplete installation of a technical barrier, could provide possible leakage pathways and represent a potential risk for vertical migration of CO_2 (Nordbotten et al., 2009).



Description	Potential Risks and Concerns	Materials
Tubing Hanger	CO_2 corrosion may be associated with well back-flushing provision and process interruptions.	CRA - Generally high Nickel Content
Conductor Casing	Some aquifers have a potential external corrosion risk.	Carbon steel - consider external coating.
Surface Casing		Carbon steel.
Injection Tubing	Provision for periodic back-flushing and process up-sets may yield water exceeding 8,000 mpy	GRE lined Carbon Steel or CRA.
Production Casing	Metallurgy in accordance with industry standards for any contaminants in CO_2.	Carbon Steel - Surface to immediately above base of sealing formation.
Production Liner	Process upsets & provision for back-flushing may result in high water content CO_2 in the injection zone. Also there may be contaminants in the CO_2 such as H_2S.	CRA. Industry standard if required for applicable contaminants.

Abbreviations used: CRA = Corrosion Resistant Alloy; GRE = resin epoxy; NACE = National Association of Corrosion Engineers.

Figure 30. Possible well design for CO_2 injection (from Cooper, 2009).

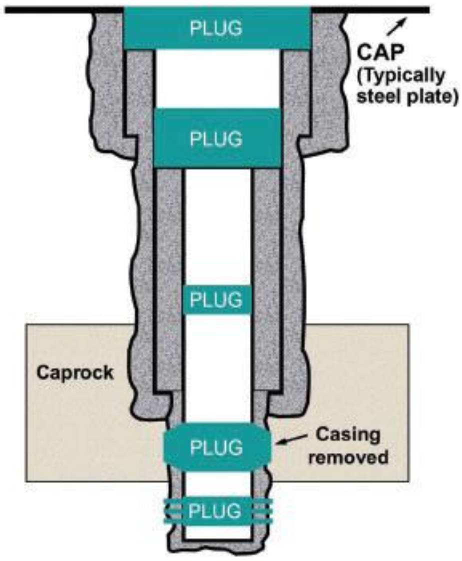


Figure 31. Typical Plug and Abandonment schematic diagram, showing from bottom-up: plugged injection zone, plug in cap-rock interval which includes drilled casing; plug above caprock, plugs at top of casing and steel plate at surface (Cooper, 2009).

Well leakage pathways

The most likely leakage pathways along a well are depicted in Figure 32 and include fluid migration along interfaces where there is insufficient bonding between the rock and cement or between the casing and cement (Gasda et al., 2004; Nordbotten et al., 2005, 2009). Other risks of fluid migration, particularly in old wells are associated with cement fractures, holes in the plug casing, space between the cement and plug casing, and flow through the cement matrix (Nordbotten et al., 2005, 2009; Rutqvist, 2012). When investigating the risk of leakage through a well, the following aspects need consideration (Orlic, 2009): a) the mechanical impact of CO_2 injection on the integrity of cement, casing and well construction materials (cement and steel); b) the long-term corrosion of cement and steel casing by carbonic acid.

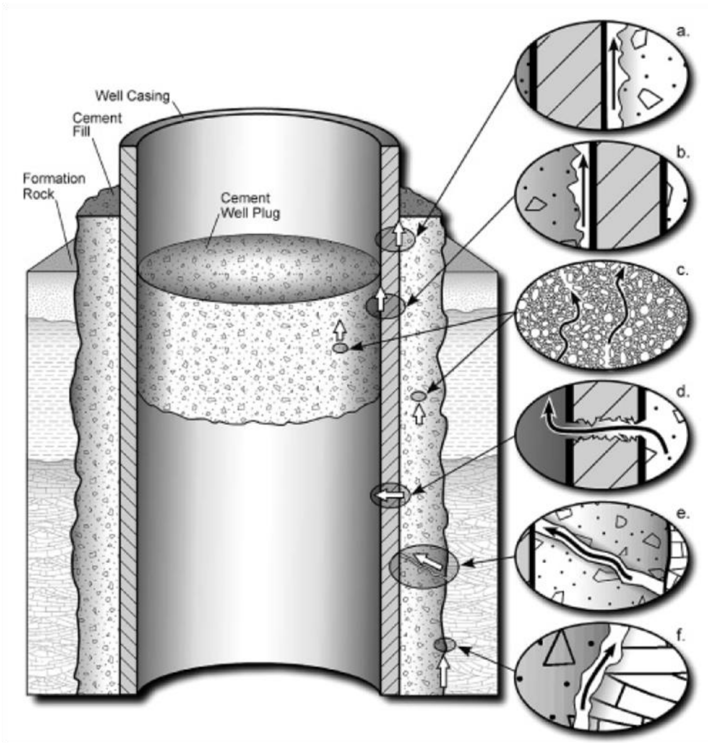


Figure 32. Diagrammatic representation of possible leakage pathways through an abandoned well. a) Between casing and cement; b) between cement plug and casing; c) through the cement pore space as a result of cement degradation; d) through casing as a result of corrosion; e) through fractures in cement; and f) between cement and rock (Gasda et al., 2004).

Well blow outs

The most extreme case of leakage up wellbores is when injected CO_2 flows up the wellbore uncontrollably driven by buoyancy and increased reservoir pressure, which could result in the sudden loss of formation water and CO_2 to the atmosphere. A blow out can either occur in the injection well due to a loss of pressure control, if the wellhead and injection system are compromised, or in damaged wellbores that penetrate the CO_2 plume. Rare examples of CO_2 leakage in the past were associated with CO_2 enhanced oil recovery (EOR) projects, including blowouts of production wells drilled into natural CO_2 reservoirs, CO_2 injection wells, active oil production wells, or plugged and abandoned wells within the EOR scheme (Duncan et al., 2009). These incidents were largely related to corrosion or general failure of mechanical components in the well or the pump. Well blowouts involving CO_2 are rare occurrences and the last fully documented case is the Sheep Mountain blowout in 1982 (Lynch et al., 1985).

A special case of a well blow out is a so-called 'coldwater geyser' with periodic eruptions of CO_2 and formation water (Michael and Ricard, 2022). Coldwater geysers are due to the degassing of CO_2 dissolved in formation water and volumetric expansion during up-well flow to the atmosphere. When formation water containing CO_2 fluid rises up a well, CO_2 comes out of solution due to a reduction of pressure and temperature. This causes a concurrent decrease in CO_2 solubility in water, which can result in the eruptive expulsion of CO_2 and water (Figure 33). Eruption occurs when bubble flow transitions to slug flow and so-called 'Taylor bubbles' reach a void fraction > 30% (Lu et al., 2005; Figure 33C). The eruption and the preferential up-flow of CO_2 depletes the fluid of gas, reducing and eventually removing the driving force for enhanced discharge until recharge of CO_2 from the reservoir starts a new eruption cycle (Figure 33E). A CO_2-driven well geyser is unlikely to occur at an adequately characterised site and only occurs at depths shallower than 400 m, which would require the improbable case of leakage of CO_2 forming a secondary accumulation of a significant volume of CO_2 at shallow depths (Michael and Ricard, 2022).

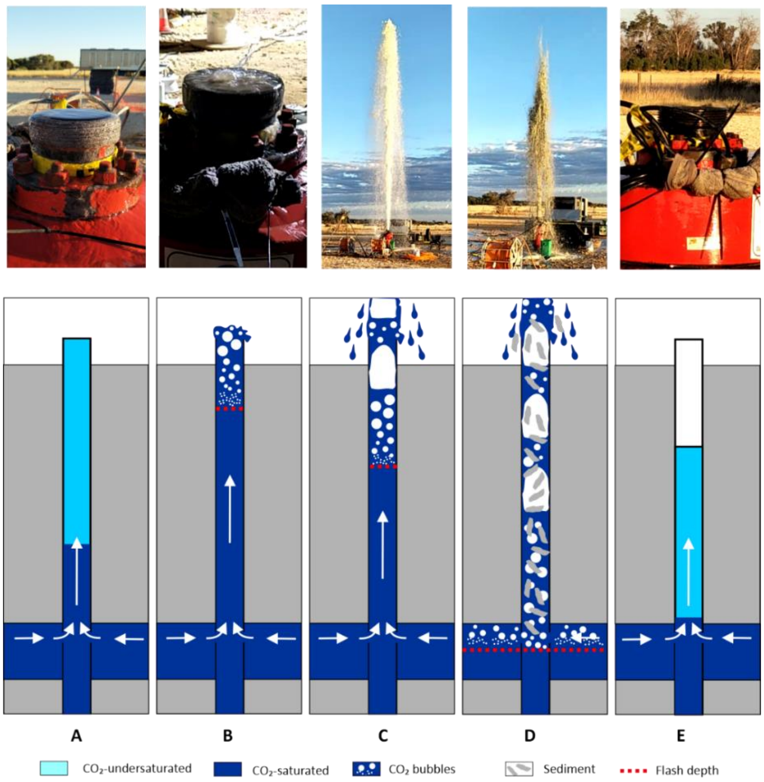


Figure 33. Conceptual representation of the various stages of well geysering (modified from Watson et al., 2014) matched to field photos from the CSIRO In-Situ Lab (Michael and Ricard, 2022).

Cement integrity

As shown in Figure 32, cement integrity is important for preventing upward fluid migration between the casing and the formation. Portland cement (or derivatives) is the most commonly used cement with the following components: 48% calcium silicate hydrate (C–S–H), 19% portlandite ($Ca(OH)_2$), 18% monosulfate ($Ca_4Al_2(OH)12SO_4.6H2O$), 9% ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$), and 6% others (Carey, 2013). Wellbore cements have the potential to degrade in contact with acidic formation waters resulting from CO_2 dissolution, which can create, enhance or seal fractures in the cement or along the casing-cement and cement-formation interfaces.

A comprehensive review of well cement alteration in CO_2-rich environments including the review of relevant laboratory experiments is provided by Bagheri et al. (2018). While defective cement matrices and bonding between cement and casing were found to form potential leakage pathways, the majority of studies reported self-healing behaviour of cements cracks observed under typical CO_2 storage conditions. However, severe conditions, such as a high acidity brine and high flow velocity, may negatively affect the self-healing behaviour of the cement. More detailed observations by Bagheri et al. (2018) are as follows:

- Experimental studies, generally under static conditions, have identified five zones being developed during the exposure of cement to CO_2 (Figure 34).
- In the presence of cracks, the typically low degree of acidity and long-residence times of CO_2-bearing fluids provide enough time for precipitation of calcium content downstream that narrow or block any flow paths. Only high acidity and short residence times result in the widening of cracks.
- Generally, steel casings are more vulnerable to corrosion than cement. However, scaling on the surface of the casing may prevent further corrosion or may clog the leaking CO_2-bearing fluids.
- Limestone rocks, in contrast to siliciclastics, increase the degree of calcium concentration of CO_2-bearing fluids before encountering the cement, thereby reducing the capability of the fluid to dissolve more calcium from the cement.
- Except for the calcite precipitation zone other affected zones decline in mechanical strength. The resulting increase in compressibility and the confining pressure may result in partial collapse of cracks and prevent moving CO_2-bearing fluids within the cement. However, this process also depends on other parameters such as the acidity, the brine composition, the confining pressure, the pore pressure, and the residence time.

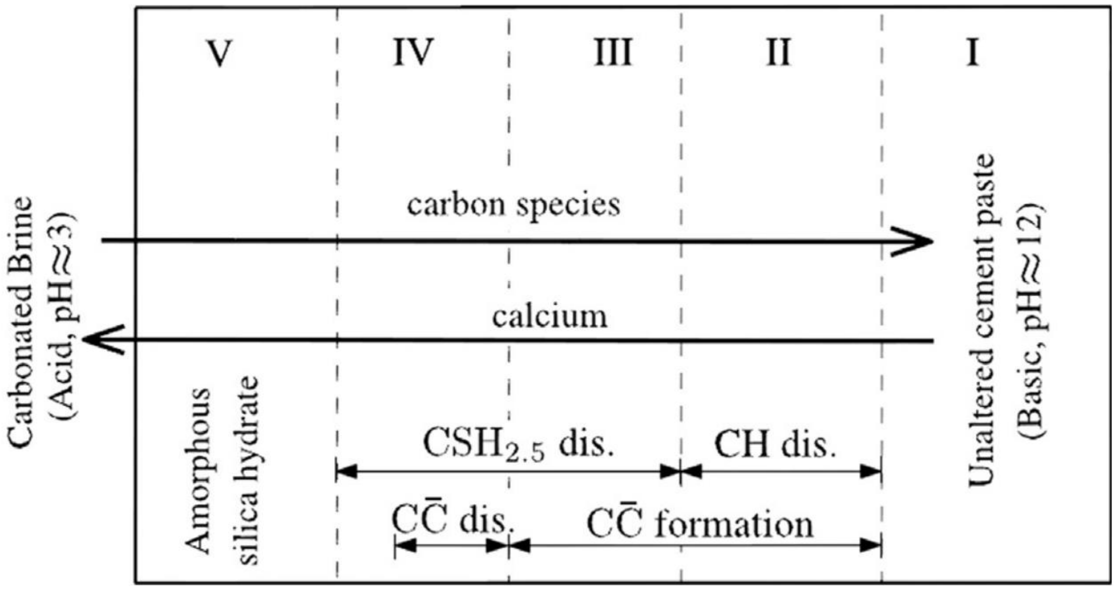


Figure 34. Formation of different zones in a cement exposed to CO_2-bearing fluids showing five zones (from right to left): unaltered zone (I); portlandite dissolution zone (II) in which calcium carbonate (CC) precipitation also simultaneously occurs; zone (III) accounted for the start of calcium silicate hydrate (C-S-H) (in this case $CSH_{2.5}$) dissolution and gradual termination of CC precipitation; zone (IV) dominated by C-S-H and CC dissolution, and; amorphous silica gel zone (V) depleted from calcium content to a great extent immediate to the brine-cement interface. Liaudat et al. (2018).

Guthrie et al. (2018) performed a comprehensive set of reactive-transport simulations which demonstrate that hydrated-Portland cement can react with carbonated brine to precipitate silica and calcium carbonate in sufficient quantities to seal the flow pathway. Self-sealing conditions move along a wellbore proportional to the flux of the leaking carbonated brine, and the reaction zone spreads out proportional to the fluid velocity (Guthrie et al., 2018).

Well casing integrity

The acidification of formation water due to the presence of CO_2 can lead to corrosion and embrittlement of casing strings, tubing and packers (e.g. Kiran et al., 2017). Casing and tubing are typically made of various grades of steel, which in the absence of corrosion resistive alloys, are susceptible to chemical alteration due to the presence of sulfates, chlorides, and acid stimulating agents. Typically, cement leaching precedes casing corrosion. The oxidation of iron takes place at the surface of the casing and is intensified at sites of stress induced effects and mechanical damage (Kiran et al., 2017). The byproduct of this redox reaction results in the formation of carbonate scales at the surface and eventually over time consumes the casing (Kiran et al., 2017).

Casing collapse in response to mechanical stress is the most extreme casing failure, typically occurring in the well production and completion stages. Cement shrinkage can cause significant stress perturbation and ultimately result in debonding and creation of voids at the cement/casing interface (Chenevert and Jin, 1989; Gray et al., 2009). Voids and cement channels pose the biggest risk to casing collapse resistance (Rodriguez et al., 2003; Berger et al., 2004).

Well integrity assessment

The evaluation of the wellbore integrity mainly comprises the following (Michael et al. 2013 and references therein):

- Spatial analysis of wells, to quantify the distribution of wells that penetrate the top seal.
- Logging information on well bore integrity (Table 7)
- Assessment of the potential compaction strains and shear strains around wellbores.
- Analysis of well geomechanics.
- Quantification of hydraulic characteristics associated with each well.
- A multiphase flow simulation to thoroughly analyse the potential of CO_2 leakage along wells.

Table 7. Uses and limitations of different wellbore logs for determining well integrity (Kiran et al., 2017).

Methods	Uses	Limitations
Cement bond log/variable density log	Predicts well-bonded cement, debonding at wet casing and formation	No prediction of mud channels, vertical cracks, gas chimney, and radial variation in cement
Ultra-Sonic Imaging Log	Shows well-bonded cement, mud channel in good cement, gas chimney, and debonding at wet casing	Unable to figure out mud channels in weak cement, vertical cracks, debonding at dry casing and formation, and radial variation in cement
Isolation Scanner	Capable of showing good cement, mud channels, gas chimneys, thick vertical cracks, debonding at wet casing and formation, and cement radial variation	No prediction on thin vertical cracks and debonding at dry casing
Radioactive Tracer Survey	Used to detects leaks	Incapable of predicting the quality of cement or casing
Temperature Log/Acoustic Log	Detects anomalies due to leak	No insight on cement
Corrosion Log	Can predict the corrosion in the casing, tubular, and even casing after the cemented zone such as surface casing.	No insight on cement
Standard annulus pressure test/vacuum insulated tubing	Assessment of the hydraulic properties of the cemented annulus zone under study	No evaluation of cement and casing quality

An initial assessment of well leakage risks can be based on the number and spatial distribution of wells that penetrate the top seal in the vicinity of a storage project (Figure 35). The statistical analysis of the well distribution, density, and clustering can be used to minimise the risk of CO_2 leakage along abandoned wells (Gasda et al., 2004). If regional stress data is available, the impact of strain on borehole integrity can be further assessed geomechanically, which requires the hydraulic characteristics associated with the mechanical components of the well assembly, linked to reservoir-scale modelling of reservoir pressure, temperature, and stress evolution (Rutqvist, 2012).

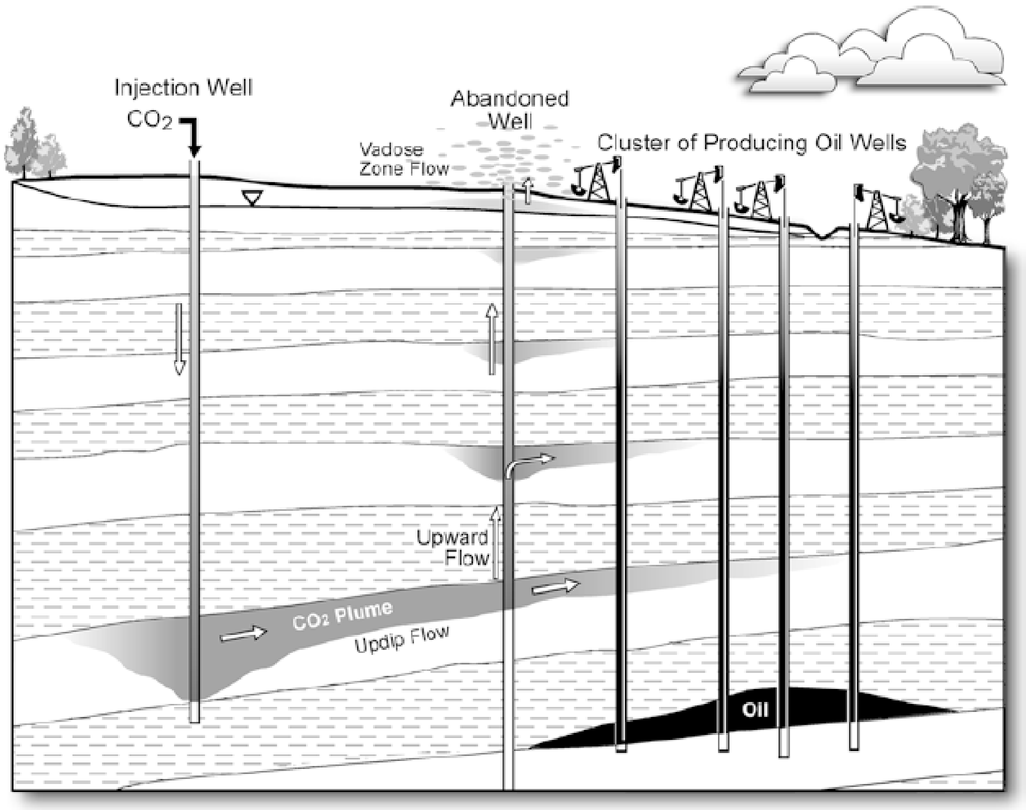


Figure 35. Diagrammatic representation of an injection well and of wells that penetrate a formation in the sedimentary succession (Gasda et al., 2004).

Estimating well leakage rates

The physics of the leakage mechanisms are well understood, and models can be constructed of CO_2 plumes moving out from an injector well, contacting a leaky well, and causing brine and then CO_2 to rise up into overlying aquifers. To apply these models, the crucial parameter of the wellbore permeability needs to be known. Wellbores however are very diverse, as the quality of their engineering depends on age, location, and regulatory framework upon abandonment. Due to the lack of actual CO_2 well leakage examples, estimation of leakage rates and risks has been limited to synoptic studies and simulations, which often are based on experience and data from the petroleum industry.

Postma et al. (2019) have modelled the CO_2 leakage flux into the atmosphere in a scenario representative of oil fields in North America (abandoned well density > 1 per km^2). Leakage to the atmosphere is predicted to be very small because the permeability of even old wellbores appears to be low and the CO_2 that rises up the wellbore thus tends to leak off into the first permeable aquifer above the reservoir layer. Postma et al. (2019) find that the leakage into the atmosphere is less than the "climate threshold" of 0.1% per annum for any plausible combination of the density of abandoned wells and the wellbore permeability, even under the very conservative assumption that all of the abandoned wells reach the depth of the storage reservoir. Also, once injection ceases (calculated up to 50 years), the leakage rates are two orders of magnitude smaller.

Alcade et al. (2018) developed a numerical program to evaluate CO_2 storage integrity and leakage over 10,000 years accounting for combined leakage through wells and geological features. They reported that a moderate well density has a 50% probability that leakage remains below 0.0008% per year, with at least 98% of the injected CO_2 retained in the subsurface over 10,000 years.

Hoydalsvik et al. (2021), relying on expert judgment from years of experience in operations, was concerned with storage risk in the North Sea, developed assessments of leakage probability by various mechanisms. The work built on extensive operators' experience in the North Sea to develop estimates of probabilities (total over 500 years) of the usual key risks; seepage up faults and fractures, leakage up defective wells, and blowouts. The study examined a hypothetical case of storing 100 Mt CO_2 over 50 years. Ten scenarios for leakage were considered with one injection well and one abandoned well, with the conclusion that 99.99 % of the injected volumes can be expected to remain securely underground for at least 500 years. Combined well leakage via active and inactive wells in their modelling scenarios added up to about 44% of the total risked leakage.

Daniels et al. (2023) modelled leakage probabilities due to geological and well leakage pathways for two representative UK offshore sites over 25 years of injection operations and 100 years of post-injection monitoring, suggesting that more than 99.9% of the injected CO_2 will be retained within the storage complex. For their study, Daniels et al. (2023) compiled and reviewed extensively leakage data and probability assessments associated with subsurface storage from the literature (Figure 36). The overall leakage risk depends on the leakage (Table 8), the duration of the leak, and the probability that this type of leak can occur (Figure 37).

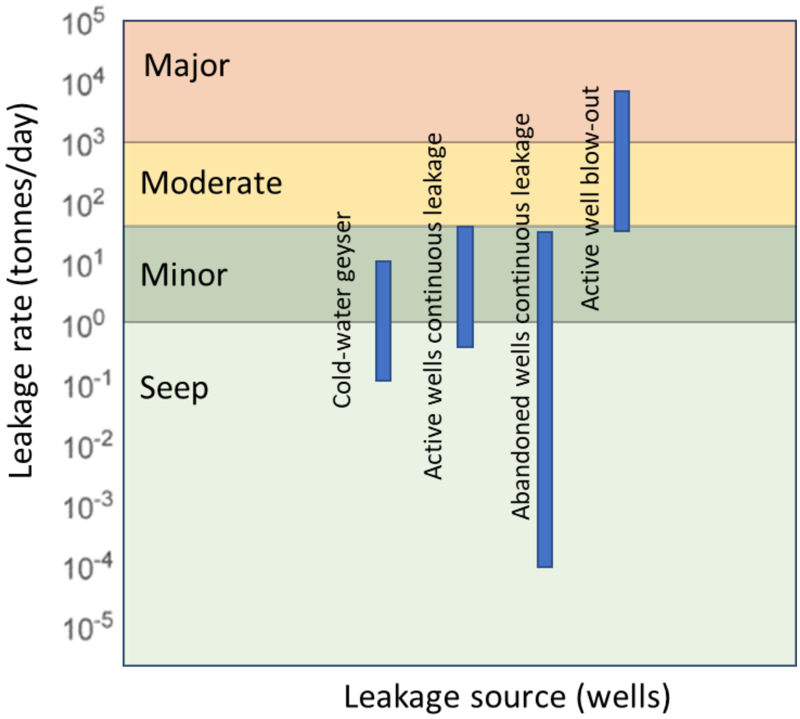


Figure 36. Representative CO_2 leakage rate data (log scale) reported in the literature for different types of well leakage (modified from Daniels et al., 2023 and references therein), Cold-water geyser data from Watson et al. (2014). The severity of leakage from Seep to Major is defined in Table 8.

Table 8. Severity of well leakage rates and pathways (Daniels et al., 2023).

Leak category	Leak rate (t/d)	Maximum time to remediation (days)	Active wells assumption	Inactive wells assumption
Seep	Less than 1	Continuous	No safety or environmental impact and potentially higher risk to remediate.	No safety or environmental impact and potentially higher risk to remediate.
Minor	1 – 50	Up to 180	Routine light or heavy well intervention. Duration set by lead time for rig for short campaign, most interventions can be executed within 3 months.	Relief well, not-expedited, to remediate the leak.
Moderate	50 – 1000	Up to 120	Assumed too high a leak rate for an intervention unless it can be shut in. Expedited relief well to minimise loss of fluid to the environment.	Expedited relief well to minimise loss of fluid to the environment.
Major	Greater than 1000	Up to 120	Expedited relief well to minimise loss of fluid to the environment.	Expedited relief well to minimise loss of fluid to the environment.

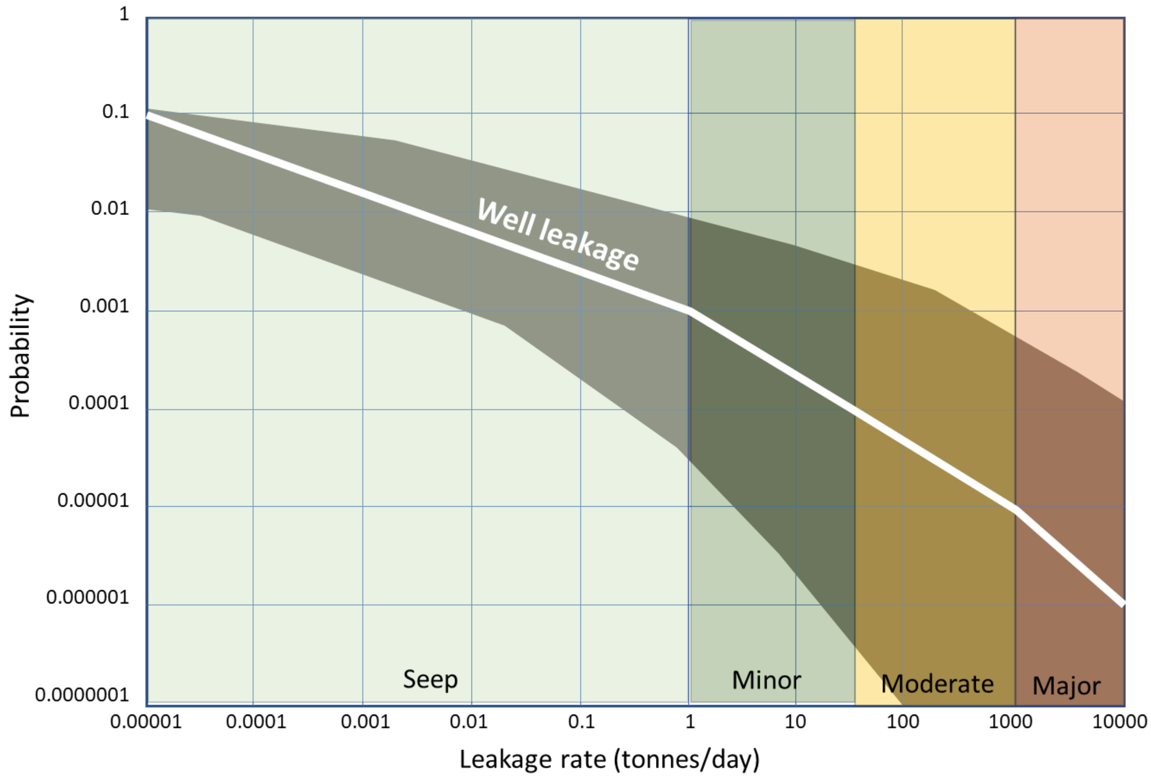


Figure 37. The probability of leakage through active and inactive well (modified from Daniels et al., 2023). The grey area represents the range of probability estimates of leakage from the literature. The white line approximately depicts the probability ranges of leakage used by Daniels et al. (2023) in their assessment of CO_2 storage sites in the North Sea. Leakage severity from Seep to Major Leak are defined in Table 8.

For example (following the white line in Figure 37), a seep occurring at a well were assigned probabilities between 1 in 10 to 1 in 1000, compared to the probabilities of a major leak ranging between 1 in 100,000 to 1 in a million by Daniels et al. (2023). These probability estimates fall within the average of probability estimates in the literature (Daniels et al., 2023 and references therein) and are assumed to be the same for active and inactive wells.

3.2.3 Assessment

Will carbon geological storage result in compromised well integrity?

<table>
<tr><th>Key questions</th><th>ANSWERS</th></tr>
<tr><td>Is it possible?</td><td>Yes. Examples of CO_2 leakage due to compromised well integrity, although rare, were associated with CO_2 enhanced oil recovery (EOR) projects, CO_2 injection wells, active oil production wells, or plugged and abandoned wells within the EOR scheme (Duncan et al., 2009).</td></tr>
<tr><td>Is it material?</td><td>Yes.

The literature review by Daniels et al. (2023) suggests following probability ranges for different leak type:

<table>
<tr><td rowspan="2">Leak category</td><td rowspan="2">Duration (months)</td><td colspan="2">Probability of defined leak rate occurrence/well</td></tr>
<tr><td>Maximum</td><td>Minimum</td></tr>
<tr><td>Seep (<1 t/day)</td><td>Continuous</td><td>1 in 10</td><td>1 in 1000</td></tr>
<tr><td>Minor (1-50 t/day)</td><td>Up to 6</td><td>1 in 1000</td><td>1 in 100,000</td></tr>
<tr><td>Moderate (50-1000 t/day)</td><td>Up to 4</td><td>1 in 10,000</td><td>1 in 100,000</td></tr>
<tr><td>Major (>1000 t/day)</td><td>Up to 4</td><td>1 in 100,000</td><td>1 in 1 million</td></tr>
</table>

Leakage from individual wells due to e.g. an inadequately completed well or well blow-out have been document in the petroleum industry. Compromised well integrity due to carbon geological storage operations can therefore be not negligible and therefore material in individual wells.

While the probability of compromised well integrity occurrence based on petroleum industry experience is extremely low, the probability of well leakage increases with the number of active and inactive wells within the area of the injected CO_2 plume.

Recent studies by Alcade et al. (2018), Postma et al. (2019), Hoydalsvik et al. (2021) and Daniels et al. (2023) agree that the leakage into the atmosphere can be expected to be less than the “climate threshold” of 0.1% per year for any plausible combination of wellbore and geological leakage pathways.</td></tr>
<tr><td>Can it be monitored</td><td>Yes. Multiple monitoring technologies are available for detecting:

Cautionary: Micro-seismic events

Critical: Wellhead injection pressure = fracture pressure of the reservoir rock or = fault re-activation pressure</td></tr>
</table>

Could it be mitigated?	**Yes.** The occurrence of compromised well integrity due to carbon geological storage operation can be mitigated through adequate design and construction of the CO_2 injector well (e.g. CO_2 resistant steel and cement) and by avoiding and properly isolating, older abandoned wells in the storage complex.
Could it be remediated ?	**Yes**. Well mitigation and remediation technologies are well-established in the petroleum and groundwater industries (e.g., Castaneda-Herrera et al., 2018).
Summary	**Possible, can be material, but can be mitigated**. Although leakage from wells can be material in individual cases, the probability of its occurrence when storing CO_2 at a well-characterised site is moderate for storage in depleted fields and low for saline aquifer storage. Well mitigation and remediation technologies are well-established.

3.2.4 References

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4 Process

4.1 Carbon dioxide in shallow aquifers

4.1.1 Definition

Injected CO_2 could migrate to shallow groundwater aquifers via leakage pathways such as wells with compromised integrity or leakage through discontinuities in the caprock such as faults. An increase in CO_2 concentrations in groundwater may directly impact water quality, e.g., by a pH decrease, or as a result of CO_2-water-rock geochemical reactions.

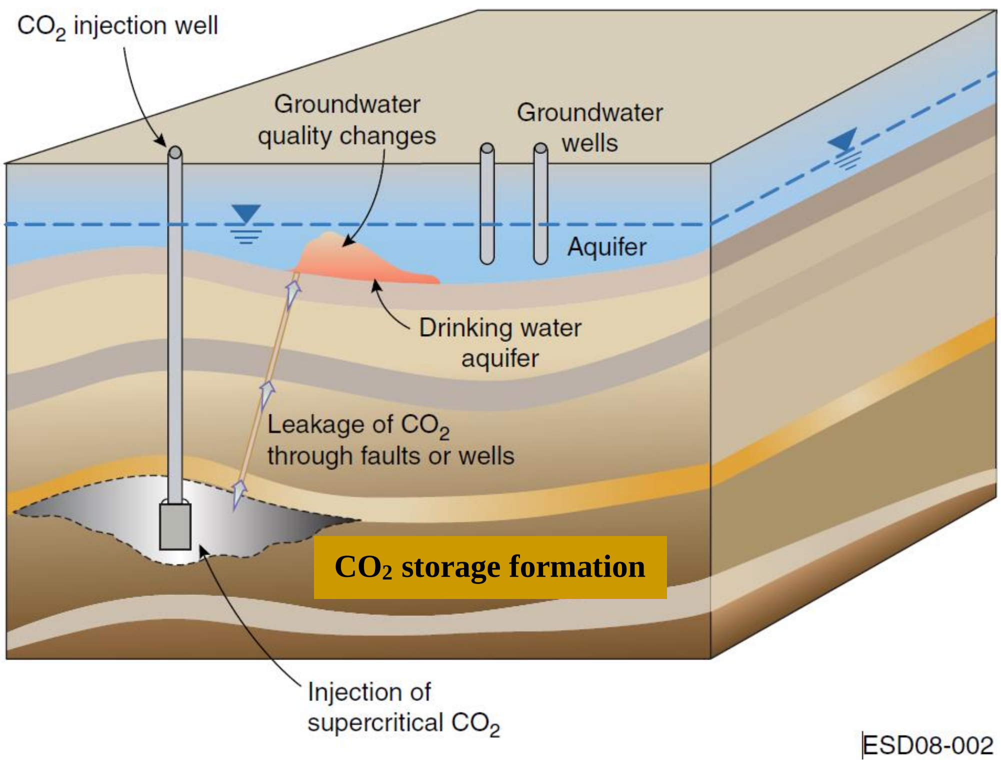

Figure 38. Potential groundwater leakage pathways and impact scenarios for CO_2 (after Birkholzer et al., 2009). Not to scale.

4.1.2 Description

Groundwater is an essential resource as a source of drinking water, stock water and irrigation purposes. The possible usage of groundwater is typically constraint by its salinity or total dissolved solids (TDS): potable water < 1000 mg/l, irrigation or domestic washing purposes < 2000 mg/l, stock water < 10000 mg/l. Water having a salinity greater than 10,000 mg/l can be used for specific industrial purposes, whereas highly saline waters (>

100,000 mg/l) are usually found only in deep portions of sedimentary basins and are sometimes used for recovery of mineral content such as potassium for fertilizers.

CO_2 occurs naturally in groundwater as dissolved and/or free-phase gas and varies both spatially and temporally due to e.g., climate, soil/plant types, aquifer minerology, as well as groundwater chemistry, pressure, temperature and residence time. Groundwater CO_2 partial pressures are typically ~10–100 times higher than atmospheric, being most variable near the water table, lowest at intermediate depth, and highest in deep saline aquifers. This is due to the thermodynamic equilibrium between the gas and water that depends on the pressure and temperature conditions of the system. The main sources of CO_2 in shallow aquifers are plant-root respiration and oxidation of modern organic carbon in the unsaturated zone, oxidation of old organic carbon in the rock matrix, acid neutralization reactions with carbonate minerals, and upward leakage of magmatic or petroleum-reservoir CO_2.

In groundwater the equilibrium of carbon dioxide (CO_2), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) changes with the pH of the water (Figure 39).

$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \Leftrightarrow 2H^+ + CO_3^{2-}$

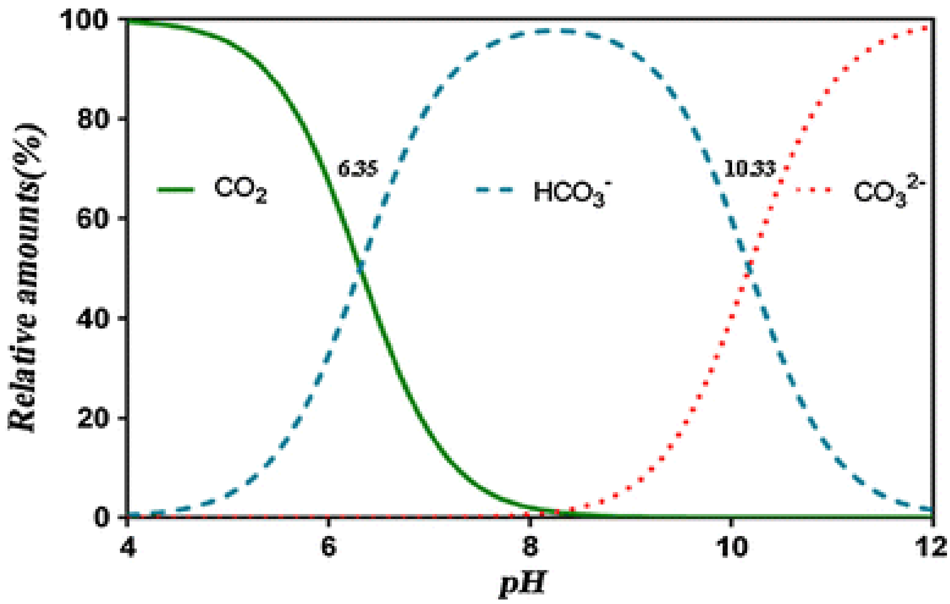

Figure 39. Equilibrium in water between carbon dioxide, bicarbonate, and carbonate with changing pH.

Carbon dioxide itself is not considered a pollutant or contaminant in groundwater and is not considered as a parameter for water quality in most groundwater jurisdictions. However, increased CO_2 concentrations could reduce the pH of groundwater, i.e., increase its acidity, and thereby enhance geochemical reactions between groundwater and aquifer sediments, potentially resulting in release and mobilization of toxic trace metals. The main processes governing the mobilisation and retention of trace elements are shown in Table 9. In most jurisdictions, acceptable ranges of pH are between 5-9 for the human consumption of water and 6.5-9 for aquatic life (e.g. US EPA: www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table).

Table 9. The main processes governing the mobilization or retention of trace elements after CO_2 intrusion in shallow aquifers (Lions et al., 2014). Occurrence: +++ (very abundant), ++ (abundant), + (not abundant), (+) (not observed but could occur).

	Elements	Fe, Mn	Al	Se, As	Sb, Mo	Cr	Hg	Ba, Sr	Cd, Co, Ni	Pb, Cu, Zn	U
Mobilization	Dissolution of host mineral	++	+	++	(+)	++	+	+++	+		++
	Desorption		++	++	+	+++		+	+++	+++	++
	Reduction	+		+		+					+
Scavenging	(Co)-precipitation	+		+++	+++	+	+	(+)	++	(+)	++
	Adsorption	+	+	+++	+++	+	+		++	+	++
	Complexation with organic phases		++	(+)			(+)		++	(+)	(+)
	Oxidation	++		++		+					(+)

Many studies on the potential impacts of CO_2 on groundwater resources have been conducted over the past 20 years, and reviewed, for example, by Lemieux (2011), Harvey et al. (2013), Lions et al. (2014), Jones et al. (2015), Fischer et al. (2016), and Varadharajan et al. (2019). Generally, these studies conclude that the environmental impacts of CO_2 leakage into groundwater appear to be low. Possible consequences result from the dissolution of CO_2 into saline or non-saline formation water and decreasing the pH of the water due to the formation of carbonic acid (Figure 39). The acidification of formation water may result in mineral reactions, either the dissolution of certain minerals or the precipitation of other minerals as cements. The dissolution rate of CO_2 in water and the extent to which mineral reactions may occur depend on temperature, pressure, formation water chemistry and the mineralogy of the aquifer. These water–mineral reactions are therefore are highly site specific and have the potential to degrade or enhance water quality and flow characteristics within the aquifer. Of specific concern are heavy metals that may be present within minerals in the rock matrix and may dissolve due to pH changes, thereby increasing the heavy metal content of the groundwater. Cement precipitation may result in the clogging of pore space and reduced ability to extract groundwater. Another, less likely potential impact, is the dissolution and transport of organic material into groundwater due to CO_2 contacting organic-rich rocks.

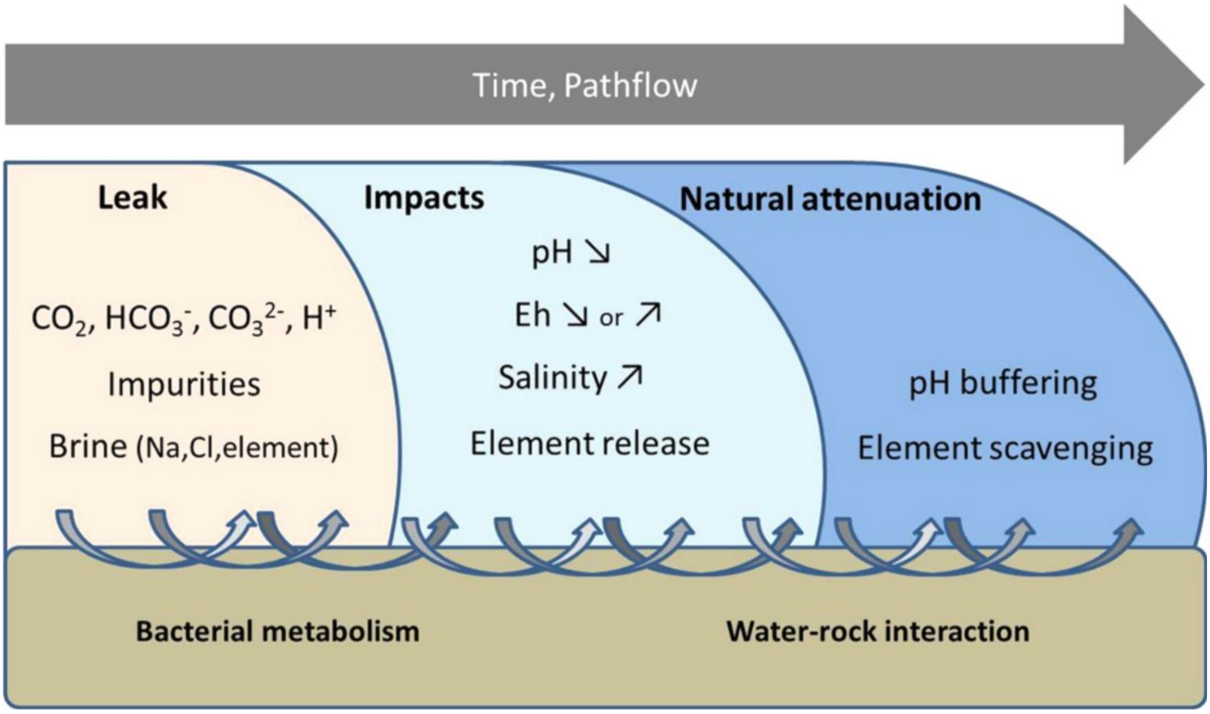

Figure 40. Schematic depiction of the impacts of CO_2 leakage on the chemical and microbial properties of shallow groundwater (Lions et al., 2014; graphical abstract).

Monitoring and mitigation

Groundwater monitoring and remediation technologies are well-established and widely applied in the environmental management of industrial subsurface developments. The early detection of small CO_2 leaks is challenging because natural CO_2 concentrations in groundwater have a relatively wide rage and exhibit daily and seasonal fluctuation. Direct detection through water sampling (for pH or salinity changes) or pressure monitoring is limited by the location and density of any well monitoring network. Remote monitoring techniques, including near-surface geophysical methods, on the other hand, have broader coverage but have a relatively low resolution, again making it difficult to identify small CO_2 leaks. A critical review of the state of art in monitoring and verification of CO_2 storage projects is provided by Jenkins et al. (2015) and updated by Jenkins (2020).

A general risk-based monitoring strategy is based on the collection of baseline data and the definition of suitable detection thresholds that account for detection limits for selected monitoring parameters and technologies (Figure 41).

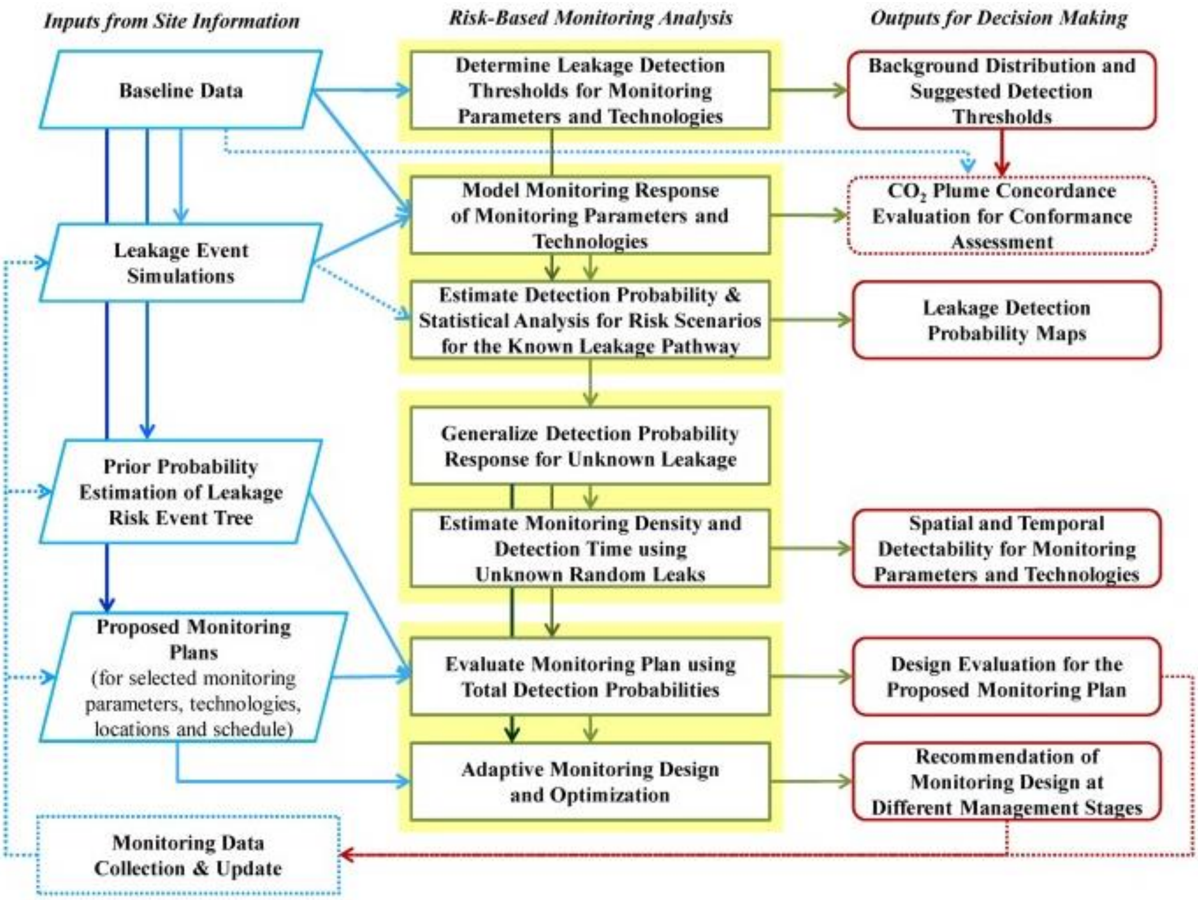

Figure 41. Risk-based monitoring network design flowchart (Yang et al., 2018).

Case studies

Shallow release experiments

Roberts and Stalker (2020) examined 14 CO_2 release project sites (Table 10), at which a total of 41 different CO_2 release experiments have been conducted. The intent of the majority of the experiments was the investigation of groundwater interactions and for the release CO_2 to remain in the shallow subsurface. Only nine of the controlled-release projects planned for the injected CO_2 to be released to the atmosphere. An important finding of Roberts and Stalker's (2020) review was that quantification of CO_2 leakage rates has proven difficult, despite intensive monitoring and multiple monitoring approaches. Further development of cost-effective approaches for quantifying leaks to the degree of confidence acceptable for relevant environmental regulations include remote sensing methods or mobile devices, or the use of chemical methods such as isotopic tracers. The experience from controlled-release projects has also shown the importance of establishing baseline conditions over an appropriate time period for adequately determining CO_2 impacts, flux rates and total leakage volumes.

Table 10. Shallow-release field studies (modified from Roberts and Stalker, 2020).

Project	Country	Years	Depth (m)	Injection length (min-max days)	Max. injection rate (t CO_2/year)	Groundwater impact	Reference
ASGARD	UK	2006-12	<25	~130-700	2.9		Smith et al., 2013
CO2 Field Lab	Norway	2011	<25	5	153.3		Jones et al., 2014
Grimsrud Farm	Norway	2011-12	<25	75	1.9		Moni and Rasse, 2014
Vrogum	Denmark	2011-12	<25	2-72	10.5	one-unit drop in pH and a twofold increase in EC, increases in major and trace element concentrations	Cahill et al., 2014; Lassen et al., 2015
CO2DEMO	France	2012-14	<25	<1	3.1		Loisy et al., 2013; Rillard et al., 2014
CIPRES	France	2013-14	<25	2	4.4		Gal et al., 2014
SIMEx	France	2013	<25	0.1	550.6		Pezard et al., 2016
Brandenburg	Germany	2011	<25		28.9	elevated major cations (Ca, Mg, K, Al, Si) and trace metals (Fe, Mn, Cu, Ni, Ba, Zn, Cd, Pb)	Peter et al., 2012; Yang et al., 2015b
PISCO2	Spain	2012	<25	46	0.96		Gasparini et al., 2015
Ginninderra	Australia	2012-13	<25	56-80	79.6		Feitz et al., 2014
Ressacada Farm	Brazil	2013	<25	12	1.3		Oliva et al., 2014
ZERT	USA	2007-14	<25	7-10	109.5	Rapid changes in pH, alkalinity, and EC; initial increase in (e.g., Ca, Mg), trace metals (e.g., Fe, Mn), and organics (BTEX)	Spangler et al., 2010
Brackenridge	USA	2012-13	<25	2	1.2		MIckler et al., 2013
K-COSEM	S Korea	2016	<25	30	21.9		Kim et al., 2018
Plant Daniel	USA		54			pH decrease from ~8 to~5; fast initial increase of major cations (Ca, Mg, Na, K) and trace metals (e.g., Ba, Sr, Fe, Mn) conductivity and alkalinity; As, Cd, Pb < detection limits	Trautz et al., 2012; 2013
Lodeve Basin	France		56			Increase in Mn, Zn, As, Ca, Mg and alkalinity and decreases in pH; due to dissolution of dolomite, ferrihydrite and siderite	Rillard et al., 2014
Cranfield	USA		73			Increases in Ca, Mg, K, Si due to dissolution of silicates and carbonate minerals. Mobilization and retardation of major and trace elements	Yang et al., 2013
In-Situ Lab	Australia	2018	340	4	875-8,750		Michael et al., 2020
Newark Basin	USA		360			decrease in pH; increase in alkalinity, Ca, Mg, Si; decrease in sulfate and Mo; increase in trace elements (Fe, Mn, Cr, Co, Ni, Cu, Zn, Rb, Sr, Ba, and U	Yang et al., 2015a

Laboratory experiments

In their review of laboratory results (Table 11), Varadharajan et al. (2019) observed that generally there is a reported decrease in pH in response to the exposure to CO_2 and a resulting increase in various alkali and alkaline metal cations due to mineral dissolution. However, quantifying the impacts of these reactions on water quality at the site scale is difficult. Many of the experiments were conducted at atmospheric pressure (1 bar) and not at typical aquifer pressures (5–15 bars). Hence, the concentrations of metals released could be underestimated, because higher hydrostatic pressures at depth would be expected to result in increased CO_2 dissolution and pH decrease, potentially further enhancing CO_2-induced mobilisation of metals (Varadharajan et al., 2019). On the other hand, experiments using unconsolidated sediments can overpredict the amount of metals released because the mineral surface area available for reactions is larger, especially in batch settings where the sediments are allowed to equilibrate with CO_2 over extended periods of time. Therefore, the mobilisation of metals in natural settings in the field can be expected to be significantly less prominent than metal release observed in laboratory experiments (Varadharajan et al., 2019).

Table 11. Laboratory experiments of CO_2 leakage into groundwater (summarised from Varadharajan et al., 2019).

Experiment conditions	Field site	Exposure time (days)	Rock type	Observations	Reference
Batch study, oxidising conditions	-	>300	various	Decrease in pH, increases in Mn, Co, Ni, Fe by one to two orders of magnitude.	Little and Jackson, 2010
Column experiments			Quartz and cadmium-laden illite	Decrease in pH, increase in cations, specifically Cd	Frye et al., 2012
Water-mineral-CO_2 batch	Albian aquifer, Paris Basin			increase in Ca, Si, Na, Al, B, Co, K, Li, Mg, Mn, Ni, Pb, Sr, Zn; decline in Fe and Be; no changes for Cl and SO_4 after initial CO_2 influx	Humez et al., 2013
Batch	Texas Gulf Coast			Two types of responses: 1. cations (Ca, Mg, Si, K, Sr, Mn, Ba, Co, B, Zn) had rapidly increasing at the start of CO_2 injection that became steady by the end of the experiment. 2. cations (Fe, Al, Mo, U, V, As, Cr, Cs, Rb, Ni, and Cu) showed an initial increase at the start of CO_2 injection followed by a decrease to values lower than prior to injection.	Lu et al., 2010
Sequential leaching experiments under redox conditions	Plant Daniel		unconsolidated sandy and organic-rich sediments	Quickly mobilized, primarily due to the decrease in pH, were alkali and alkaline earth metals (Ca, Mg, Ba, Sr, Na, Li, Rb), and a few other elements (Co, Fe, Ge, Mn, Ni, Si, Zn), carbonate ligands appeared to either enhance (U, Ba, As, Mo, Sr, Mn, Co, Ge, Mg) or suppress (weak trends observed for Fe and Li) the release of metals. Constituents that were mobilized were As, Ba, Ca, Fe, Ge, Mg, Mn, Na, Ni, Si, Sr, and Zn	Varadharajan et al., 2013
Batch: 0.01–1 bar CO_2		40	limestone	Increasing concentrations of Ca, Mg, Sr, Ba, Tl, U, Co, As, and Ni from the dissolution of mostly calcite and to a lesser extent pyrite	Wunsch et al., 2014
Batch: 0.01–1 bar CO_2		27	sandstone	Rapid increase in major (Ca, Mg) and trace (As, Ba, Cd, Fe, Mn, Pb, Sr, U) elements, due to the dissolution of calcite.	Kirsch et al., 2014
Batch and continuous flow experiments	Newark Basin			increase in major ions including Ca, Mg, Si, K, and alkalinity; enhanced dissolution of carbonate minerals; increase of trace elements including Mn, Fe, Be, Cr, Co, Cu, Zn, Rb, Zr, Cd, Sb, Ba, Pb, and U.	Yang et al., 2015a
Batch experiment to test the leaching of As	Chimayo, Mexico			Sharp increase in As concentrations as soon as pH dropped but then a slow decrease of concentrations although pH remained low, suggesting that the initial metal release was driven by the pH decrease, but subsequently the source of As was depleted	Viswanathan et al., 2012

Batch and column experiments, spiked with Cd & As	Kansas		Sand & gravel	Cd and As were adsorbed to the sediments, even after the solution pH decreased suggesting that sediments could potentially mitigate the effects of CO_2 leakage and brine intrusion, although the mitigation capacity will depend on the sediment mineralogy, such as the content of constituents like carbonates and phosphates.	Shao et al., 2015
Batch; supercritical CO_2-brine mixture	In Salah		Sst and shale	As, Cd, Cr, Cu, Ni, Pb, and U could be released into the formation fluids	Carroll et al., 2011
Mobilization of organic compounds			Fruitland coal and Gothic shale; transport after release through quartz sand and Sst	Lighter organic compounds (benzene, toluene) were more susceptible to mobilization by $scCO_2$ and transport through overlying media compared to heavier compounds	Zhong et al., 2014; Cantrell et al., 2015
12 MPa; 60°C	Surat Basin	16	Sst and siltstone	Increase of most major (e.g., Ca, Fe, Si, Mg, Mn) and minor (e.g., S, Sr, Ba, Zn) ions due to initial dissolution of carbonates, chlorite, and biotite and, in the long term, due to dissolution of feldspars.	Farquhar et al., 2015
50°C, 10 MPa		15	Berea Sst	Increase in Ca, Mg, Fe, Mn, and Si, due to carbonate and reactive silicate dissolution	Dawson et al., 2015

Numerical simulations

While there is large potential for mineral reactions near the CO_2 injection well and within the CO_2 plume, numerical studies (Table 12) predict only minor impacts in the far-field except for some specific geological conditions such as a reservoir complex with high-permeability caprock (Lemieux, 2011).

More recently, simulation results for the Quest site in Alberta, Canada have shown that CO_2 leakage could result in the increase of the acidity of the Belly River aquifer (Li et al., 2018). This would, in turn, result in an increase in heavy-metal concentrations, such as lead (Pb), in the groundwater. However, the maximum concentrations of Pb after 100 years of CO_2 leakage would still be lower than the maximum acceptable concentration of Pb established by the WHO and the Canadian drinking-water guidelines.

Xiao et al. (2017) investigated the risks of arsenic mobilisation through a combination of batch experiments and reactive transport modelling with the general conclusion that arsenic may be considered an insignificant long-term concern in a CO_2-rich environment because of clay adsorption. Likewise, in a saline environment, high concentrations of major ions (Ca, Mg, Na etc.) could impede arsenic release from the clay mineral sites.

The review by Varadharajan et al. (2019) concludes that reactive transport models can be used to predict the potential long-term changes in aquifer response to CO_2 leakage, to conduct uncertainty quantification, and to provide a basis for risk management and mitigation.

Table 12. Summary of numerical studies relevant to assessing the potential impacts on water quality in response to CO_2 leakage from deep geological storage (modified after Lemieux, 2011).

Authors	Name of model	Location	Chemicals	Potential impacts
Romanak et al. (2012)	PHREEQC	SACROC site in Scurry County, Texas, U.S.	Major ions	Yes
Zheng et al. (2012)	TOUGHREACT	MSU-ZERT site in Montana, U.S.	Major and trace elements	Yes
Apps et al. (2009)	EQ3/6	Generic; potable aquifers in the U.S.	Cd, Sb, Ba, Pb, Zn, As	Yes
Apps et al. (2010)	TOUGHREACT	Generic	Pb, As	Yes
Zheng et al. (2009a,b)	TOUGHREACT	Generic; mineralogy of aquifers along the Eastern Coastal Plain, U.S.	Pb, As	Yes
Jiang (2011)	TOUGHREACT	Jiangham Basin, China	Major ions; metals	Yes: sensitivity modeling
Kharaka et al. (2009)	SOLMINEQ	Frio site in Texas, U.S.	Fe, Mn, Ca	Yes
Xu et al. (2010)	TOUGHREACT	Frio site in Texas, U.S.	Fe	Yes
Audigane et al. (2009)	TOUGHREACT	Paris Basin, France	Fe	Yes
Humez et al. (2011)	TOUGHREACT	Paris Basin, France	Fe	Yes: water is currently treated to reduce Fe
Birkholzer et al. (2008)	TOUGHREACT	Generic	Pb, As	Yes
Jaffe and Wang (2003)	In-house GW flow and solute transport model; MINTEQA2	Generic	Pb	Yes
Wang and Jaffe (2004)	Same as above	Generic	Pb	Yes
Keating et al. (2010)	PHREEQC	New Mexico, U.S.	As, U, Pb	Yes: co-transportation of metals with upwelling CO_2
Berger and Roy (2011)	React	Illinois Basin - Decatur Project site, U.S.	Mg, Ca	No

Natural leakage

Observations of natural CO_2 accumulations (i.e., Keating at al., 2010;2011; 2014; Lions et al., 2014; Gemeni et al., 2016; Delkhahi et al., 2020) demonstrate that hydraulic communications leading to upward CO_2 migration to shallow aquifers does not prevent the long-term storage of a substantial amount of CO_2 at depth and that some degree of leakage may not necessarily have a detrimental impact on shallow groundwater. However, reactions in natural analogues may not accurately represent impacts of leakage into a shallow aquifer from an industrial storage operation, since the sediments would have been equilibrated with CO_2-saturated waters over very long timescales (Varadharajan et al., 2019).

4.1.3 Assessment

The assessment of the impacts on shallow aquifers will be addressed in two parts: 1. Impact from *compromised subsurface integrity* and 2. Impact from *compromised well integrity*.

Will compromised subsurface integrity result in an increase in carbon dioxide in shallow aquifers?

Key questions	ANSWERS
Is it possible?	**Yes.** Geological features in the form of faults or fracture zones may form leakage pathways for stored CO_2 to shallow groundwater aquifers.
Is it material?	**No.** • Leakage rates are small and diffuse or patchy. • Multiple barriers and migration within intervening aquifers will reduce volume ending up in the groundwater aquifers. • Buffering, dissolution, residual saturation will retard migration and reduce volume ending up in the groundwater aquifers. Based on statistical estimates by Daniels et al. (2023), worst-case leakage amounts are less than 0.002 % and 0.024% of the total storage volume for storage in depleted fields and saline aquifers, respectively. Hydrogeological and hydrochemical attenuation of CO_2 flux limits the potential of CO_2 leakage to lead to a non-negligible increase in CO_2 partial pressure in a shallow aquifer.
Can it be monitored?	**Yes.** Water sampling/monitoring in groundwater wells. Cautionary: CO_2 concentration/salinity/pH > background; detection of plume above reservoir
Could it be mitigated?	**No**. Stop of injection and back- pumping will obviously limit the amount of CO_2 available for leakage. However, when a CO_2 leakage pathway is established through compromised subsurface integrity, there are no interventions possible to avoid or mitigate the flux of CO_2 that has already escaped the storage reservoir. The link between carbon geological sequestration operations and compromised subsurface integrity outlines strategies to minimise occurrence of compromised subsurface integrity due to carbon geological sequestration.
Could it be remediated?	**No**. Plugging geological leakage pathways to shallow groundwater aquifers is challenging because these are generally difficult to locate, can be of a diffuse nature and are therefore difficult or expensive to access and effectively seal.
Summary	**Possible but not material**. Material leakage of CO_2 into shallow aquifers via geological pathways is negligible at a properly characterised site. Leakage detection is difficult and remediation options are limited.

Will compromised well integrity result in an increase in carbon dioxide in shallow aquifers?

Key questions	ANSWERS
Is it possible?	**Yes**. Damaged or improperly completed wells could form vertical leakage pathways for CO_2 from the storage complex into overlying aquifers. Examples of CO_2 leakage in the past, although rare, were associated with CO_2 enhanced oil recovery (EOR) projects, including blowouts of production wells drilled into natural CO_2 reservoirs, CO_2 injection wells, active oil production wells, or plugged and abandoned wells within the EOR scheme (Duncan et al., 2009).
Is it material?	**Yes.** A compromised well can create a direct pathway for CO_2 to enter a shallow aquifer (e.g. Delkahahi et al. 2020), with less opportunity for hydrogeological and hydrochemical attenuation. This can lead to a locally non-negligible change in aquifer partial CO_2 pressure. Based on statistical estimates by Daniels et al. (2023), worst-case leakage amounts are less than 0.07 % of the total storage volume.
Can it be monitored?	**Yes.** Groundwater sampling and monitoring. **Cautionary**: CO_2 concentration/salinity > background; seismic detection of plume above reservoir
Could it be mitigated?	**Yes.** An increase in CO_2 concentration in shallow aquifers due to compromised well integrity can be avoided and mitigated by ensuring any sections of aquifer intersected by injector wells or existing abandoned wells are adequately sealed.
Could it be remediated?	**Yes**. Well mitigation and groundwater remediation technologies are well-established in the petroleum and groundwater industries (e.g., Castaneda-Herrera et al., 2018).
Summary	**Possible and can be material but can be mitigated**. While material leakage of CO_2 into shallow aquifers via compromised wells is unlikely at a properly characterised site, leaks are generally easy to detect and quickly remediated.

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4.2 Carbon dioxide in soils

4.2.1 Definition

Soil is porous, and the spaces between grains contain a diverse mixture of gases, mostly at near-atmospheric concentrations (Figure 42). Soil gas is a mixture that contains components of air (nitrogen, oxygen, argon and minor amounts of CO_2, noble gases, methane and hydrogen) and could also contain volatile organic carbon compounds, noble gases such as radon or other gases released from deep underground.

Because CO_2 is produced naturally in the soil by plant and microbial respiration at rates which depend on temperature, moisture, and many other factors, CO_2 concentration in soil is very variable across locations, depths and seasons. Soil gas has been long studied for its relevance to ecology, geology, and pollution control.

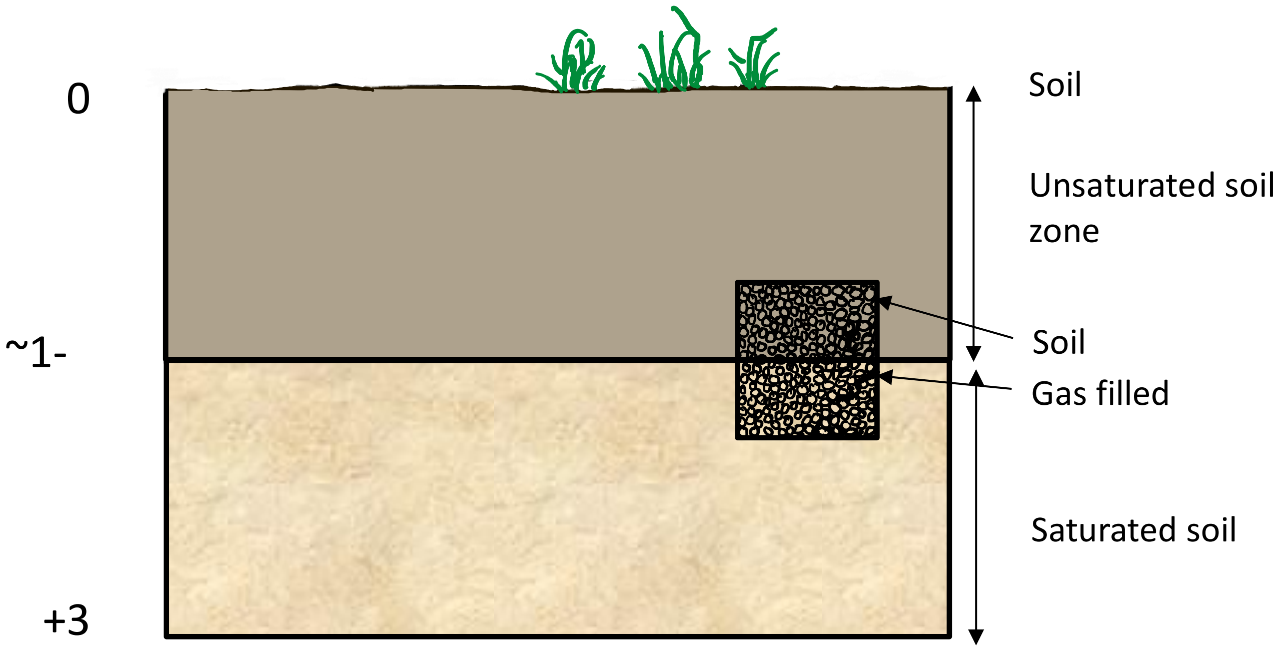

Figure 42. Soil gas diagram showing distribution of gas in the subsurface. Modified after (Shao et al., 2019).

4.2.2 Description

It seems obvious that CO_2 from a leak at reservoir level might eventually find its way into near-surface soils. There are documented examples and analogues in nature that demonstrate how this occurs, and these natural analogues can be used to better understand both risks, rates and impacts of CO_2 leakage to the surface (see Roberts and Stalker, 2020 and references therein).

In volcanic areas, it is well known that CO_2 from deep sources can reach the surface, often resulting in small patches of altered or dead vegetation (e.g., Krüger et al., 2011). These fumaroles/mofettes tend to be part of active volcanism that are caused by specific geological situations (like volcanic events), and not something that is typical of large-scale geological storage within sedimentary rocks and basin features. However, natural analogues and numerous laboratory and field experiments indicate that high concentrations of CO_2 in the root zone are harmful to plants through oxygen depletion (e.g., Ko et al., 2016) and could cause plant stress responses such as change in leaf area and chlorophyll content. There are also risks to humans (Roberts et al., 2011) in locations where high rates of flux and low topography occur (Figure 43).

Figure 43. Impact of CO_2 release in a depression in Italy. Image from Mefite D'Ansanto, 2010. Photo: J. Roberts & M. Naylor.

Because the sites of geological storage of CO_2 are at the very least 800m deep, and usually far greater (in the range of approximately 1 - 2.5 km), the risk of leakage direct to surface is both unlikely and at very low rates. As numerous aquifers (porous rocks) and aquitards (impermeable rocks) are typically interposed between a deep source/storage interval and the surface, it is implausible that CO_2 would be able to bypass all the obstacles and accumulate in near-surface soils at scale.

One exception is that CO_2 could migrate up a faulty wellbore (see 3.2 Compromised well integrity) and spread out near the surface in the soil. Concerns about leakage and environmental impact have prompted several controlled release experiments at field scale (e.g., Strazisar et al., 2009). A compilation of data on releases is in Roberts and Stalker (2020; Figure 44 and Figure 45). Some examples of notable controlled release experiments are Strazisar et al. (2009), Feitz et al. (2014), Jones et al. (2014) and Kim et al. (2018). It is not known if the buried release points design of field experiments for CO_2 are useful models of how CO_2 might approach the surface, but some observations from consolidated and harmonised values (Figure 44; Roberts and Stalker, 2020) can provide some context. However, the controlled releases tests all show the same patchy surface expression of CO_2 leakage also seen in the volcanism sourced leaks.

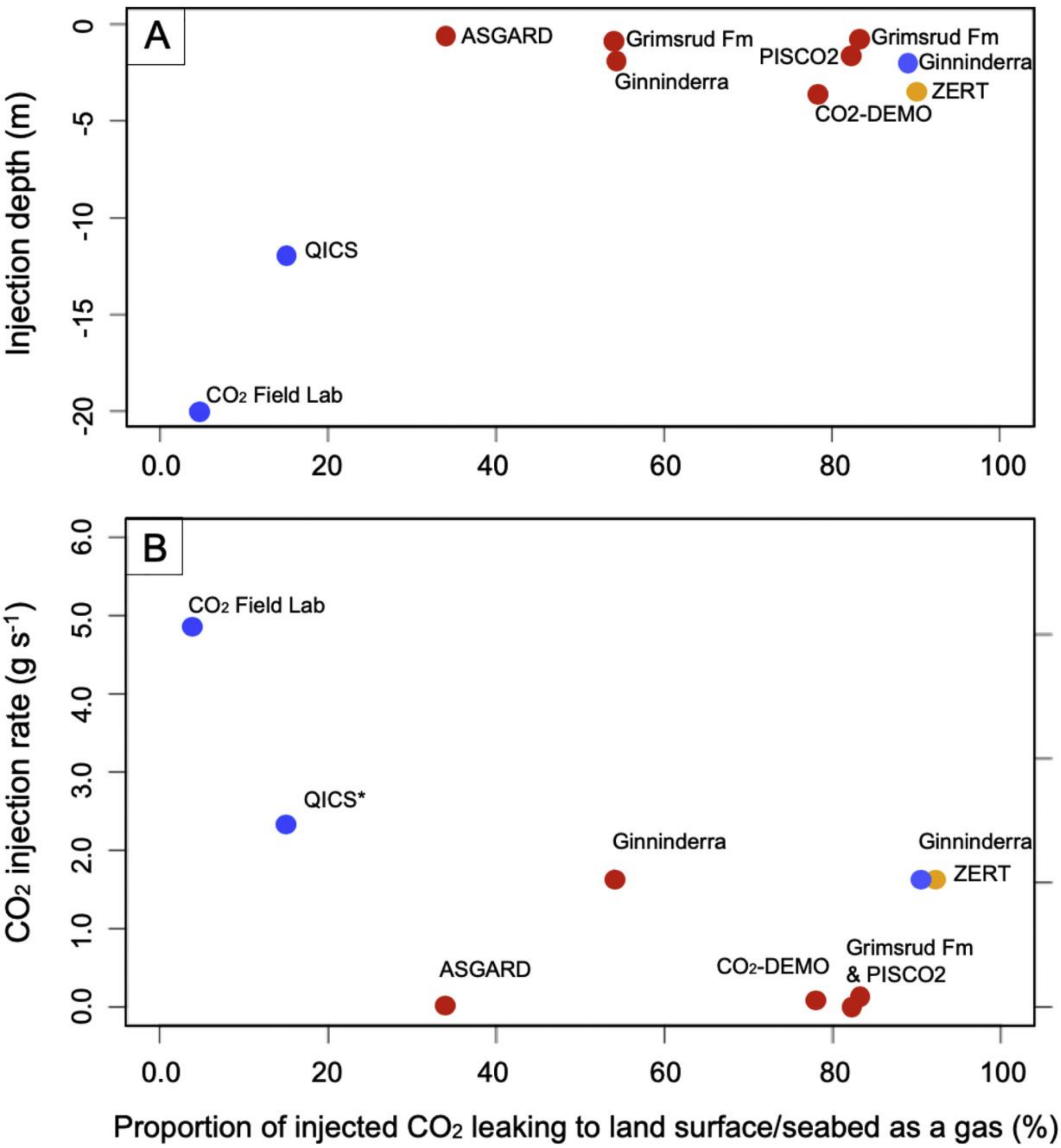

Figure 44. The estimated proportion of injected CO_2 that leaked to land surface or seabed as a gas at the field experiments plotted against (A) injection depth and (B) injection rate. The symbol colour indicates whether the CO_2 injection depth was into the saturated zone (blue) or the vadose zone (red) or if this was variable throughout the experiment (orange). Figure from Roberts and Stalker (2020).

The rates of injection into many shallow or controlled release sites are far smaller than the "minimum" rates implied by Hepple and Benson (2005). For example, two of the studies at the ZERT site in Montana, USA have injection rates of over 3g/s^{-1} which is equivalent to approximately 100 tonnes per annum. This equates to only 0.01% of the leakage rate of a 1 million tonne per annum injection rate at a commercial scale operation. While this may be far lower than the floor often referred to when using Hepple and Benson (2005), the ability to monitor and measure CO_2 leakage at these low levels implies that a 1% leakage rate if using the 1 million tonnes per annum example, would be equivalent to a 10,000 tonnes leakage.

Monitoring soil gas of CCS sites, where there is no leakage, also shows large spatial variability in CO_2 concentrations, suggesting this is an inherent consequence of the interaction between the variability of soils, and two-phase flow effects as a soluble gas (CO_2) as it makes its way through pore spaces containing water. Therefore, surveys are often made up from a combination of baseline survey and follow up survey data and the evaluation of that data to determine the different potential processes that could result in the observed soil gas compositions and concentrations (Romanak et al., 2012).

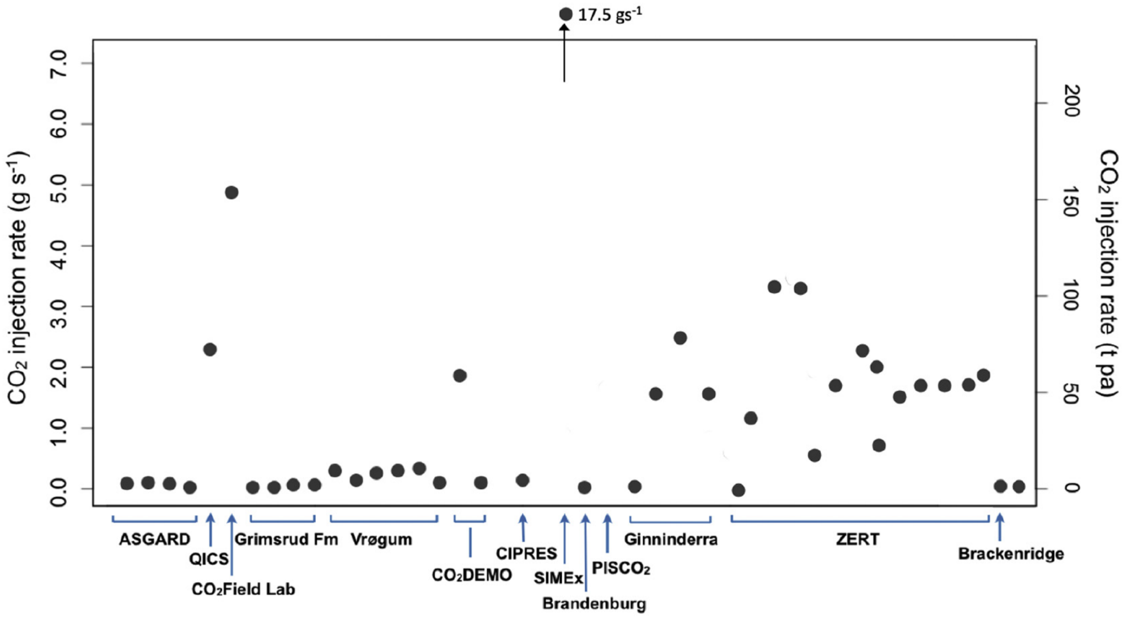

Figure 45. Maximum injection rates at a range of shallow release sites comparing the injection rates of the tests (left axis in grams per second) converted to what those injections would be over the course of a year (right axis in tonnes per annum). From Roberts and Stalker (2020).

Overall, the literature on soil gas in CCS is very extensive and there are a number of references suggested to provide entry points into various topics and support the general observations made in this section. A comprehensive early review of the technical options and issues of soil gas monitoring can be found in Schlömer et al. (2013). The utility of soil gas monitoring was considered in Jones et al. (2015) from the point of view of environmental monitoring and critiqued as a leak-detection method in Jenkins et al. (2015) and Jenkins (2020). Natural analogues formed an early inspiration for monitoring soil gas and illustrated the potential impact on plants and people. There are a number of European studies for example Beaubien et al. (2008), Krüger et al. (2011) and Ziogou et al. (2013) which demonstrate the benchmarking of tools and approaches to quantifying leakage. Roberts et al. (2011) used analogues to bound the risks to human health from leakage examples.

Soil gas monitoring has been tested over two decades, with an early example of soil gas monitoring at a storage site by Klusman (2003) at the Rangely field. The method was also deployed for baseline studies at possible CCS sites (Schlömer et al., 2014), and at operational sites, including Weyburn (Romanak et al., 2013), an early application of the process-based method), Otway (Schacht and Jenkins, 2014, demonstrating the wide spatial and temporal variability of soil gas concentrations), Lacq (Gal et al., 2019) and Decatur, Illinois (Shao et al., 2019).

Contributions and impacts relating to plants and microbes in elevated CO_2 in soil gas

There are many dynamic sources and sinks of CO_2 in soil due to plant and microbial processes (Kuzyakov, 2006). This means that it can be challenging to differentiate between the CO_2 arising from these natural processes with CO_2 arising from deep subsurface storage.

Investigations into the response to CO_2 from different vegetation types, climates and vadose zone depths have been documented at a range of shallow and controlled release experiments such as the K-COSEM site near Eumseong, South Korea (Kim et al., 2018), Ginninderra, Australian Capital Territory (Feitz et al., 2018) and the Asgard site at the University of Nottingham, England (Smith et al., 2013). Other controlled or shallow release experimental assessments are summarised in Roberts and Stalker (2020).

ASGARD saw order of magnitude decrease in microbial community overall with increased CO_2 presence caused by not only the elevated CO_2 concentration but also seasonal variability and the depth of sample. The overall conclusion was that elevated CO_2 concentrations were damaging to soil microbiology (Smith et al., 2013).

The impact of CO_2 leaking in soil can have both positive or negative outcomes; (Zhao et al., 2017) note that low concentrations have been shown to help plant growth while higher concentrations can lead to deleterious effects due to oxygen displacement. Other studies (e.g., Zhang et al., 2016; 2018) based on simple pot experiments have shown that it is the oxygen reduction or displacement by CO_2 that is more deleterious than change in acidity or pH.

Monitoring and mitigation

There have been numerous deployments of soil gas monitors, both at sequestration sites and controlled release sites (e.g., Klusman, 2003). A variety of technical solutions have been tried and there is no doubt that CO_2 can be monitored in soil gas (e.g., Schlömer et al., 2013). A clear result is that CO_2 concentrations are extremely variable, even when no leakage is present, and reflect many details of the natural metabolic processes taking place in the soil system.

Relationships between soil gases can be informative as natural respiratory processes lead to well-defined relationship between the concentrations of O_2 and CO_2 in a soil gas sample (Romanak et al., 2012). Deviations (essentially, too much CO_2 for the amount of oxygen that is present) indicate that the CO_2 is exogenous. This is the essence of the process-based method of interpretation of soil gas. Evaluation of potential processes that result in a particular gas composition (and concentration of volumes and isotopes) and is an approach used by gas geochemists to understand source and any alteration of gas caused by secondary effects (biodegradation or maturation; see Gürgey et al; 2005 and references therein).

The process-based method allows one to detect that the CO_2 in soil gas is not natural: the next steps would be to attribute it to a specific source and evaluate any environmental harms (Dixon & Romanak, 2015). Attribution is a complex problem, and may involve isotopic ratios, noble gases, or artificial tracers (Romanak et al., 2014; Gilfillan et al., 2017; Myers et al., 2013).

Soil gas can only be measured at a relatively small number of discrete points. Since it appears that the surface expression of CO_2 from depth manifests as isolated patches, the chances of soil gas sampling points detecting anomalous CO_2 is low. It may be that environmental effects are noticed first, and soil gas sampling follows at targeted points (Romanak et al., 2014).

There are a large variety of soil monitoring tools that can potentially be deployed and a range of installation styles. Feitz et al. (2018 and references therein) have conducted several experiments that compared methods and accuracy while monitoring a known injection rate at the Ginninderra controlled release site in Australian Capital Territory. These have included cavity ringdown mass spectrometers, laser-based methods, eddy covariance, hyperspectral imaging, open path FTIR, unmanned aerial vehicle, unmanned ground robot and infrared cameras, some of which involved sample collection from a range of methods (e.g., flux chambers, shallow gas wells, mobile equipment) and a range of data analyses treatments.

Others have used different statistical approaches by examining CO_2 concentration time series (Oh et al., 2019; Seo et al., 2020). With the advancement in machine learning techniques and increases in computational power combined with miniaturization and automation of monitoring systems it is anticipated that these techniques could lead to significant improvements in leak detection capabilities in the future.

There are no examples from CCS of soil gas mitigation. Since CO_2 is a natural part of ecosystems and not persistent, mitigating excess CO_2 in soil gas would require a strategy that precedes the CO_2 reaching such shallow levels of the subsurface. It is more likely that if identified, any leakage would be mitigated either through well remediation (the most likely leakage scenario) or ceasing injection to reduce pressure such that any excess would then recover naturally over time.

Tracers in monitoring and attribution

Some attempts to better quantify leakage rates and attribution have involved research into the use of artificial tracers and/or naturally occurring (inherent) tracers. These have been used at several pilot or demonstration sites (e.g., CO2CRC Otway Project (Stalker et al., 2015); West Pearl Queen; Wells et al., 2007), controlled or shallow release experiments (some of which are summarised in Roberts and Stalker, 2020) and in commercial scale operations such as Weyburn, Canada (e.g., Romanak et al., 2014). With a low background concentration and very little naturally occurring sources/sinks for these tracers, they could potentially be a valuable tool to validate that assumption that CO_2 leakage over a thousand years is less than 1 % (Hepple and Benson, 2005) given that the quantity of tracer can be scaled to a suitable sensitivity level. This may be more suited to inherent tracers than for artificial tracers as discussed below.

Case studies using tracers

Inherent tracers were used at the Weyburn EOR Site to determine whether environmental impact observations at the Kerr Farm in Saskatchewan, Canada, was caused by leakage of injected CO_2 or not. The absence of ^{14}C CO_2 and the presence of O_2 and N_2 in concentrations typical of soil gas respiration suggested that there was no leakage from the injection process. This was further corroborated by ^{13}C CO_2 isotope data which was also consistent with a soil gas origin (see Flude et al., 2016 and references therein). Comparisons with inherent tracers in the ground water chemistry added to the body of evidence that showed any surface observations were not from the injected CO_2.

Other projects considered the addition of chemicals as artificial tracers. The CO2CRC Otway site, in Victoria, Australia facilitated the conduct of a series of pilot-scale injection studies where tracers were added to the CO_2 gas stream (Stage 1 and Stage 2B, and possibly subsequent campaigns). The lessons learned at the time and subsequent research summarised by Stalker and Myers (2014) and Stalker et al. (2015) suggest that while adding a suite of tracers with different chemical behaviours can be illuminating for understanding the migration of CO_2 and interrogating reservoir behaviour, it would not be easily introduced to tag a commercial scale operation. For example, using the data from the West Pearl Queen depleted oil reservoir, 0.5L of a PFC tracer was added to 20 tonnes of CO_2. The tracer was detectable in their study and extrapolating to a 1 million tonne per annum injection rate approximately 25,000L of PFC would be required to be co-injected with the CO_2 to achieve similar outcomes. This introduces both risks related to additional GHG impacts if released to surface (PFCs have significant global warming potential) and there is risk of spill or leakage of larger volumes of tracer during administration, which could result in significant false positives. Any artificial tracers used in any pilot or demonstration scale CO_2 injection activities are typically in such low concentrations, that they would have little environmental and human health impacts. The amount of CO_2 remains the greater risk, but as has been described in other sections, this risk and consequence is generally low.

4.2.3 Assessment

The assessment of the impacts on shallow aquifers will be addressed in two parts: 1. Impact from *compromised subsurface integrity* and 2. Impact from *compromised well integrity*.

Will compromised subsurface integrity result in an increase in carbon dioxide in soils?

Key questions	ANSWERS
Is it possible?	**Yes.** Geological features in the form of faults or fracture zones may form leakage pathways for stored CO_2 to the soil zone.
Is it material?	**No.** For CO_2 leaking from a storage reservoir through compromised subsurface integrity to reach soils, it needs to flow through an extensive stack of sedimentary strata including aquitards and aquifers. This will provide ample opportunity for the flux to be attenuated, especially through buffering, dissolution and residual saturation in aquifers contained in the sedimentary column and not result in a material change in soil CO_2 pressure.
Can it be monitored?	**Cautionary**: Indications of exogenous gas from the process-based method would be a flag to prompt more investigation.
Could it be mitigated?	**No**. Should a CO_2 leakage pathway be established through compromised subsurface integrity, there are no interventions possible to avoid or mitigate CO_2 flux. The link between carbon geological sequestration operations and compromised subsurface integrity outlines strategies to minimise occurrence of compromised subsurface integrity due to carbon geological sequestration.
Could it be remediated?	**No**. Remediating CO_2 leakage along geological leakage pathways to the soil zone is challenging because these are generally difficult to locate, can be of a diffuse nature and are therefore difficult or expensive to access or effectively seal.
Summary	**Possible but not material**. Material leakage of CO_2 into the soil zone via geological pathways is unlikely at a properly characterised site.

Will compromised well integrity result in an increase in carbon dioxide in soils?

Key questions	ANSWERS
Is it possible?	**Yes**. Damaged or improperly completed wells could form vertical leakage pathways for CO_2 from the storage complex to the soil zone. Examples of CO_2 leakage in the past, although rare, were associated with CO_2 enhanced oil recovery (EOR) projects, CO_2 injection wells, active oil production wells, or plugged and abandoned wells within the EOR scheme (Duncan et al., 2009).
Is it material?	**Yes.** • Multiple barriers and partial migration into various intervening aquifers will reduce volume ending up in the soil zone. • Buffering, dissolution, residual saturation in intervening aquifers will retard migration and reduce volume ending up in the soil zone. Leakage can be material (>0.1%) in individual cases, but the probability of its occurrence is extremely low (Hoydalsvik et al., 2021). A compromised well can create a direct pathway for CO_2 to enter soils. This can lead to a locally non-negligible change in soil partial CO_2 pressure. Based on statistical estimates by BEIS (2023) however, worst-case leakage amounts are less than 0.07 % and 0.064% of the total storage volume for storage in depleted fields and saline aquifers, respectively.
Can it be monitored?	**Yes.** Soil gas monitoring/sampling. **Cautionary**: Indications of exogenous gas from the process-based method would be a flag to prompt more investigation.
Could it be mitigated?	**Yes**. The risk of CO_2 leaking to the soil zone via leaky wells can be significantly limited by using adequate material, CO_2 resistant steel and cement, for the CO_2 injector, and by avoiding, or at least properly isolating, older abandoned wells in the storage complex. Particularly, the intersection of soil by injector wells or existing abandoned wells should be adequately sealed. Even in the unlikely event a leak should occur, leakage rates are expected to be small and easy to remediate.
Can it be remediated?	**Yes**. Well mitigation and groundwater remediation technologies are well-established in the petroleum and groundwater industries (e.g., Castaneda-Herrera et al., 2018).
Summary	**Possible and can be material but can be mitigated**. While material leakage of CO_2 into soils via compromised wells is unlikely at a properly characterised site, leaks are generally constrained to the well, which facilitates rapid detection and mitigation.

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4.3 Carbon dioxide in surface waters

4.3.1 Definition

CO_2 in surface waters (e.g., lakes, rivers) is caused by transfer of gases at the soil-atmosphere boundary that is interrupted by a body of water. Similar to soil-gas, there are a variety of sources and sinks within water. Furthermore, CO_2 can exist in shallow water as bubbles transiting through the body of water or as a dissolved species.

4.3.2 Description

The Australian National Aquatic Ecosystems Classification Framework (Aquatic Ecosystems Task Group, 2012) defines *lacustrine* systems based on a US system presented by Cowardin et al. (1979) as those aquatic ecosystems situated in a topographic depression or a dammed river channel, having sparse vegetation coverage (less than 30 percent of their coverage area is made up of vegetation such as trees, shrubs or persistent emergent vegetation), and the total area exceeds 8 hectares. Similar habitats less than 8 hectares are also included if active wave-formed or bedrock shoreline features make up all or part of the boundary, or their depth is greater than 2 metres. Ocean-derived salinity is always less than 0.5‰. This definition also applies to modified systems (e.g. dams), which possess characteristics like lacustrine systems.

Lakes may be groundwater-fed, rain-fed, stream-fed, tide-fed (in estuarine systems) or filled by overland flow of water across a floodplain via networks of flood-runners and anabranches that deliver water from the primary river channel. Lakes generally occur whenever water accumulates in the landscape, and often exist as deeper sections of flood-runner and anabranch networks.

Gases, including CO_2 may migrate into surface waters via a range of processes summarised by Oldenburg and Lewicki (2006; Table 13 and illustrated in Figure 46. Often studies compare the behaviour of CO_2 to CH_4 to illustrate the differences in solubility, wettability and other factors (e.g., Oldenburg and Lewicki, 2006; Myers et al., 2019). A range of studies have modelled migration of CO_2 in terms of movement through the vadose zone in onshore environments, summarised by Oldenberg and Lewicki, 2006). In the case of areas with higher rainfall, or coastal areas, a range of waterbodies (lakes, rivers, wetlands, estuaries, coastal or marine environments) may overlie storage areas. Therefore, it is important to understand the passage of leaked gas via saturated zones for the purpose of determining environmental impacts and for identifying appropriate monitoring methods to identify and quantify the leaked gas.

Table 13. Definitions and terminology related to gas migration into surface waters (from Oldenburg and Lewicki, 2006).

Term	Definition
Leakage	Migration in the subsurface away from the primary containment formation, e.g., through a fault or abandoned well
Seepage	Migration across a boundary such as the ground surface or from subsurface rock or sediments into surface water. Bubble immiscible volume of a secondary fluid phase (e.g., supercritical, gas, liquid) within a primary connected phase (e.g., aqueous)
Ebullition	Formation of bubbles from a liquid supersaturated with respect to dissolved gases, either in surface water or in groundwater
Bubble flow, or gas-phase transport	Flow component(s) as transported in discrete bubbles
Channel flow	Flow of component(s) as transported in a secondary connected fluid phase within a primary liquid phase
Dissolution	Uptake of volatile components into solution in the liquid phase
Advection	Component transport driven by movement of a phase containing the component
Diffusion	Component transport driven by concentration gradients within a phase
Dispersion	Component transport by small-scale advective motions and by diffusion that can be modelled collectively as a diffusive process

A range of physical processes influence CO_2 migration through sediments into overlying surface waters as bubbles or dissolved gas (Figure 46). In cases where there are low CO_2 fluxes and high CO_2 solubility, the transport mechanism is typically driven by dissolution and dispersive transport, while the rare case of high fluxes and low solubility is more likely to promote ebullition and bubble flux (Oldenburg and Lewicki, 2006). As described in Section 3 and reiterated by Oldenburg and Lewicki (2006), abandoned wells, or fault zones are the two most likely mechanisms that would result in leakage from a carbon storage location. Due to the depths and the large distance required to transport, it is acknowledged that any leaked CO_2 could be in the form of a gas, liquid or supercritical state, however at the point of entry into a surface waters be that lacustrine or marine this CO_2 will be in a gaseous or dissolved state.

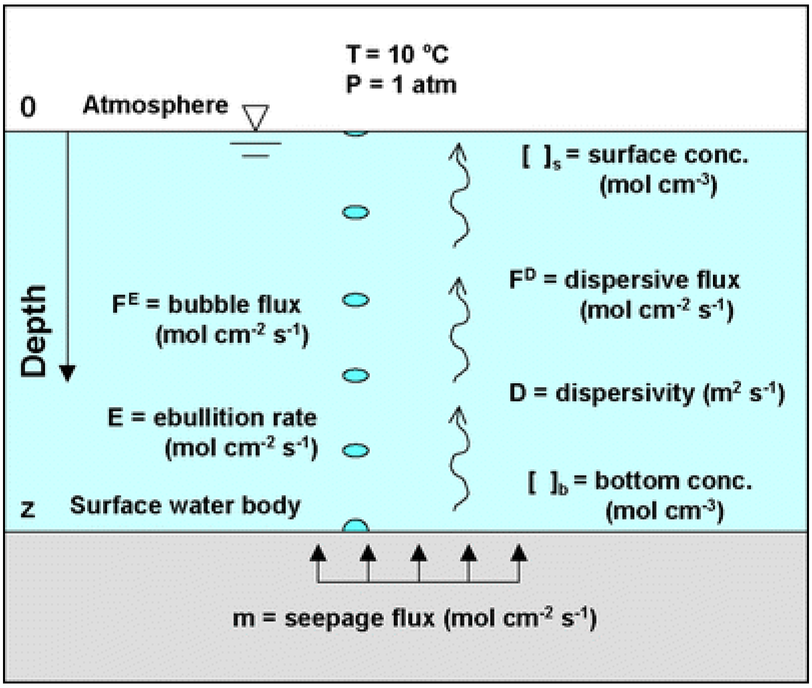

Figure 46 How each of the processes that involve migration of gas in and through surface waters occurs (Oldenburg and Lewicki, 2006).

Analogues for gas transport from the subsurface through water bodies are well known, studied and documented such as various regions of Italy (Chiodini et al., 1999; 2000) Mammoth Mountain, California, USA (Evans et al., 2002), Paradox Basin in Utah, USA (Shipton et al., 2004a; b) and more recently at Daylesford, Victoria, Australia (Roberts et al., 2019). Any springs charged with CO_2 can directly release gas emissions or from the groundwater as it is transported to the surface.

Less easy to quantify and observe are leaks in high energy fluvial systems, though Shipton et al., 2004a, b) has observed gas bubbles in lines consistent with fault traces where the Little Grand Wash Fault Zone crosses the Green River in Utah, USA. This may be why there is consistently more focus on lakes and reservoirs in the research literature. Oldenburg and Lewicki (2006) in their review are specific in their summary of this category to be non-volcanic lakes as volcanic lakes represent a distinct class of water body that receive CO_2 inputs (see how these lakes do not represent appropriate analogues in the case study box below).

Molecular diffusion and bubble flow are the main pathways of gas exchange in lake environments. Though it must be noted that because of the higher solubility of CO_2 relative to other gases typically found in these environments (i.e., CH_4), elevated concentrations can build up at depth and become supersaturated with respect to CO_2. This is enhanced in winter due to reduction in productivity and photosynthetic uptake.

Due to their restricted geographic extent, volume and their location in depressions, lakes can become highly stratified (e.g., temperature). In temperate regions this can be particularly strongly expressed in spring and summer months where weather conditions in many regions can be relatively benign. This can lead to enhanced concentrations of CO_2 in the deeper waters. Tropical lakes are also impacted by stagnation due to few changes in meteorological behaviours.

Other controls on CO_2 composition and distributions in lakes are overall depth of water/geometry, temperature, barometric pressure, wind and general water movement and flow. These controls determine the degree of mixing and stratification. in these water bodies and thus rates of atmospheric exchange of CO_2.

Volcanic lakes, an extreme and atypical analogue

Volcanic lakes are often taken as a separate subgroup when considering leakage of CO_2 as they are atypical of leakage of CO_2 into water bodies. In these cases, CO_2 is delivered to the lake from the out-gassing of underlying or nearby volcanos. Many examples of these lakes include caldera lakes which can be deep, and as a function of their position within calderas, may not be affected by other processes that aid mixing and atmospheric transfer of CO_2 in other settings, such as wind and water flows.

Many volcanic lakes have been studied in more temperate regions such as Laacher See, Germany, Dieng, Indonesia and Mt. Gambier, Australia and whilst these lakes receive CO_2 inputs from volcanic sources these lakes overturn seasonally thus mitigating large scale build-up of CO_2.

Where large CO_2 inputs occur into volcanic lakes AND where seasonal surface forcing is limited (e.g. within the tropics) water column stratification can occur and lead to saturation of bottom waters with $CO_{2.}$

An often-cited example is the tragic events that occurred at Lake Nyos and Monoun (Krajick, 2003 and references therein) in Cameroon, in the 1980s These examples are often brought up in association with CO_2 leakage and as a form of evidence for likely environmental and human health impacts if CO_2 were to leak from geological storage.

The crater lake at Nyos is unusually deep (> 200 m) and sits atop a volcanic breccia pipe. These features have interpreted extensive permeability allowing migration of volcanic gases buoyantly upward to the lake or earth's surface (Krajick, 2003). The lake's depth allowed stratification of the water with the deep layers holding increasing amounts of CO_2 (Sigurdsson et al., 1987). The equatorial location of the lake led to thermocline development and other stratification mechanisms which were rarely perturbed by seasonal temperature swings or winds. This could mean that the deepest layers were rich in CO_2 and could have sat untouched for centuries (Sigurdsson et al., 1988; Krajick, 2003).

This large reservoir of CO_2 was released after a landslide (Figure 47), which may have been a sufficient disturbance to set off a chain of events that included a large, uncontrolled release of CO_2 rich gas around the lake (Sigurdsson et al., 1987; Bang, 2022).

The volume of CO_2 was calculated by Sigurdsson et al. (1987) to be of the order of 1.24 million tonnes CO_2 (Bang, 2022) or 1.94×10^6 tons (Sigurdsson et al., 1987). Because of the geography of Lake Nyos, the denser CO_2 filled the low-lying ground, displacing air. CO_2 can, depending on concentration, act as both an asphyxiant or toxicant (Permentier et al., 2017). Tragically, approximately 1,800 people died after the uncontrolled release and many were injured along with deaths of domesticated animals, wildlife and insects (Sigurdsson, 1988; Krajick, 2003).

Whilst this event and others like it are catastrophic, they are not representative of potential leakage of CO_2 from CO_2 storage activities for the following reasons:

- Site selection would identify water bodies within the vicinity of storage site and assess risk of CO_2 leakage into them and the potential impacts

- CO_2 leakage magnitude would be low in a CCS storage site, and not >1 million tonnes within a short (one day) time period
- Robust risk-based monitoring frameworks, where water bodies of risk were identified would include monitoring of CO_2 content in these water bodies
- Risks could be mitigated through artificial degassing of lacustrine waters as has occurred in Lake Nyos since the degassing event (Krajick, 2003)

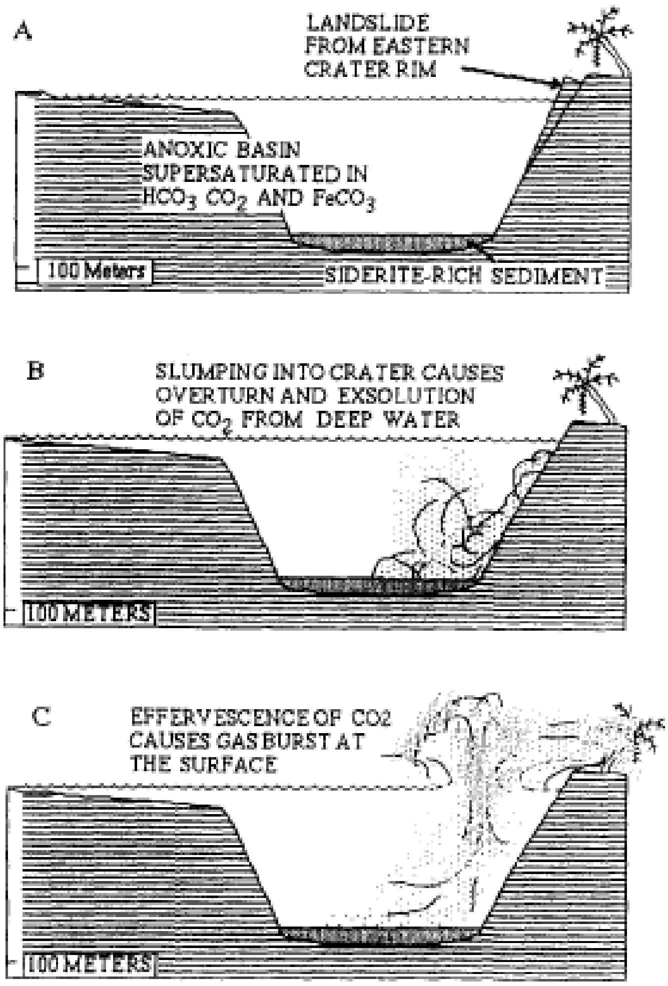

Figure 47. Potential mechanism for CO_2 release at Lake Nyos. From Sigurdsson et al., 1987.

Studies of gas leakage in marine environments are typically related to searching for sub-sea seeps of oil and natural gas, so migration of CH_4 is well documented along fault lines and above anticlinal traps. They can be detected using sonar data and are seen as positive identification of active petroleum source kitchens and means of de-risking hydrocarbon exploration. The rate of release of gas can be influenced by tidal forcing depending on depth. A fuller description can be found in section 4.5 and or 4.6).

For porous media that interfaces with water bodies, the passage of CO_2 is restricted by the presence of the solid grains of rock that make up the rock or sediments it is travelling through. This pathway can be quite tortuous and be further impacted by capillary forces depending on the grain size and distribution. Discrete bubbles may travel through the porous media or coalesce to act as a wetting agent and move through that media by channel flow (Figure 48).

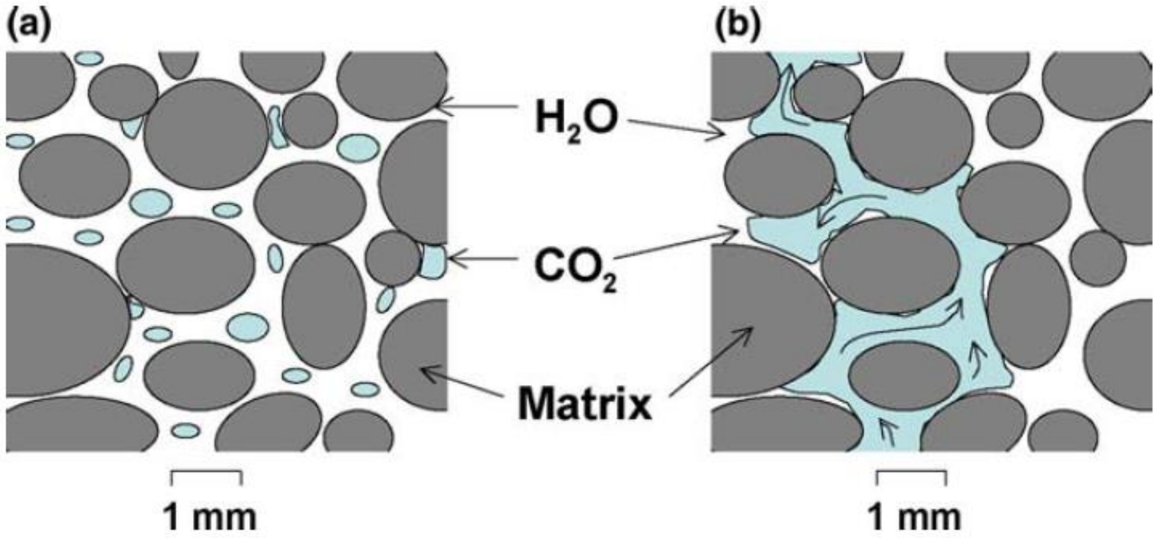

Figure 48. Schematic representation of (a) bubble flow and (b) channel flow. Note the capillary entrapment of some gas in (a). From Oldenburg and Lewicki (2006).

In the case of coarser rocks, such as gravels or sands, bubble flow may dominate through buoyancy, while fine porous media results in stronger capillary forces. This latter can be a significant trapping mechanism of CO_2 in deeper formations.

On arriving in surface waters the gas bubbles can migrate and become released at the surface, or may dissolve and migrate through diffusive or dispersive processes. Some lakes may not experience such high energy input and so mixing is limited or absent – especially in the case of deep equatorial lakes or those with permanent ice cover. Solubility can also be impacted by the salinity of the waters, and any contrast between saline and freshwater aquifers can mean that bubbles of CO_2 in a saline aquifer may become dissolved in fresher water systems (Oldenburg and Lewicki, 2006).

When Oldenburg and Lewicki (2006) brought their review together they concluded the following:

- CO_2 transport through deeper surface waters is by ebullition/bubble flux for high seepage flux
- CO_2 transport through shallower surface waters is by diffusion/dispersion for low seepage flux
- CO_2 solubility is strongly controlled by pressure and temperature, but also salinity

Seepage of CO_2 is not attenuated by water bodies irrespective of the transport mechanism or water body type in virtually all cases. The exception is perhaps highly unusual cases where deep volcanic lakes in equatorial regions are prone to stratification, stagnation and no overturning over 10s to 100s years, such as the case studies reported below.

'Teal carbon', which has only recently entered the carbon colour nomenclature, refers to the carbon stored in freshwater wetlands and includes surface waters – whether natural, modified, or artificial – that are subject to permanent, periodic, or intermittent inundation (Nahlik and

Fennessy, 2016). Inland waters are classified as riverine (having an open channel), lacustrine (large open water systems such as lakes) or palustrine (small vegetated non-channel environments including billabongs, swamps, bogs, and springs) wetlands.

There are no estimates for freshwater wetlands in Australia at present (Fitch et al., 2022). Estimates of carbon storage in freshwater inland wetlands in the United States total 11.52 PgC, much of which is within soils deeper than 30 cm. Freshwater inland wetlands, in part due to their substantial areal extent, hold nearly ten-fold more carbon than tidal saltwater sites—indicating their importance in regional carbon storage (Nahlik and Fennessy, 2016).

Monitoring

Monitoring in aqueous environments is considerably more complex and expensive relative to onshore monitoring techniques. But there are a broad range of tools available, many of which are covered in sections 4.5 and 4.6 where marine/offshore projects may be located. In offshore scenarios, the water depth tends to be a major challenge, and thus significant effort may be made to ruggedise tools to withstand significant pressures in deeper environments.

Figure 49 Example of gas seepage at Daylesford springs. Image from J. Roberts & A. Feitz.

In the case of surface waters, tools need not necessarily be required to withstand deeper waters, and so cheaper alternatives may be utilised. Tools such as simple bubble detectors or localised pH measurements may give suitable indications. High resolution GPS tools may be of benefit if returning to monitor changes or establish baseline data.

Flux systems have been used in locations where water table is close to surface or natural springs are emanating CO_2 (Roberts et al., 2019). An altered flux chamber and LI-COR gas analyser was employed to measure springs in Daylesford, Vic, Australia (Figure 49). At some sample points, a floating flux chamber was employed over deeper water zones.

Shallow water bodies may also be able to be assessed by acoustic sensors (see Section 4.5) but the sensors have to be configured differently for the beams to be directed through the smaller water bodies that may have a very different geometry to open waters. Because of that geometry challenge, there may be a negative impact on the quality or resolution of the data.

Other methods can be employed to evaluate presence and impacts of CO_2 in surface waters that may be easier to use than those for deeper ocean waters. Examples of monitoring and verification approaches in shallow waters and benthic sediments are well covered in the QICS controlled release experiment (see CCS and the Marine Environment Special Issue, 2015 for an overview of shallow water approaches). Taylor et al. (2015) noted that approx. 15% of CO_2 reached the sediment-water interface and 14 – 63% of injected CO_2 was likely to dissolve in sediment pore waters at QICS (Taylor et al., 2015) the losses and uncertainty was one of several reasons why Roberts and Stalker (2020) highlighted the need for further marine-based controlled release experiments to better understand residence of CO_2 and trapping in near-surface sediments. Further, experiments by Myers et al. (2019) investigated through a series of experiments rates of leakage in shallow waters using chemical tracers to gain an idea of how hard it is to quantify and attribute leakage.

Ultimately pH meters might be a more easily deployable option in shallow, surface water environments for first pass evaluation of potential leakage that could cause environmental impacts (Stalker et al., 2011).

4.3.3 Assessment

The assessment of the impacts on surface water will be addressed in two parts: 1. Impact from *compromised subsurface integrity* and 2. Impact from *compromised well integrity*.

Will compromised subsurface integrity result in an increase in carbon dioxide in surface waters?

Key Questions	**Answers**
Is it possible?	**Yes.** Geological features in the form of faults or fracture zones may form leakage pathways for stored CO_2 from the storage interval to eventually reach river, pond or related surface waters.
Is it material?	**No**. For CO_2 leaking from a storage reservoir through compromised subsurface integrity to reach rivers, ponds or other surface water features, it needs to flow through an extensive stack of sedimentary strata. This will provide ample opportunity for the flux to be attenuated, especially through buffering, dissolution and residual saturation in intervening aquifers and not result in a material change in CO_2 pressure in surface water.
Can it be monitored?	**Yes**. Water sampling. Cautionary: Evaluation of water bodies overlying the storage area and their geographic situation would rapidly identify those locations at risk of unintended concentration of CO_2.
Could it be mitigated?	**No**. Should a CO_2 leakage pathway be established through compromised subsurface integrity, there are no interventions possible to avoid or mitigate CO_2 flux. The link between carbon geological sequestration operations and compromised subsurface integrity outlines strategies to minimise occurrence of compromised subsurface integrity due to carbon geological sequestration.
Could it be remediated?	**Yes**. Controlled degassing of the stratified zone in the water body by pumping or stimulating water circulation can reduce the CO_2 accumulation in lakes.
Summary	**Possible but not material.**

Will compromised well integrity result in an increase in carbon dioxide in surface waters?

Key Questions	**Answers**
Is it possible?	**Yes.** Damaged or improperly completed wells could form vertical leakage pathways for CO_2 from the storage complex to surface waters. Examples of CO_2 leakage in the past, although rare, were associated with CO_2 enhanced oil recovery (EOR) projects, including blowouts of production wells drilled into natural CO_2 reservoirs, CO_2 injection wells, active oil production wells, or plugged and abandoned wells within the EOR scheme (Duncan et al., 2009).
Is it material?	**Yes.** IF injector wells and abandoned wells are situated in the immediate vicinity of a surface water body, potential attenuation pathways may not be sufficient to avoid a locally non-negligible change in CO_2 pressure in surface water. However*, a*s injector wells or abandoned wells are not sited in surface water features, a compromised well integrity occurrence will not create a direct pathway of CO_2 leakage into a surface water body. The CO_2 flux will need to pass through sediments, aquifers and/or soils to reach a surface water body. This provides opportunity for hydrogeological and hydrochemical attenuation of CO_2 flux.
Can it be monitored?	**Yes. Water sampling.** Cautionary: Evaluation of water bodies overlying the storage area and their geographic situation would rapidly identify those locations at risk of unintended concentration of CO_2.
Could it be mitigated?	**Yes**. An increase in CO_2 concentration in surface water bodies due to compromised well integrity can be avoided and mitigated by ensuring the intersection of aquifers and soils by injector wells or existing abandoned wells is adequately sealed.
Could it be remediated?	Yes. Well mitigation and remediation technologies are well-established in the petroleum and groundwater industries (e.g., Castaneda-Herrera et al., 2018). Also, CO_2 accumulations in starified lakes can be minimised by pumping or stimulating water circulation.
Summary	**Possible and can be material but can be mitigated**

4.3.4 References

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4.4 Carbon dioxide in the atmosphere

4.4.1 Definition

Leakage from storage into the atmosphere may be the endpoint of processes covered in earlier sections or may result from failure of surface equipment.

4.4.2 Description

Changes to atmospheric concentrations of CO_2 are the key focus of emissions reduction to avoid environmental impacts such as climate change. Well-designed CCS projects are expected to have no or minimal leakage. There are numerous barriers between the storage complex and the atmosphere, as detailed in previous sections. As explained there, the probability of leakage for properly selected storage sites is expected to be small (Alcalde et al., 2018; Hoydalsvik et al., 2021, Daniels et al., 2023). The results from these authors are consistent with numerous other estimates, beginning with the well-known "1% in 1000 years" estimate in the original IPCC report on CCS (IPCC, 2005).

Leakage would be expected to be detected by the monitoring methods that are tailored to detect CO_2 in the various barriers between the storage complex and the atmosphere. Details are given in previous sections. The issue of leakage directly to the atmosphere comprises two distinct risks to those considered earlier.

1) Leakage from surface equipment is usually the main concern of operators. This can be seen in the M&V plans submitted to the US EPA for "Subpart RR" reporting (which leads ultimately to a tax credit for successfully sequestered CO_2). These plans can be found at https://www.epa.gov/ghgreporting/subpart-rr-geologic-sequestration-carbon-dioxide#decisions and the annual monitoring reports are at https://www.epa.gov/ghgreporting/subpart-rr-annual-monitoring-reports . It is clear from these assessments and reports that in practice, CO_2 losses into the atmosphere are minimal and have negligible environmental consequences.
2) Leakage up wellbores and into the atmosphere is the only direct conduit from the storage complex to the atmosphere. If there is leakage at the wellhead, it will be quickly detected by the methods and procedures developed for dealing with surface equipment referred to at (1) above. There have been many statistical studies of wellbore leakage, of which the most recent is Postma et al. (2019). The key conclusion of this body of work is that the impact of CO_2 leakage up a wellbore annulus will be felt in possible contamination of groundwater. The many aquifers that intervene between the storage complex and the surface are almost certain to act as thief zones and absorb any CO_2 making its way up an annulus.

Reviews of CO_2 leakage events at the surface in the USA have concluded that accidents are rare (Duncan et al., 2009; Duguid et al., 2022). The impact (in terms of fatalities) has been very small and is predicted to remain so (Ha-Duong and Loisel, 2011).

In volcanic areas where naturally-occurring CO_2 reaches the surface, there are occasional fatalities of livestock or (rarely) humans, typically caused by seeped CO_2 pooling overnight in lower-lying areas, cellars, and so on. The incidence of fatalities is estimated to be very small in Italian volcanic areas (Roberts et al., 2011). While an imperfect analogy for CCS operations, this does illustrate that the risks of even improbably high leakage can be managed.

Fugitive emissions are losses of gas to the atmosphere from plant and equipment used in the operation and production of natural gas, oil and coal. In the same way, CO_2 may also escape during the capture, compression and storage (CCS) process. However, leakage from surface facilities can be monitored and measured quite robustly. Most work done to date has been on methane monitoring such as research aimed at monitoring methane emissions from gas fields (e.g., in coal seam gas rich basins such as the Surat, Queensland as described by Day et al., 2015). Detection of CO_2 by similar methods would be straightforward, with numerous commercial monitors available.

Monitoring methods have been developed for the detection of direct leakage into the atmosphere (e.g., Lewicki et al., 2009; Humphries et al., 2012; Luhar et al., 2014) for onshore leakage. These methods can detect changes in the atmospheric composition of CO_2 corresponding to leaks of order a few thousands of tonnes per year at a distance of the of order a kilometre from the leak. Sensitivity depends strongly on atmospheric conditions such as wind and convection. Offshore, very small leaks may be readily detectable by the strong acoustic signature of bubble streams, at least close to the bottom of the seafloor before they dissolve in the water column.

The conclusion is therefore that direct leakage into the atmosphere is improbable, and if it occurs can be monitored and managed. Were leakage to occur into the atmosphere by indirect routes, it would probably be detected and remediated at intermediate barriers.

4.4.3 Assessment

The assessment of the impacts on the atmosphere will be addressed in two parts: 1. Impact from *compromised subsurface integrity* and 2. Impact from *compromised well integrity*.

Will compromised subsurface integrity result in an increase in carbon dioxide in the atmosphere?

Key questions	ANSWERS
Is it possible?	***Yes.*** Geological features in the form of faults or fracture zones may form leakage pathways for stored CO_2 to the atmosphere.
Is it material?	***No.*** For CO_2 leaking from a storage reservoir through compromised subsurface integrity to reach the atmosphere, it needs to flow through an extensive stack of sedimentary strata, and potential through soil and water bodies. This will provide ample opportunity for the flux to be attenuated, especially through buffering, dissolution and residual saturation in intervening aquifers and therefore not result in a material change in CO_2 pressure in the atmosphere.
Can it be monitored?	**Yes.** Monitoring methods have been developed for the detection of direct leakage into the atmosphere (e.g. Lewicki et al., 2009; Humphries et al., 2012; Luhar et al., 2014) for onshore leakage. These methods can detect changes in the atmospheric composition of CO_2 corresponding to leaks of order a few thousands of tonnes per year at a distance of order a kilometre from the leak.
Could it be mitigated?	**No**. Should a CO_2 leakage pathway be established through compromised subsurface integrity, there are no interventions possible to avoid or mitigate CO_2 flux. The link between carbon geological sequestration operations and compromised subsurface integrity outlines strategies to minimise occurrence of compromised subsurface integrity due to carbon geological sequestration
Can it be remediated?	**No**. Remediating CO_2 leakage along geological leakage pathways to the atmosphere is challenging because these are generally difficult to locate, can be of a diffuse nature and are therefore difficult or expensive to access or effectively seal.
Summary	**Possible but not material**. Material leakage of CO_2 to the atmosphere via geological pathways is negligible at a properly characterised site. Mitigation and remediation options are limited.

Will compromised well integrity result in an increase in carbon dioxide in the atmosphere?

Key questions	ANSWERS
Is it possible?	**Yes**. Damaged or improperly completed wells could form vertical leakage pathways for CO_2 from the storage complex to the atmosphere. Examples of CO_2 leakage in the past, although rare, were associated with CO_2 enhanced oil recovery (EOR) projects, including blowouts of production wells drilled into natural CO_2 reservoirs, CO_2 injection wells, active oil production wells, or plugged and abandoned wells within the EOR scheme (Duncan et al., 2009).
Is it material?	***Yes.*** A compromised well can create a direct pathway for CO_2 to enter the ocean. This can lead to a locally material change in atmospheric CO_2 pressure. Based on statistical estimates by BEIS (2023), worst-case leakage amounts are less than 0.07 % of the total storage volume.
Can it be monitored?	**Yes.** Monitoring methods have been developed for the detection of direct leakage into the atmosphere (e.g. Lewicki et al., 2009; Humphries et al., 2012; Luhar et al., 2014) for onshore leakage. These methods can detect changes in the atmospheric composition of CO_2 corresponding to leaks of order a few thousands of tonnes per year at a distance of order a kilometre from the leak.
Could it be mitigated?	**Yes**. An increase in CO_2 concentration in the atmosphere due to compromised well integrity can be avoided and mitigated by ensuring adequate barriers are constructed between injector wells or existing abandoned wells and the atmosphere.
Could it be remediated?	**Yes**. Well mitigation and groundwater remediation technologies are well-established in the petroleum and groundwater industries (e.g., Castaneda-Herrera et al., 2018).
Summary	**Possible and can be material but can be mitigated**. While material leakage of CO_2 to the atmosphere via compromised wells is unlikely at a properly characterised site, leaks are generally easy to detect and quickly remediated.

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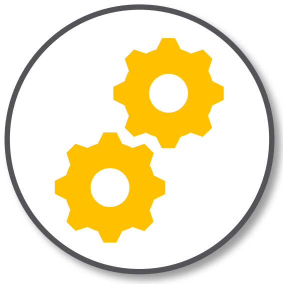
4.5 Carbon dioxide in the ocean

4.5.1 Definition



CO_2 that has leaked from the storage container and has migrated through the overburden and entered the marine environment through seepage either in a dissolved or gaseous phase.

4.5.2 Description

Processes

CO_2 in the world's oceans and seas is constrained by air-sea exchange driven by natural processes. Concentrations of CO_2 in the oceans tend to be in equilibrium with the atmosphere over long time periods. When CO_2 dissolves into seawater water it forms carbonic acid (H_2CO_3) and carbonate and bicarbonate ions, increasing seawater acidity. Therefore, the CO_2 concentration is often considered in terms of changes in pH of waters. pH is a -log scale such that a decrease in pH represents an increase in acidity and vice-versa. A change of 1.0 in terms of pH represents and order of magnitude increase or decrease in the concentration of hydrogen ions, in laypersons terms the acidic strength of the solution. The pH of waters can be driven by several processes as show in Figure 50 (Carstensen and Duarte, 2019). Changes in pH associated with freshwater inputs are principally driven by Total Alkalinity (TA) of those waters and the mixing of higher salinity oceanic waters (Carstensen and Duarte, 2019). Mixing of waters can also include upwelling, where oxygen-deficient (hypoxic waters) can lower pH (Melzner et al. 2013). There are other drivers of pH within oceanic and coastal waters. Biological activity either through primary production, where chlorophyll a (Chla) is typically used as an indicator of primary production, decreasing acidity, or respiration of marine organisms which conversely increases acidity lowering pH (Figure 50).

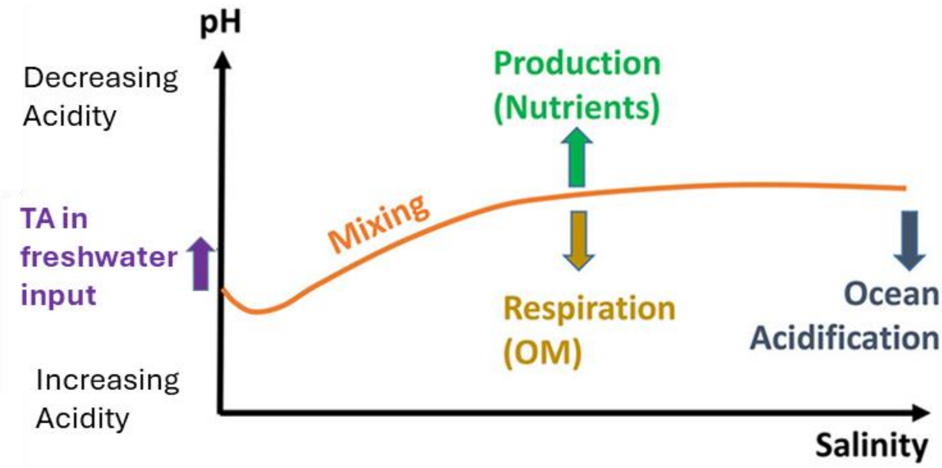


Figure 50. Key drivers of pH variability in coastal ecosystems (modified from Carstensen and Duarte, 2019). TA=total alkalinity.

The pH and therefore CO_2 within coastal and oceanic waters is also impacted by seasonal and interannual variations associated with the aforementioned processes. In their study of pH from 83 coastal sites compared to the Hawaii Ocean Time-series (HOT http://hahana.soest.hawaii.edu/hot/) and the Bermuda Atlantic Time Series (BATS; http://bats.bios.edu/) seasonal and interannual variations in coastal waters of typically 1 pH unit could be observed, although variability to could be as high as 1.4 and 1.6 respectively (Carstensen and Duarte, 2019).

As discussed above, CO_2 content in waters is driven by air-sea exchange and an equilibrium between the two. Atmospheric emissions of CO_2 from human activities have generated an imbalance resulting in increasing amounts of CO_2 being absorbed into the oceans, effectively buffering the build-up of CO_2 in the atmosphere (Church et al. 2017). The increased amounts of CO_2 in the atmosphere is causing ocean acidification associated with decreasing pH, as can be seen in Figure 51.

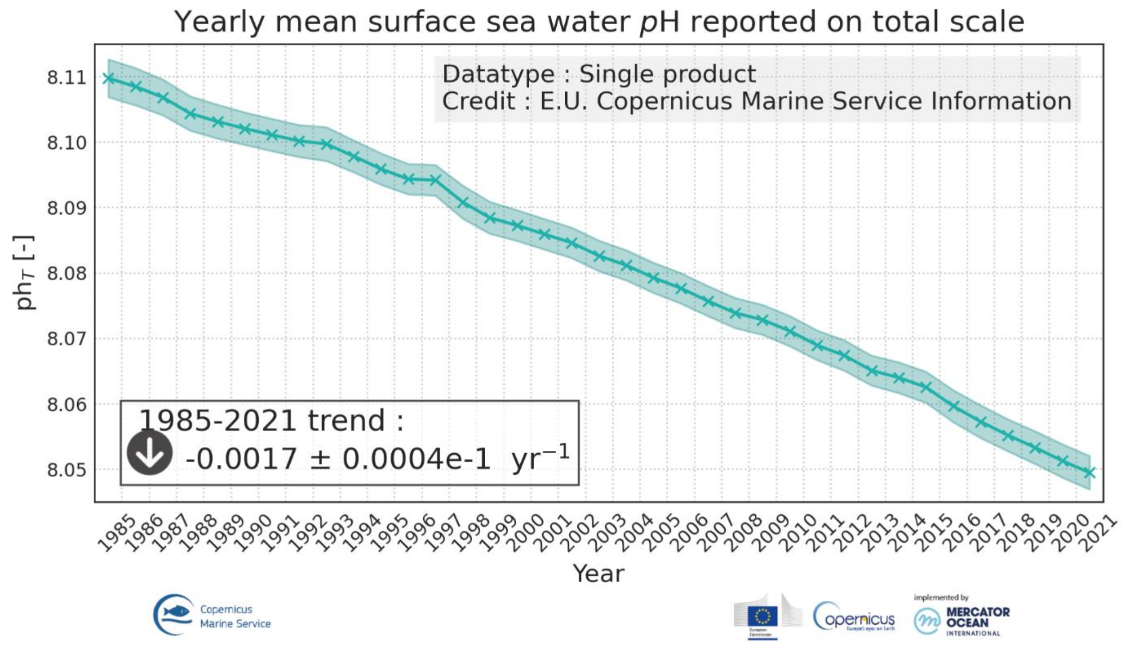


Figure 51. Global Ocean acidification - mean sea water pH time series and trend from Multi-Observations Reprocessing, E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). DOI: 10.48670/moi-00224. (Accessed 09-Aug-2023).

CO_2 seeps

The process of point source CO_2 leakage into the water column is a well understood phenomenon. Globally there are numerous natural submarine CO_2 seeps (Figure 52) that have been studied to understand the impacts of ocean acidification and the impact of CO_2 release from subsurface CO_2 storage (e.g. Price and Giovannelli 2017; Aiuppa et al. 2021). The CO_2 submarine seeps are typically associated with shallow subsurface hydrothermal and volcanic activity, and as well as being found in deep water settings are also found in shallow waters, the latter being more amenable to detailed study and characterisation. It should be noted that volcanic seeps can contain other gases and as such may not be a direct analog for CO_2 leakage from CCS projects but can provide valuable insights.

Further to the CO_2 seeps studies there is a large body of literature on the occurrence and processes associated with cold and hydrocarbon seeps which has application to the study of the processes and mechanisms of seepage (e.g., Joye, 2020; Talukder 2012).

CO_2 seeps typically manifest at the seafloor not as a single point source but as a number of discrete bubble plumes in the water column (Figure 53). This is due to subsurface leakage utilising shallow fault conduits or the gas fluidising unconsolidated near surface sediments resulting in multiple and dendritic fluid/gas conduit networks (Talukder 2012 and references therein).

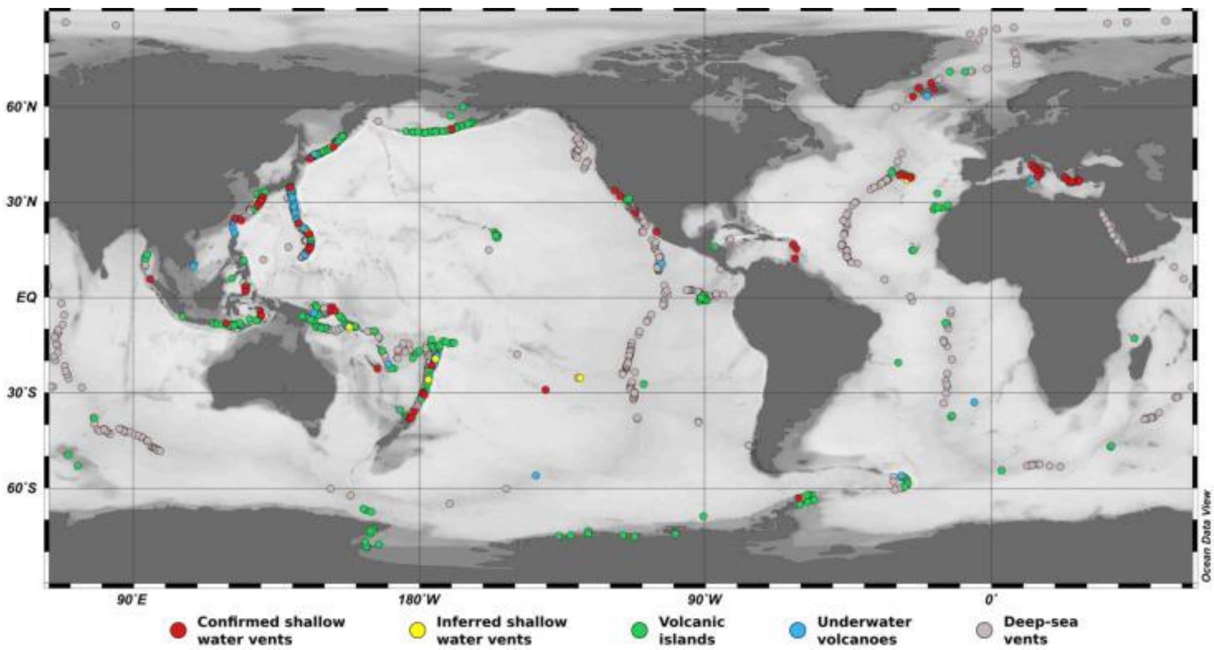


Figure 52. Map showing the location of confirmed and inferred shallow-water hydrothermal vents, volcanic islands, underwater volcanoes, and deep-sea hydrothermal vents. Deep-sea hydrothermal vent locations have been obtained from the InterRidge database Ver. 3.3 (Beaulieu, 2013; http://vents-data.interridge.org/), volcanic island and underwater volcanoes locations obtained from the Holocene Volcano Database (Smithsonian Institution Global Volcanism Program, http://volcano.si.edu/), and the location of shallow-water hydrothermal vents (confirmed and inferred) was obtained from the InterRidge database Ver. 3.3 and manual searches of published scientific literature (Price and Giovannelli 2017).

Figure 53. Example of vent forming sites/fields in shallow waters from Baia di Levante, Vulcano Island (Italy) (Photo credit: Nicolas Floc'h, Aiuppa et al 2021).

The release of CO_2 from the seabed from CO_2 seeps is in the form of CO_2 and CO_2 saturated waters and brines. CO_2 bubbles typically have spherical diameters of 5-100 mm (Gros et al. 2019, Li et al., 2021; Figure 54) and bubbles will divide, coalesce or collapse as pressure diminishes as they rise through the water column (Sellami et. al. 2015). As they rise, CO_2 will rapidly dissolve into the water from the bubbles causing them to shrink, and bubble plumes may not reach the sea surface, especially in deeper waters (Figure 54, Gros et al. 2019). The bubble plumes are readily detected using active acoustic methods such as single or multibeam echo sounders, however their detection can be confounded by fish schooling (Scoulding et al. 2023 and references therein).

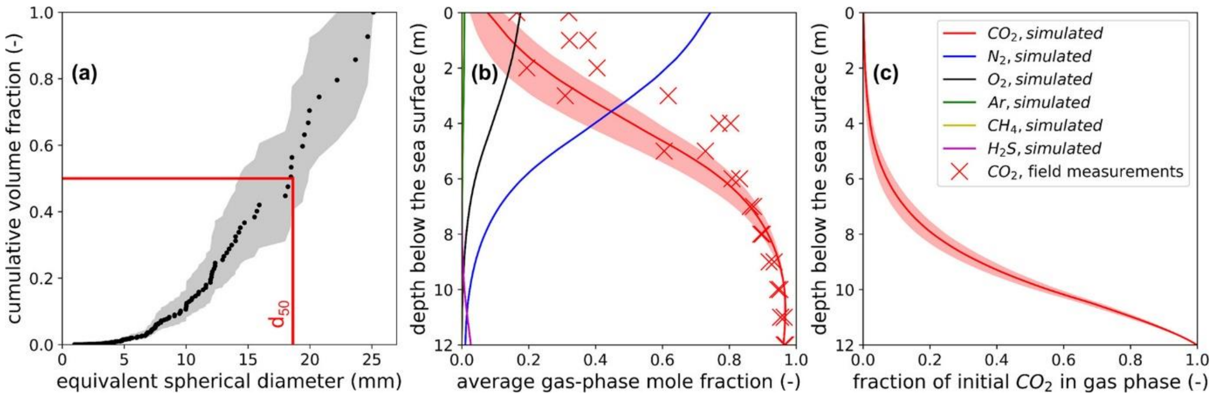


Figure 54. (a) Observed initial CO_2 bubble size distribution at Bottaro crater, offshore Panarea, Italy on May 12, 2014 (solid dots) and bootstrap 95% confidence interval (gray area). (d50 = volume median diameter). (b) Evolving average composition of the gas phase from the emission source at a 12 m depth (vent C) to the sea surface, as predicted by Texas A&M oil spill (outfall) (TAMOC) calculator for all simulated compounds (solid lines = measured initial bubble size distribution, shaded area = 95% confidence interval as defined on panel a, displayed only for CO_2), and measured in the field for CO_2 (×). (c) Fraction of the CO_2 released at the emission source remaining within gas bubbles as a function of depth, according to the TAMOC simulation (Gros et al. 2019).

The dissolution of CO_2 from the CO_2 plumes and released CO_2 saturated waters and brines will change the pH of the nearby waters. Field data collection from natural CO_2 seeps has been used in high resolution simulations of pH changes in waters in the vicinity of the CO_2 seeps to predict the extent of changes in pH (e.g., Gros et al. 2019, Figure 55) and possible impacts of CO_2 leakage.

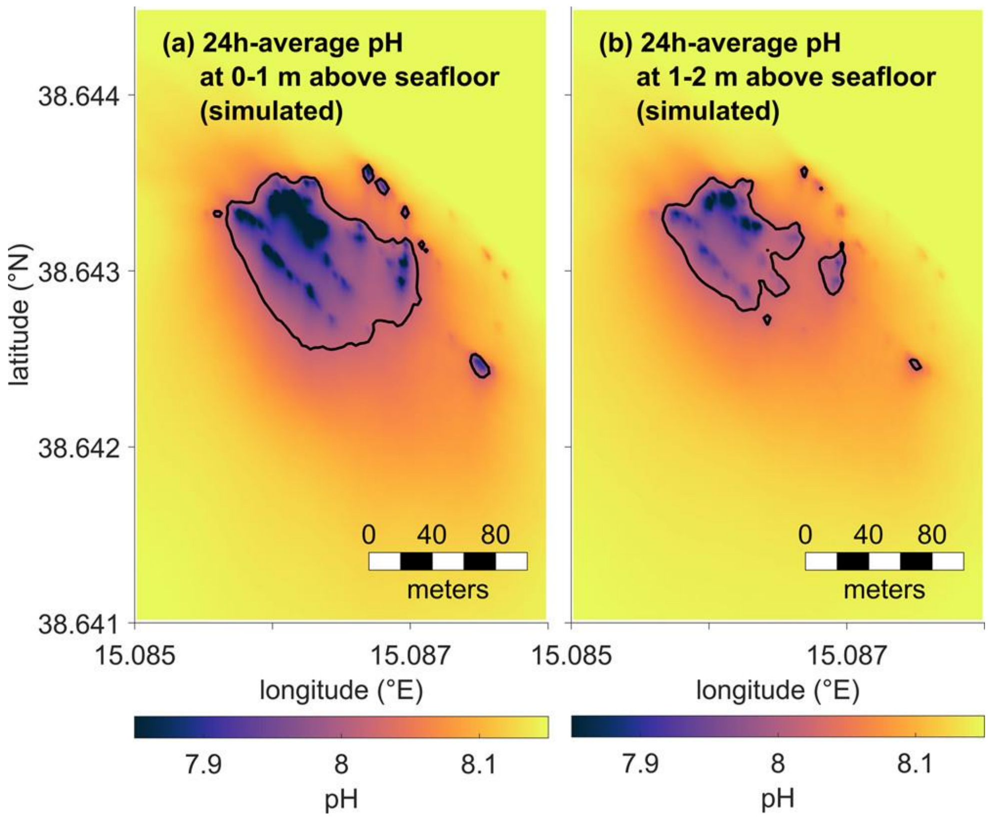


Figure 55. Simulated average pH at the natural analog Bottaro crater, offshore Panarea, Italy over a 24 h period (May 8–9, 2014, from 8 am to 8 am), at (a) 0–1 m and (b) 1–2 m above the seafloor. The solid black line indicates the potential impact limit (ΔpH = 0.15) (Gros et al. 2019).

CO_2 leakage modelling

For CCS projects any potential CO_2 leakage is typically simulated using time evolving, 3D coupled hydrodynamic-biogeochemical systems which describe physical flows and biogeochemical fluxes, often explicitly modelling CO_2 chemistry. Considerable effort has been devoted within the global CCS research community over the last decade to developing and applying such marine system models to advance offshore storage (e.g., Blackford et al. 2008; Blackford et al., 2017; Blackford et al. 2018; Chen et al. 2009; Dewar et al. 2013; Greenwood et al. 2015; Phelps et al. 2015). Whilst some of these models consider both gas and liquid CO_2 phases, the primary purpose is to simulate chemical change in the water column (Greenwood and Mongin, 2020). In the absence of realistic natural analogues or deliberate controlled CO_2 release experiments at locations associated with CO_2 storage, models provide the only viable option to characterise the morphology of hypothetical release events, and thereby quantify detection targets.

Whilst a small number of deliberate controlled CO_2 release experiments have been conducted elsewhere, for example as part of the QICS (http://www.bgs.ac.uk/qics/home.html) and STEMM

CCS (http://www.stemm-ccs.eu) projects, as with the CO_2 seeps, the resultant distributions and impacts are location-specific and difficult to generalise because ocean conditions at each site are unique. Ideally, a local controlled release experiment could be used to calibrate a suitable model, but this is often not possible. In that case, observations of controlled release experiments at other sites and natural CO_2 seep locations are used to help parameterise the relevant aspects of CO_2 behaviour within the models. The most sophisticated models can characterise the chemical signal arising from hypothetical releases whilst concurrently quantifying the natural variability, allowing anomaly detection criteria to be tested within the modelling system itself (e.g. Blackford et al. 2017). Models can also be used to devise the most cost-efficient deployment of sensors to maximise detection of hypothetical releases (e.g. Hvidevold et al. 2015; Greenwood et al. 2015) and contribute to environmental risk assessments by quantifying the potential impact from hypothetical releases (Blackford et al. 2018). Ideally models should be coupled with observational data to ensure accuracy.

Suitable 3D marine models require considerable effort to develop, parameterise, evaluate and interpret. They are computationally intensive to run, limiting the amount of spatial and temporal resolution that can be afforded, and often must be tailored to each storage site (Blackford et al. 2018; Greenwood & Mongin, 2020). Because of the rapid dilution of any artificially added CO_2, the restrictions on model spatial resolution are particularly important in the context of quantifying hypothetical releases of CO_2, especially within highly dynamic coastal areas where dispersion rates are high. Equally, the relatively low temporal resolution can limit the type of analysis that can be undertaken (Greenwood & Mongin, 2020).

Understanding of effects of CO_2 leakage in the water column

As described above, effects of CO_2 leakage into the water column will be expressed as a change in pH of waters in the vicinity of the leakage point(s). The total area over which a theoretical release of CO_2 noticeably reduces the water-column pH, compared with the natural background level increases with time as the artificial plume spreads, eventually defining a detection 'footprint' for a given release rate and anomaly detection limit. The size of the detection footprint is strongly dependant on average current speeds and mixing, with high flow rates diluting any hypothetical addition of CO_2 more rapidly, thereby reducing the area over which a pH change can be detected. The detection footprint will typically not have a uniform distribution as the dissolved CO_2 plume may be elongated by currents. Thus, the detection footprint will change from one location to another depending on the hydrodynamic conditions. The detection footprint provides critical information about the distance over which a theoretical release can be distinguished from the natural background by a chemical sensor (Ross et al. 2022).

A range of simulations can determine detection footprints across a range of leakage scenarios (see Blackford et al., 2020 and references therein). An example of this type of analysis has been undertaken for different leakage scenarios in the coastal Gippsland region of Victoria, Australia by Ross et al. (2022). In this case the detection footprint is elongated in the long-shore direction, where the detection length scales are greater along the coast than they are in the cross-shore direction. Estimates of the detection length scale in both the long-shore and cross-shore direction for hypothetical releases between 5 and 50 t CO_2 d^{-1} and anomaly detection limits of -0.01 and -0.02 pH units are shown in Figure 56.

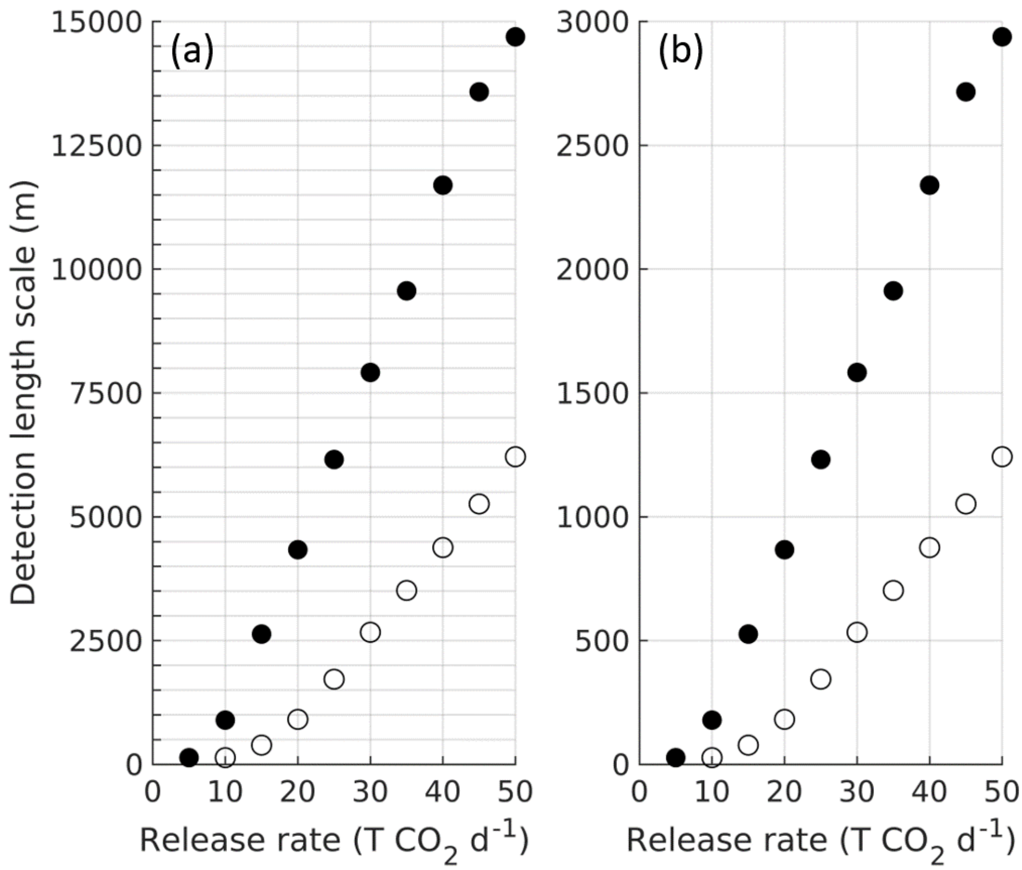


Figure 56. Example of detection length scales for the coastal Gippsland region of Victoria, Australia for an area experiencing a drop in pH of either 0.01 units (closed symbols) or 0.02 units (open symbols) in (a) the long-shore and (b) cross-shore direction as a result of a hypothetical release of CO_2 between 5 and 50 t/day. Calculation assumes an aspect ratio for the area affected of 5:1. (Ross et al. 2022).

In the coastal Gippsland region natural seasonal variability of pH is ~ 0.1 units suggesting that changes of pH less than this are likely to be tolerated by marine organisms. Model results show that a hypothetical release of 45 t CO_2 d^{-1} will reduce the pH by at least 0.1 units over an area approximately 30 m in the longshore direction and 6 m in the cross-shore direction. Releases of CO_2 volumes smaller than this will have impact length scales that reduce to just a few metres.

Importantly, setting the change in pH associated with CO_2 leakage in context with pH variability of the environment, and its likely change over time, is critical to understanding its overall impact. Any localised changes in pH would occur in tandem with global changes in seawater pH resultant from anthropogenic increases in atmospheric CO_2. Near-future acidification is anticipated to bring the pH of surface waters to 7.8, whereas far future acidification is expected to bring the pH to 7.6 (Byrne and Przeslawski, 2013). In trying to predict the impacts of ocean acidification, pH changes in the range of 0.2-0.4 are commonly studied as a consequence (Byrne and Przeslawski, 2013). Unlike ocean acidification, pelagic changes in pH from release from a CCS reservoir are expected to be ephemeral and localised as the acidified water is mixed by waves, tides and currents (Blackford et al., 2010).

Temperature and pH normally undergo diurnal variation due to tides and other natural forces (Byrne and Przeslawski, 2013). In coastal areas, variance in pH may already exceed predicted 0.2-

0.4 near future oceanic pH change due to natural processes, such as changes in algal production and freshwater inundation (reviewed in Menu-Courey et al., 2019). In the coastal Ardmucknish Bay, UK area where the QICS CO_2 release study was conducted, pH can range by 0.4 daily units due to natural factors (Blackford et al., 2015), whereas in coastal Gippsland model projections, a change of 0.05 would be expected over a small spatial and temporal scale (Greenwood & Mongin, 2020). By contrast, a recent study of long-term ecological monitoring for US estuaries, as described above, have found typical seasonal variation of greater than 1 pH unit or more in estuaries that were influenced by eutrophication (Baumann and Smith, 2018).

Therefore when compared to the natural variation within pH and the medium term changes in pH associated with ocean acidification, changes of ~0.1 pH units over impact length scales of metres to tens of metres associated with 45 t CO_2 d^{-1} leakage in a well-mixed coastal environment is unlikely to significantly impact marine biodiversity (Figure 57, See section 5.3 below).

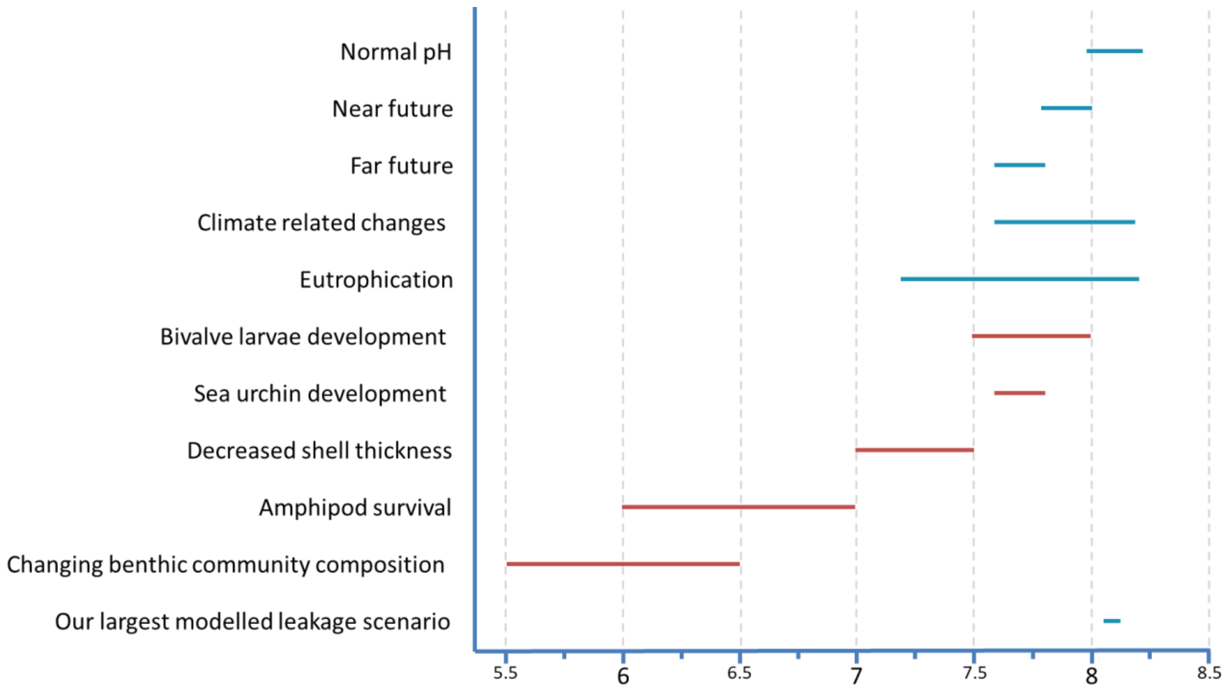


Figure 57. Summary of current variability in ocean pH and future predicted pH associated with ocean acidification due to climate change (blue bars at top of graph). pH range over which there are potential impacts to various biota (red bars), 0.1 pH change associated with 30 m in the longshore direction and 6 m in the cross-shore direction 45 t CO_2 d^{-1} modelled leakage scenario pH change of Greenwood and Mongin, 2020, Ross et al. 2020 (blue bar bottom of graph).

4.5.3 Assessment

The assessment of the impacts on the ocean will be addressed in two parts: 1. Impact from *compromised subsurface integrity* and 2. Impact from *compromised well integrity*.

Will compromised subsurface integrity result in an increase in carbon dioxide in the ocean?

Key Questions	**Answers**
Is it possible?	***Yes.*** Geological features in the form of faults or fracture zones may form leakage pathways for stored CO_2 from the storage interval to the ocean floor.
Is it material?	***No.*** For CO_2 leaking from a storage reservoir through compromised subsurface integrity to reach the ocean, it needs to flow through an extensive stack of sedimentary strata. This will provide ample opportunity for the flux to be attenuated through, especially through buffering, dissolution and residual saturation in aquifers contained in the sedimentary column, and not result in a non-negligible change in CO_2 pressure in ocean water. There is well characterised natural CO_2 seepage into the marine environment, deliberate CO_2 releases for scientific studies and biogeochemical modelling studies which show the limited localised impact of any CO_2 leakage into the marine environment.
Can it be monitored?	**Yes.** There are numerous marine monitoring technologies available for leakage detection throughout the water column (e.g. Dean et al., 2020, Ross et al., 2022). A number of acoustic monitoring technologies are available to identify low level CO_2 leakage. Cautionary: Evaluation of the seabed overlying the storage area and the water column above would rapidly identify those locations at risk of unintended leakage and elevated concentrations of CO_2.
Could it be mitigated?	***No***. Should a CO_2 leakage pathway be established through compromised subsurface integrity, there are no interventions possible to avoid or mitigate CO_2 flux. The link between carbon geological sequestration operations and compromised subsurface integrity outlines strategies to minimise occurrence of compromised subsurface integrity due to carbon geological sequestration.
Could it be remediated?	***No.*** However over time CO_2 would equilibrate between the ocean and atmosphere.
Summary	**Possible but not material.**

Will compromised well integrity result in an increase in carbon dioxide in the ocean?

Key Questions	**Answers**
Is it possible?	***Yes.*** Damaged or improperly completed wells could form vertical leakage pathways for CO_2 from the storage complex to the ocean floor. Examples of CO_2 leakage in the past, although rare, were associated with CO_2 enhanced oil recovery (EOR) projects or CO_2 exploration wells (Duncan et al., 2009), typically the leakage rates from these wells were low.
Is it material?	***Yes.*** A compromised well can create a direct pathway for CO_2 to enter the ocean. This can lead to a locally material change in partial CO_2 pressure in seawater. Well leakage would likely be expressed on the seafloor as a number of small seepages and therefore dispersion and dilution would be enhanced. Papers by various authors have shown that CO_2 leakage into the ocean even at relatively high rates of leakage would have impact length scales where pH changes were over 0.1 pH units of metres to 10s of metres. The zone of any measurable change in water chemistry would be dependent on how well mixed the marine environment is at the location of leakage.
Can it be monitored?	**Yes.** There are numerous marine monitoring technologies available for leakage detection throughout the water column (e.g. Dean et al., 2020, Ross et al., 2022). A number of acoustic monitoring technologies are available to identify low level CO_2 leakage. Cautionary: Evaluation of hydraulic integrity of wells within the vicinity of the CO_2 injection well. Modelling to understand dispersion of CO_2 and impact length scales, as well as active monitoring of the wells and overlying marine environment. Evaluation of the seabed overlying the storage area and the water column above would rapidly identify those locations at risk of unintended leakage and elevated concentrations of CO_2
Could it be mitigated?	**Yes**. An increase in CO_2 concentration in the ocean due to compromised well integrity can be avoided and mitigated by ensuring adequate barriers are constructed between injector wells or existing abandoned wells and the ocean.
Could it be remediated?	**Yes**. Well mitigation and remediation technologies are well-established in the petroleum and groundwater industries (e.g., Castaneda-Herrera et al., 2018).
Summary	**Possible and can be material but can be mitigated**

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4.6 Carbon dioxide in benthic sediments

4.6.1 Definition

CO_2 that has leaked from the storage container and has migrated through the overburden and entered, but has not been expelled, from marine sediments.

4.6.2 Description

Benthic sediments represent the most pervasive habitat on Earth (Snelgrove 2024) these sediments encompass complex three-dimensional biogeochemical gradients that change rapidly over scales of the millimetres (Snelgrove 2024). The term benthic sediment has broad applicability and can principle include the entire submarine sedimentary sequence. However, for the purpose of understanding carbon dioxide in benthic sediments it is limited here to near seabed, typically unconsolidated sediments, characterised by a series of redox zones (Figure 58) in which diverse microbial and infaunal communities are present.

Whilst most of these redox zones occur close to the seabed, the depth of these redox zones are highly variable and can penetrate to several hundred metres in deep sea sediments (e.g. D'Hondt et al., 2004). Redox zonation is determined by a number of factors, including but not limited to, sediment grain size, deposition, overlying and pore water chemistries, organic and inorganic carbon and bioturbation. Understanding the effect of CO_2 and pH on these zones allows understanding of the impact of the CO_2 on sediment infaunal biodiversity.

Marine benthic faunal communities, living in shallow unconsolidated sediments, could be exposed to elevated levels of CO_2 in the event of point-source leakage occurring at the seafloor. Many benthic fauna are sessile or have limited mobility, have reduced dispersal potential, and slow generation times, making them potentially more vulnerable than pelagic species to exposure from a leak.

A CO_2 leakage is anticipated to have two pathways for effects on benthic sediments (Lessin et al., 2016); one where CO_2 enters benthic sediments from deeper geological intervals, and another mediated by CO_2 rich plumes in the water column. As described in section 4.5 the effects on benthic sediments from dissolved CO_2 and reduced pH associated with carbon dioxide release into the ocean are expected to be highly localised and ephemeral due to the processes of mixing. Therefore, changes in benthic sediments associated with this pathway may be expected to be limited.

Where CO_2 enters the benthic sediments directly from the deeper subsurface intervals, the CO_2 may be expected to have a more pronounced effect on both the benthic sediments, in sediment processes, and the organisms present. As described in section 4.5, CO_2 would likely enter these sediments via multiple and dendritic fluid conduit networks (Talukder 2012) associated with structural (e.g., faults and fractures), stratigraphical features (e.g., bedding planes along the crest of folds and sedimentary ridges, erosional surfaces at the base, flanks and margins of canyons, palaeocanyons and near slide scarps, entrapped high permeable layers such as buried channels) and both structure-stratigraphic in nature (e.g., sand intrusions, salt and mud diapirs) (Cartwright et al., 2007; Gay et al., 2007). Vertical fluid and gas flow will be aided via fluid flow through faults and mobilised sediments (Talukder 2012). As well as discrete fluid and gas leakage conduits, CO_2 will diffuse in benthic sediments through sediment porewaters and eventually into the overlying seawater (Blackford et al., 2010; Blackford and Kita, 2013; Blackford et al., 2014).

Gas leakage through sediments can be detected via several different high resolution geophysical and acoustic techniques, these include methods such as short offset seismic surveys, sub-bottom profilers and seafloor backscatter measurement (e.g. Robinson et al., 2021, Roche et al., 2021, Waage et al., 2021). However, these techniques rely on sound propagation changes due to changes in density contrasts between gas and water and are therefore unlikely to be able to identify leakage of dissolved CO_2 into the benthic sediments unless this leakage is manifest as subsurface sediment mobilisation.

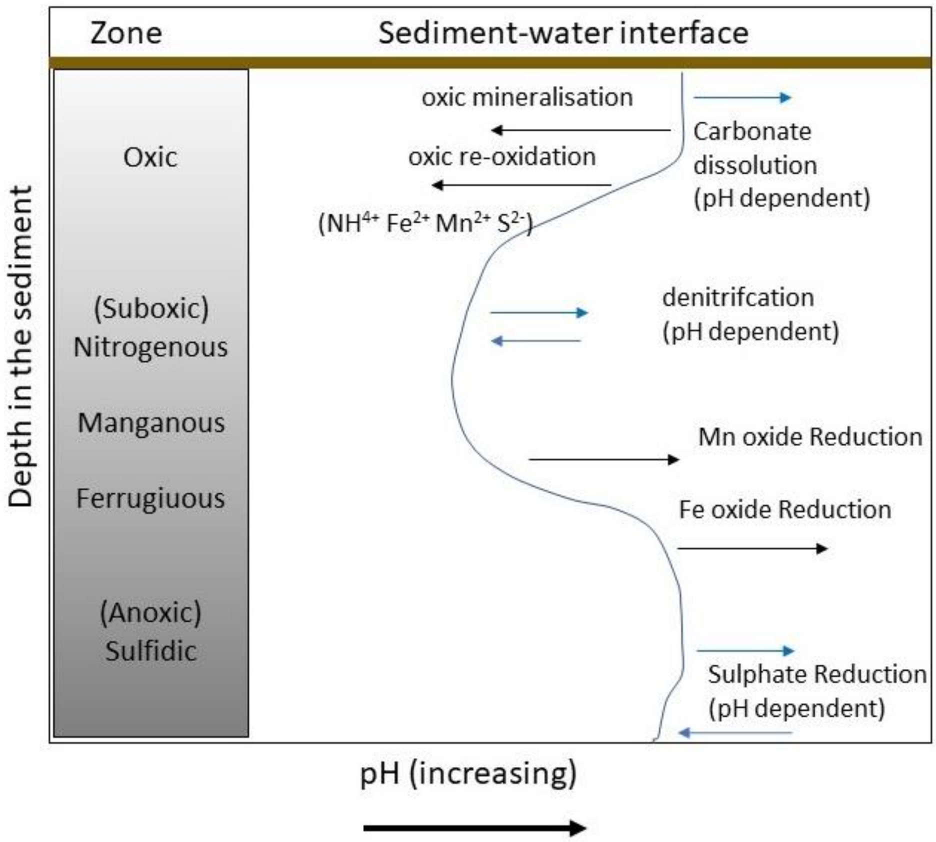

Figure 58. Changes in porewater pH with diagenetic processes. pH dependent processes are shown in blue. Reproduced from Silburn et al. (2017).

Laboratory and field CO_2 injection experiments in shallow benthic sediments have shown that sediments will retain significant volumes of CO_2 and therefore reduce leakage volumes into the water column. Scaled laboratory experiments by Myers et al. (2019) estimated 90% CO_2 injected was released from sediments in experiments designed to mimic the QICS site. Experimental observations at the QICS field site assessed that 15% of the CO_2 injected into the benthic sediments was releases as a gaseous phase across the sediment–water interface, with estimates of around 50% released in the dissolved phase (Blackford et al., 2014). Experimental observations of CO_2 trapping in benthic sediments at the STEMM-CCS site using various monitoring methods (excluding passive acoustic methods) determined that 61-73% (Flohr et al., 2021; Gros et al., 2021; Koopmans et al., 2021, Schaap et al., 2021) of the injected CO_2 was released from the seabed. For each site the capacity of the benthic sediments to trap CO_2 leakage prior to release to the ocean will differ and will be influenced by stratigraphy, sedimentary grain size, organic matter, and mineral buffering capacity.

The magnitude and spatial extent of chemical perturbation in the unconsolidated surface sediments (0 - 100 cm depth) during a potential CO_2 leak depends on many factors, including the nature of the leakage pathway, the rate of leakage, its duration, and the physico-chemical composition of the overburden, including shallow sediments.

With CO_2 leakage, increases in pCO_2 in sediment porewater could be greater than those in the overlying water because of the increased diffusivity of gas in fluids, depending on the geochemistry of the system. The diffusivity of CO_2 into overlying seawater will depend on the porosity of the sediment, which in turn is influenced by the sediment grain size and organic carbon content (Silburn et al., 2017). However, in many coastal systems, this change in pH units may be difficult to detect because surface sediment porewater pH is normally quite low and quite variable (e.g., less than 7, but ranging by as much as 1.5 pH units, Silburn et al., 2017). Studies have also found that sediment porewater pH can vary by as much as 1.5 pH units due to seasonal factors (such as the input of organic matter from spring algal blooms, Silburn et al., 2017). As described above, porewater pH is known to vary with depth in the sediments due to redox diagenetic processes, and typically is at a minimum at the oxic/anoxic transition, as shown in Figure 58 (Soetaert et al., 2007). Porewater pH will also vary with oxygen penetration and the input of organic detritus, and is likely to show high spatial and temporal heterogeneity (Silburn et al., 2017). Measured pH heterogeneity is also greatest in surface sediments and at the oxic/anoxic transition (Silburn et al., 2017).

Porewater pH can be influenced by myriad other processes including nitrification, metal reduction, or biological processes such as primary production and calcification, as well as the geochemical composition of the sediments themselves, (reviewed in Soetaert et al., 2007). The changing pH of the sediments are also thought to mobilise metals, as their speciation changes and they become more bioavailable (Blackford et al., 2015). Methane and sulphide gases are also normally present in sediments and would be expected to vary with seasonal and other factors, and as such some baseline characterisation of their normal composition should be conducted (Blackford et al., 2015). The pH of sediments in deep sediment cores (e.g., >1 m), below the depth of bioturbation, where input of organic material is minimised, are typically more stable. Changes in pH and carbonate ion concentration from a leaking CCS reservoir are expected to rapidly dissipate with distance from the source of the leak (Amaro et al., 2018).

As described above, detection of changes in pCO_2 and associated pH changes in benthic sediments requires care as they are subject to spatial and temporal changes which may be falsely attributed to leakage, or may mask low level diffusive leakage. Each location where CO_2 storage occurs will have unique benthic sediment attributes necessitating baseline data collection. In some cases, spatial and temporal heterogeneity may be such that this monitoring may have limited utility and attribution of potential impacts of CO_2 leakage into benthic sediments may only be possible in locations where there is discrete leakage of CO_2 from the seafloor.

4.6.3 Assessment

The assessment of the impacts on the atmosphere will be addressed in two parts: 1. Impact from *compromised subsurface integrity* and 2. Impact from *compromised well integrity*.

Will compromised subsurface integrity result in an increase in carbon dioxide in benthic sediments?

Key Questions	**Answers**
Is it possible?	***Yes.*** Geological features in the form of faults or fracture zones may form leakage pathways for stored CO_2 from the storage interval to the ocean floor.
Is it material?	***Yes.*** For CO_2 leaking from a storage reservoir through compromised subsurface integrity to reach benthic sediments, it needs to flow through an extensive stack of sedimentary strata. This will provide ample opportunity for the flux to be attenuated, especially through buffering, dissolution and residual saturation in aquifers within the sedimentary column and therefore not result in a non-negligible change in CO_2 pressure in benthic sediments. This will lead to acidification of sediment pore waters potentially affecting redox conditions and the mobilisation of chemical species.
Can it be monitored?	**Yes.** There are numerous marine monitoring technologies available for leakage detection throughout the water column (e.g. Dean et al., 2020; Ross et al., 2020). A number of acoustic monitoring technologies are available to identify low level CO_2 leakage into the water column and presence of gas in the seabed. Whilst there are well established and existing sampling and analysis technologies for benthic sediments and porewaters, caution needs to be taken in understanding sediment heterogeneity.
Could it be mitigated?	**No**. Should a CO_2 leakage pathway be established through compromised subsurface integrity, there are no interventions possible to avoid or mitigate CO_2 flux. The link between carbon geological sequestration operations and compromised subsurface integrity outlines strategies to minimise occurrence of compromised subsurface integrity due to carbon geological sequestration
Could it be remediated?	**No.** However, over time and in the absence of further CO_2 charge it is likely that in most sediments (particularly coarse grained sediments) pore water chemistries would equilibrate with overlying water.
Summary	**Possible but not material.**

Will compromised well integrity result in an increase in carbon dioxide in benthic sediments?

Key Questions	**Answers**
Is it possible?	***Yes.*** Damaged or improperly completed wells could form vertical leakage pathways for CO_2 from the storage complex into the seabed sediments. Examples of CO_2 leakage in the past, although rare, were associated with CO_2 enhanced oil recovery (EOR) projects, CO_2 injection wells, active oil production wells, or plugged and abandoned wells within the EOR scheme (Duncan et al., 2009).
Is it material?	**Yes.** A compromised well can create a direct pathway for CO_2 to enter benthic sediments. This can lead to a locally non-negligible change in partial CO_2 pressure in benthic sediments. This will lead to acidification of sediment pore waters potentially affecting redox conditions and the mobilisation of chemical species. Leakage in the subsurface originating from wells would likely be expressed in benthic sediments in several locations as a number of small seepages which could impact a broader area of sediments.
Can it be monitored	There are numerous marine monitoring technologies available for leakage detection throughout the water column (e.g., Dean et al., 2020; Ross et al., 2020). Several acoustic monitoring technologies are available to identify low level CO_2 leakage into the water column and presence of gas in the seabed. There are well established existing sampling and analysis technologies for benthic sediments and porewaters and characterisation of sediments in the vicinity of wells is prudent to understand impacts of leakage on the sediments and any infaunal communities. Caution needs to be taken in understanding sediment heterogeneity. Cautionary: Evaluation of hydraulic integrity of wells within the vicinity of the CO_2 injection well.
Could it be mitigated?	**Yes.** An increase in CO_2 concentration in sediments due to compromised well integrity can be avoided and mitigated by ensuring the intersection of benthic sediments by injector wells or existing abandoned wells is adequately sealed.
Could it be remediated?	**Yes**. Well mitigation and remediation technologies are well-established in the petroleum and groundwater industries (e.g., Castaneda-Herrera et al., 2018).
Summary	**Possible and can be material but can be mitigated**

4.6.4 References

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5 Endpoint

5.1 Climate change mitigation

5.1.1 Definition

The fundamental goal of CCS is to contribute to the reduction of global warming. Global warming is well-understood to be linked to increasing concentrations of CO_2 (and other greenhouse gases) in the atmosphere. If geological storage sites leak CO_2 back to the atmosphere, how much impact will that have? What leak rates are allowable and still give a climate benefit? How does time interplay with overall atmospheric concentrations?

5.1.2 Description

The impact of leaky CCS is not straightforward to calculate and requires full earth system models depending on many assumptions. Overall, even leaky CCS can result in global cooling. The reason is that the rate and scale of CCS reduces emissions promptly, with smaller volumes of leaked CO_2 only slowly returning to the atmosphere: this buys time for slow dissolution into the ocean to occur. The ocean can only absorb CO_2 at a fixed rate and so evidently leaked CO_2 is competing with other emissions into the atmosphere for this oceanic capacity. From this brief sketch we can see that calculating the effected of leaky CCS on the climate requires a carbon cycle-climate model, estimates of the emissions of CO_2 over several hundred years, guesses as to how much of this is captured, and guesses about the energy penalty of CCS and whether that results in yet more emissions. In addition, innovations such as direct air capture (DAC) or other technological or nature-based solutions may be able to mitigate those small leaks.

There are several models in the literature which make a variety of choices about these assumptions (Haughan and Joos, 2004; Hepple and Benson, 2005; Enting et al., 2008, Stone et al., 2009; Shaffer, 2010). Despite their different assumptions, they all arrive at tolerable leakage rates of CCS (net benefit to climate) at fractional rates around 0.001 to 0.0001 per year. Despite the complexity of the models, ultimately this number arises because the residence time of CO_2 in the atmosphere is of order 1000 years: so, for CCS to “buy time” the retention time in storage must be at least 1000 years.

These numbers, it is important to note, refer to tolerable leakage from the global suite of CCS projects. Individual projects could leak less or more but average to the same impact. They also refer to leakage to the atmosphere and say nothing about important matters such as pollution of aquifers or acidification of the oceans.

A specific industrial-scale project might eventually store 50 Mt, suggesting that leakage to the atmosphere must be held below 0.0001 x 50 Mt = 5000 t /yr. This level of leakage would be easily detectable from its environmental impact at the surface, unless spatially very diffuse, and once observed and cause identified, it can be quickly remedied through a range of mitigation approaches discussed earlier (See Section 3).

5.1.3 Assessment

Will carbon dioxide leakage to the atmosphere result in an increase in climate change?

Key Questions	**Answers**
Is it possible?	**Yes.** Climate change is well-understood to be linked to increasing concentrations of CO_2 (and other greenhouse gases) in the atmosphere.
Is it material?	**No.** Material 0.1 – 0.01 % leakage of total storage volume will only be reached in rare cases. Recent studies by Alcade et al. (2018), Postma et al. (2019), Hoydalsvik et al. (2021) and Daniels et al. (2023) agree that the leakage into the atmosphere can be expected to be less than the "climate threshold" of 0.1% per year for any plausible combination of wellbore and geological leakage pathways.
Can it be monitored?	**Yes.** Monitoring methods have been developed for the detection of direct leakage into the atmosphere (e.g. Lewicki et al., 2009; Humphries et al., 2012; Luhar et al., 2014) for onshore leakage. These methods can detect changes in the atmospheric composition of CO_2 corresponding to leaks of order a few thousands of tonnes per year at a distance of the order of a kilometre from the leak.
Could it be mitigated?	**No.**
Can it be remediated?	**No**. Remediation would entail capturing the leaking CO_2 at the source or from the atmosphere, i.e. direct air capture, and would be costly and only effective from a climate mitigation perspective in the case of very large leaks.
Summary	**Possible but not material.**

5.1.4 References

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5.2 Lacustrine biodiversity

5.2.1 Definition

Lacustrine biodiversity refers to the diverse and complex flora and fauna in the ecosystems that inhabit lakes, and includes benthic communities in lake sediments. Lakes are generally larger than 8 ha, situated in a topographic depression or dammed river channel and lack vegetation cover (<30%) (EPA, 2005). Lake condition describes the hydrological and ecological state and function (i.e., degree of permanence) of a lake at a given point in time. It is governed by temporal changes in water quantity, water quality (i.e., temperature, turbidity, salinity and chemical composition) and species composition, all of which are influenced by a combination of climate and hydrological processes, as well as a range of anthropogenic activities.

5.2.2 Description

While CO_2 is not considered a contaminant in surface water, an increase in CO_2 due to leakage would result in a decrease in pH, i.e. an increase in acidity. pH is one of the most important environmental factors limiting species distributions in aquatic habitats because it affects most chemical and biological processes in water. Acceptable ranges of pH are between 6.5-9 for aquatic life (e.g. US EPA: www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table). A sustained pH outside this range can result in decreased reproduction, decreased growth, disease or death of lacustrine species.

Natural fluctuations of pH in surface water occur daily (e.g. due to consumption of CO_2 during photosynthesis) and seasonally (e.g. due to high rainfall, snow melt or drought). pH can vary both horizontally and vertically in a lake or river. For example, pH is often higher near the surface of lakes where light is available for photosynthesis, whereas in thermally stratified lakes, pH in the deeper water is often lower due to the lack of photosynthesis and due to respiration by organisms decomposing organic matter. Certain lithologies, e.g. limestones, can buffer the acidification of surface water (www.epa.gov/system/files/documents/2021-07/parameter-factsheet_ph.pdf).

Even small changes in pH can shift community composition in lakes and stream because a change in pH changes the solubility and transport of many pollutants and nutrients, which can lead to aquatic fauna and flora being exposed to toxic metals or to a change in nutrient availability.

A pH of less than 6 can potentially cause damage to gills, decreased growth, reproductive failure, respiratory inhibition, mortality and displacement of acid-sensitive species, and a prolonged pH <5 is lethal to many lacustrine species (Figure 59; www.epa.gov/caddis/ph). A summary of potential biological changes due to a material decrease in surface water pH is shown in Table 14.

Other contributing impacts due to surface water acidification can involve metals (e.g., aluminium, copper, zinc) (Playle et al. 1989), toxic compounds (e.g., phenols, cyanides) (Saarikoski 1981; Rand, 1995) and ammonia (Wurts, 2003).

Figure 59. pH values that can be tolerated by different species (www.epa.gov/caddis/ph).

Detecting a small CO_2 leak in surface water can be challenging because pH varies spatially, and it fluctuates daily and seasonally. In the absence of directly measuring the pH of surface water, indirect signs for acidification due to a CO_2 leak may include metal precipitates (iron, manganese, and aluminium) or the presence of filamentous algae that are tolerant of low pH (Niyogi et al., 1999).

Table 14. Biological changes due to surface water acidification (from Baker et al., 1990).

pH range	General biological effects
6.5 to 6.0	Small decreases in plankton and benthic invertebrate species richness resulting from loss of a few highly acid-sensitive species, but no measurable change in total community abundance or production.
	Some adverse effects (decreased reproductive success) may occur for highly acid-sensitive fish species (e.g., fathead minnow, striped bass).
6.0 to 5.5	Loss of sensitive species of minnows and dace (e.g., fathead minnow and blacknose dace); in some waters, decreased reproductive success of lake trout and walleye, which are important sport fish species in some areas.
	Visual accumulation of filamentous green algae in near-shore zone of many lakes and in some streams.
	Distinct decrease in species richness and change in species composition of plankton and benthic invertebrate communities, although little if any change in total community abundance or production.
	Loss of some common invertebrate species from zooplankton and benthic communities, including many species of snails, clams, mayflies, amphipods, and some crayfish.
5.5 to 5.0	Loss of several important sport fish species, including lake trout, walleye, rainbow trout and smallmouth bass, as well as additional nongame species such as creek chub.
	Further increase in the extent and abundance of filamentous green algae in lake near-shore areas and streams.
	Continued shift in species composition and decline in species richness of plankton, periphyton and benthic invertebrate communities; decreases in total abundance and biomass of benthic invertebrates and zooplankton may occur in some waters.
	Loss of several additional invertebrate species common in surface waters, including all snails, most species of clams and many species of mayflies, stoneflies and other benthic invertebrates.
	Inhibition of nitrification.
5.0 to 4.5	Loss of most fish species, including most important sport fish species (e.g., brook trout and Atlantic salmon). A few fish species are able to survive and reproduce in water below pH 4.5 (e.g., central mudminnow, yellow perch).
	Measurable decline in whole-system rates of organic matter decomposition, potentially resulting in decreased rates of nutrient cycling.
	Substantial decrease in number plankton and benthic invertebrate species and further decline in plankton and periphyton species richness; measurable decrease in total community biomass of plankton and benthic invertebrates of most waters.
	Loss of additional plankton and benthic invertebrate species, including all clams and many insects and crustaceans.
	Reproductive failure of some acid-sensitive species of amphibians (e.g., spotted salamanders, Jefferson salamanders, leopard frogs).

5.2.3 Assessment

Will carbon dioxide leakage into shallow aquifers result in a decrease in lacustrine biodiversity?

Key Questions	**Answers**
Is it possible?	***Yes.*** CO_2 leaking from geological storage into a shallow aquifer may impact on the biodiversity in hydraulically connected water bodies.
Is it material?	***No.*** Carbon dioxide itself is not considered a pollutant or water contaminant and is not considered as a parameter for water quality in most jurisdictions. Acceptable ranges of pH are between 6.5-9 for aquatic life (e.g. US EPA: www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table). As surface waters do not act as a barrier, the accumulation of high concentrations of CO_2 is unlikely except for some highly specific sets of circumstances where deep, small surface area, tropical lakes may be restricted and not overturn seasonally like most water bodies.
Can it be monitored	**Yes.** Water sampling and water analyses can detect high concentrations of CO_2, but sampling would need to be close to the point of leakage
Could it be mitigated?	**Yes**. The understanding of the connection between shallow aquifers and surface water bodies that could result in unintended leakage, stratification and storage of CO_2 in the water column are well understood. Screening of water bodies, geographic locations, and latitude would be able to identify those water bodies that could be at risk. Monitoring methodologies could be used to provide early warning or degassing of such bodies.
Could it be remediated?	**Yes**. Groundwater mitigation technologies (i.e. pump and treat) are available and mature. Degassing of stratified CO_2 accumulations in lakes is possible.
Summary	**Possible but not material.**

Will carbon dioxide leakage into surface waters result in a decrease in lacustrine biodiversity?

Key Questions	**Answers**
Is it possible?	***Yes.*** CO_2 leaking from geological storage into river, ponds or related surface waters may impact on the biodiversity in these water bodies.
Is it material?	***No.*** Carbon dioxide itself is not considered a pollutant or water contaminant and is not considered as a parameter for water quality in most jurisdictions. Acceptable ranges of pH are between 6.5-9 for aquatic life (e.g. US EPA: www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table). As surface waters do not act as a barrier, the accumulation of high concentrations of CO_2 is unlikely except for some highly specific sets of circumstances where deep, small surface area, tropical lakes, in volcanic regions may be restricted and not overturn seasonally like most water bodies.
Can it be monitored?	**Yes.** Water sampling and analysis of surface water overlying the storage area can be used to identify leakage locations CO_2 leakage locations.
Could it be mitigated?	**Yes**. Given the understanding of key features of water bodies that could result in unintended stratification and storage of CO_2 are now well understood, screening of water bodies, geographic locations, and latitude would be able to identify those water bodies that could be at risk. Monitoring methodologies could be used to provide early warning or degassing of such bodies.
Could it be remediated?	**Yes**. Degassing the stratified zone in the water body retarding upward migration of the CO_2.
Summary	**Possible but not material.**

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5.3 Marine biodiversity

5.3.1 Definition

Marine biodiversity is a catchall term that describes the variety of life in oceans and the shallow sediments beneath. This includes microorganisms, animals and plants. Marine biodiversity is the essential foundation for the structure and functioning of ocean ecosystems and for providing the full range of ecosystem services (i.e., food production, coastal protection, water purification, carbon sequestration, tourism and recreation) that benefit humans on local, regional, and global scales (Lotze, 2021).

5.3.2 Description

Marine biodiversity and the ocean ecosystems services that it provides include visible as well as unseen functions such as the oxygen we breathe, the seafood we eat, the support of local livelihoods, marine plants storing ‘blue’ carbon and protecting our shorelines, provision of medical and biochemical compounds found in marine species, and tourism (Lotze 2021).

An accidental release of CO_2 from a reservoir, or a well, that manifests at the seabed and within the overlying water column, may impact on marine biodiversity through a loss of diversity or changes to ecosystem diversity (i.e., change in habitats, communities and ecological processes).

Impacts of CO_2 could affect infauna (organisms living within sediments), epifauna/benthic (organisms living on or attached to the seafloor) or pelagic (organisms living within the water column) biota. The impacts of CO_2 leakage will not affect these biological assemblages uniformly; nor will fauna be impacted uniformly at each trophic level. For example, microbial populations could be unequally altered due to a combination of pH changes, toxicity, or conversely, stimulation from the CO_2 itself (Yu and Chen, 2019).

Infauna and benthic marine communities are thought to be at greatest risk from CO_2 from a CCS leak as they are sessile, in direct contact with the sediment, and often lack a planktonic larval dispersal. Consequently, they are more at risk to increased concentrations of carbonate ions in sea water and decreased pH in porewater, and possibly overlying seawater, from a loss of containment from a CCS formation (Amaro et al., 2018; Blackford et al., 2010). Pelagic organisms may not be affected by CO_2 release, because pH changes in the water column are likely to be of small magnitude and disperse quickly (Lessin et al., 2016). In addition, coastal organisms (both benthic and pelagic) are thought to be least sensitive to changes in pH as they are frequently exposed to low alkalinity water from terrestrial run off (Hofmann et al., 2010).

Impacts of CO_2 on infaunal biodiversity

When considering the impacts of CO_2 leakage from wells or reservoirs on marine biodiversity the first impacts are like to be expressed in microbial communities living within sediments. However, many of the bacterial taxa that have been identified as being potential indicators of CO_2 release have also been identified by Ross et al. (2020) and Keesing et al. (2021) in seabed sediments overlying a potential future CO_2 sequestration site, indicating that their presence is not in itself diagnostic of CO_2 leakage.

The presence of excess CO_2 disrupts microbially mediated biogeochemical cycling (Blackford et al., 2010) however reduced bacterial biodiversity does not equate to a measured loss in community function on exposure to CO_2 (Maas et al., 2013). For example, assessments of soils in areas that are naturally high in CO_2 (such as volcanic vents and wetlands) have found reduced bacterial abundance overall, however there was increased abundance of methanogens and acidophilic bacteria (reviewed in Yu and Chen, 2019).

Experiments using acidified seawater to simulate CCS leakage, using enzyme activity as a proxy for measuring the microbial community, found a change in biodegradative enzyme activity in the surface sediments (Rastelli et al., 2016). Protein degradation and nitrogen regeneration rates decreased, but degradation of carbohydrates and organic phosphorus increased (Rastelli et al., 2016). Other mesocosm experiments also found changes in microbial processes, including increased methane production and sulphate reduction at 5000 pCO_2, despite a decrease in the abundance of bacteria (Ishida et al., 2013). There was, however, a slight increase in the abundance of archaea (Ishida et al., 2013). An increase in organisms in the 2-32 µm size class was also recorded (Ishida et al., 2013). Other microcosm studies have also shown that microbial community composition within sediments does not change significantly with changing pH of the overlying water over short time periods (Tait et al., 2013). This suggests that localised releases and oceanographic mixing may not lead to infaunal microbial changes over wider areas.

When considering the broader range of taxa within infaunal communities recent mesocosm studies have simulated the impact of CO_2 releases from CCS (Amaro et al., 2018). They found losses in species richness and changes in benthic infaunal community structure with short-term exposure during a simulated release of CO_2. These losses dissipated with distance from simulated release source and exposure time (Amaro et al., 2018). The differences in these studies were largely due to differences in the polychaete worm's abundance (Amaro et al., 2018).

Other studies have been performed using natural CO_2 vents around volcanoes to simulate the environmental consequences of submarine gas flows and changing pCO_2 in porewater (Molari et al., 2019). Following a transplant experiment and 1-year exposure to acidified porewater (pH =5.5 or 5.6), the authors noted a decrease in both bacterial and invertebrate (measured as nematodes and polychaetes worm) biodiversity, but unchanged overall abundance (Molari et al., 2019). The authors hypothesized that the changing environmental pH favoured organisms with metabolic plasticity, whereas those unable to cope with the changing conditions were lost from the system. These systems were slow to recover following return to normal porewater pH reviewed in Molari et al., 2019).

Experiments conducted during the Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage (QICS) controlled CO_2 release experiment showed that impacts on macroinfauna were significant but extremely localised, however strong temporal changes were observed in all community attributes away from the controlled release experiment that were at least as large as those induced by the CO_2 leakage (Widdicombe et al., 2015). The experiment also showed that that once CO_2 release stopped there was rapid microinfaunal community recovery (Widdicombe et al., 2015).

Impacts on benthic communities

Changing oceanic pH is anticipated to have an impact on benthic communities with the release of CO_2, expected to impact calcifying organisms, such as bivalves, gastropods, sea urchins and corals the most, as the solubility of the minerals they use as shells and skeletons is expected to increase (Byrne and Przeslawski, 2013; Kroeker et al., 2010; Kroeker et al., 2013; Wittmann and Portner, 2013). These anticipated impacts may also be due to the organisms' low capacity to regulate intracellular pH and their low metabolic rates (Melzner et al., 2009; Wagner et al., 2008).

A recent meta-analysis of the vulnerabilities of different groups of organisms to changing seawater pH identified cnidaria, mollusca, and echinodermata as the most sensitive to changes in dissolved CO_2, with other taxa either not sensitive (Chordata and Arthropoda), or lacking sufficient data to judge sensitivity (haptophyte and heterokontophyte – two algal species where positive effects were anticipated) (de Vries et al., 2013). The sensitivity between different organisms within these broad taxonomic groups was found to be highly variable and dependent on the form of calcium carbonate the taxa utilise (Kroeker et al., 2010). The inter-species variability in responses to increased pCO_2 on calcification rates may also be influenced by genetic factors, nutritional status, and ambient concentrations of other nutrients (Hofmann et al., 2010; Kroeker et al., 2013).

Crustaceans, which also utilise a calcified exoskeleton but have more efficient ion-regulatory systems than molluscs and other sensitive invertebrate taxa, were not found to be as sensitive as other calcifying organisms (Kroeker et al., 2010). The capacity for organisms to adapt to decreasing pH and increasing CO_2 is unknown and not frequently studied (Hofmann et al., 2010).

Larvae that form calcareous shells may be especially sensitive to changes in ocean pH (Byrne and Przeslawski, 2013). Larval sensitivity is thought to be enhanced in organisms that use a more soluble form of calcium carbonate as juveniles than as adults (Kroeker et al., 2013). Planktonic and early life stages of these types of invertebrates are likely to be the most susceptible to changing pH (Byrne and Przeslawski, 2013).

Numerous studies have been conducted with the goal of predicting organism susceptibility within biological communities to either the ocean acidification that is expected to occur with changing atmospheric CO_2 levels or through the release of CO_2 from CCS reservoirs. Although few studies have shown direct lethality from changes in pH, especially for acute exposures, many have shown physiological stress, leading to uncertain ecological trade-offs (Murray et al., 2013). A selection of these studies is briefly summarised below.

A recent study compared the sensitivity of different marine invertebrates to increased pCO_2 in seawater to determine if there were taxonomic differences in anticipated responses to near future conditions (Ries et al., 2009). At pCO_2 less than 1000, there were no inter-treatment differences amongst a wide range of benthic marine invertebrates (Ries et al., 2009). Another recent study examined changes in benthic communities by creating mesocosms where CCS reservoir releases were simulated by bubbling the seawater with CO_2. Changes in the abundance of some taxa were only noted at pH 6.5 and below (Passarelli et al., 2018b).

Several studies have also specifically examined the responses of specific groups of marine invertebrates that were previously identified as being sensitive to changes in pH to either near future ocean acidification or to simulated releases of CO_2 from CCS reservoirs.

For example, in studies of sea urchins, one of the species thought to be sensitive to ocean acidification, showed that there can be a lot of inter-individual variability in the response of fertilisation success in sea urchins to changes in seawater pH (reviewed in Byrne and Przeslawski, 2013). Normal development is 20% less frequent at pH of 7.8 (reviewed in Hofmann et al., 2010), however, there is significant variability within the response of this taxonomic group.

Studies conducted near a subsea volcano that vents CO_2 have found differences in the pH tolerance of different species of sea urchin, largely related to their acid-base and ion regulatory capacity (Calosi et al., 2013).

There is a lot of interest in impacts of increased CO_2 on molluscs because of their economic importance and hard calcium carbonate shell (reviewed in Gazeau et al., 2013). Most studies show changing pH is unlikely to cause mortality in adult molluscs, and instead, may slow growth rates and increase rates of shell dissolution (Gazeau et al., 2013). Slower rates of shell growth were noted in mussels exposed to decreases in pH greater than 0.5-1 unit (reviewed in Gazeau et al., 2013). Thinner shells were reported in some species of oysters exposed to similar pH range changes. Decreases in shell length and weight, but not changes in tissue mass, were measured in bivalves exposed to water with increased pCO_2 (Thomsen and Melzner, 2010). Bivalves that have an infaunal life history (such as clams) have also shown increased rates of shell dissolution, as well as decreased settlement rates with decrease in porewater pH (Clements and Hunt, 2017) and impacts on organisms living in sediments with naturally low porewater pH (e.g., those with high inputs of organic carbon) are expected to be more severely impacted (Clements and Hunt, 2017).

Metabolic depression, resulting from increased pCO_2 was ruled out as contributing to the change in shell morphology measured in bivalves exposed to decreased pH (Thomsen and Melzner, 2010). The metamorphosis, growth and survival of several types of bivalve larvae were decreased at 650 pCO_2, and in a separate study, in oysters grown at 800 pCO_2 (reviewed in Hofmann et al., 2010). As a generalisation, oysters appeared to be more sensitive than mussels to pH changes (Gazeau et al., 2013). However, many studies have found a great deal of variability in the sensitivity of different molluscs to changing pH, and this variation can occur between different individuals of the same species, making predictions difficult (Gazeau et al., 2013). Even tolerant organisms may have weaker shells under future ocean pHs, and therefore in areas of potential CO_2 leakage, making them more vulnerable to predation (Byrne and Przeslawski, 2013).

Survival and development of mollusc larvae is likely to be the most sensitive endpoint to changes in pH. Some impacts were measured as decreased growth of bivalve larvae at pH 8.0 (Byrne and Przeslawski, 2013). Decreases in fertilisation success, development, shell normality and growth rates were also noted in oyster larvae at pH changes of 0.1-0.2 units (Parker et al., 2012). Growth rates and energetic stores of other types of bivalve larvae were also impacted by comparatively small changes in pH (0.1-0.2 units). Decreased survival of larvae and changes in biomarker assays were seen in *Mytilus galloprovincialis* at pH less than 7.5, though the contribution of the increased bioavailability of metals in the response was uncertain (Passarelli et al., 2018a). Other studies have also recorded declines in fertilisation and development success of bivalve larvae, but these occurred at much greater pH changes (e.g. 0.7 and 1.4 pH units) (Swiezak et al., 2018). Settlement cues may also be interrupted by pH changes (Byrne and Przeslawski, 2013).

Some gastropod species have decreased growth and survival at pH changes anticipated though ocean accidifcation (Gazeau et al., 2013), but this sensitivity is not obseved uniformly. The shells of marine gastropods are known to dissolve in low pH water, and shell deformities are commonly observed near CO_2 seeps (reviewed in Marshall et al., 2019). Erosion of gastropod shells has been proposed as an indicator of acidification (Marshall et al., 2019). Gastropods collected from rocky intertidal areas with highly variable pH (subject to shore based acidic runoff, pH as low as 5.9) were found to have a rounder shape, to be shorter, and visibly more eroded (Marshall et al., 2019).

As mentioned previously, crustaceans do not seem particularly sensitive to ocean acidification however, reproductive rates of amphipods and isopods were decreased in mesocosm experiments with changes of 0.5 and 1 pH unit (Conradi et al., 2019). Survival was also decreased with decreases of 1 pH unit (Conradi et al., 2019). In a separate study, increased mortality of amphipods was only noted at pH 7.0 and was only consistent across different sediment types at pH < 6.0 (Passarelli et al., 2017). The difference between sediment types was attributed to metal concentrations in the sediment, which were mobilised at low pH (Passarelli et al., 2017). However, the reproduction of calanoid copepods was unaffected at environmentally realistic concentrations (McConville et al., 2013). Similarly, survival of American lobster juveniles was only decreased at pCO_2 concentrations greater than 1200 pCO_2 (Menu-Courey et al., 2019).

Brittle stars can be extremely sensitive to changes in pH, with larval survival decreasing dramatically (DuPont et al., 2008; reviewed in Melzner et al., 2009). Increased frequency of deformation in brittle star larvae was noted in lab studies performed pH 7.7 (reviewed in Hofmann et al., 2010). However, studies simulating rapid loss of containment from CCS by bubbling CO_2 through seawater found that the pH changes did not kill a European brittle star, although the depth of bioturbation was reduced (Murray et al., 2013).

Impacts on planktonic organisms

As noted above the impacts to planktonic organisms due to CO_2 release from the seabed may be of a low magnitude as pH changes in the water column are likely to be of small and to disperse quickly.

As with infaunal and benthic communities, changes in planktonic biodiversity may be expected to be expressed most predominantly within microbial communities. Studies with experimentally acidified seawater reported an increase in bacterial number, but a decrease in bacterial diversity, as measured via early genomics techniques (Maas et al., 2013). The activity of the bacteria (measured via extracellular enzymes) increased, with some functional groups (such as carbohydrate metabolism) affected more than others (Maas et al., 2013). The decrease in diversity did not equate to a measured loss in community function (Maas et al., 2013).

Microcosm experiments that acidified sea water to pH 7.67 collected from the North Sea found changes in bacterial community composition, but not overall bacterial abundance (Krause et al., 2012). The bacteria with changed abundance included some of the most common marine bacteria – members of the *alphaproteobacteria, gammaproteobacterial, epsilonproteobacteria,* and *flavobacteria* (Krause et al., 2012). However, these studies involved acidifying seawater with HCl and culturing marine bacteria, so may not be representative of real-world scenarios. Other mesocosm experiments using pelagic microbes found negligible impacts on bacterial abundance or community structure (Roy et al., 2013).

In studies of marine microbial populations, decreases in seawater pH have led to increased abundances of ammonia oxidising bacteria, particularly those from the *Nitrosomonas ureae* clade (Bowen et al., 2013). Other studies that experimentally acidified seawater also found a decrease in the rates of ammonia oxidation in the water column, but not in sediments, at both experimentally acidified sites and sites with natural CO_2 venting (Kitidis et al., 2011).

Some bacteria are also able to regulate their intracellular pH within a range between 5-9 pH units using proton efflux pumps (reviewed in Molari et al., 2019). The transcriptomic patterns showed an increase in the abundance of these pumps with a change in pH of 0.2 units (Molari et al., 2019).

Ocean acidification studies have focussed attention on the solubility of tests of calcified plankton and these studies can be used as a proxy for the impacts on these organisms as a result of CO_2 leakage, noting that changes in pH can be temporally and spatially constrained. Although different studies have produced differing results, a meta-analysis of cocolithophores (phytoplankton with calcite skeletons referred to as coccoliths) have shown that, on average, they are less calcified with increasing pCO_2 (Beaufort et al., 2011). However, there is substantial interspecies and within species variability in this trend, with heavily calcified individuals having been isolated from waters with high pCO_2 (Beaufort et al., 2011). Foraminifera have also been shown to be less calcified in waters with increasing pCO_2, although the difficulty of culturing this group has meant that they are not as well studied as the cocolithophores (Hofmann et al., 2010).

Shells of pteropods (pelagic snail-like zooplankton) have been shown to dissolve under extant lower pH, as observed by scanning electron microscopy (Bednarsek et al., 2012). A meta-analysis indicated that all species of pteropods are sensitive to acidification (Gazeau et al., 2013). Impacts on plankton are likely to be driven by atmospheric CO_2 levels, making the influence of a localised CO_2 release difficult to discern.

Impacts on fish

There are expected to be comparatively few impacts to fish populations at near future pH levels associated with ocean acidification. Many active marine ectotherms have a comparatively high tolerance to changes in pCO_2, which is adaptive for exercise induced changes and changes due to food consumption (Melzner et al., 2009). Marine fish seem relatively tolerant of changes in pCO_2, and adapt without measurable changes in performance (Melzner et al., 2009).

However, some studies have raised concerns about sublethal impacts of CO_2 exposure on fish behaviour. A variety of olfactory cues are disrupted at increased pCO_2, leading to disruption of normal predator prey interactions (Blackford et al., 2010). For instance, at 1000 pCO_2, receptors in the olfactory rosette and the brain are interrupted, and as a consequence fish are less sensitive to odours in the water column, leading to a decreased ability to find food, attract mates, and escape predators (Porteus et al., 2018). Recent studies in tropical larval fish have reported behavioural changes at near future pH ranges (Munday et al., 2009), however the response has not been consistent across studies (reviewed in Wittmann and Portner, 2013). Fish are generally highly mobile and are not likely to be exposed to elevated levels of enhanced pCO_2 over long periods if encountering discrete point sources of CO_2.

5.3.3 Assessment

Will carbon dioxide leakage into benthic sediments result in a decrease in marine biodiversity?

Key Questions	Answers
Is it possible?	**Yes.** The leaking CO_2 will dissolve in seawater, which will lead to a decrease in pH (acidification) and a dissolution of carbonate minerals in the sediments. This can result in an increase of microphytobenthos productivity and a decrease in faunal biomass and trophic diversity. It can also affect bacterial communities by reducing the composition of heterotrophs and microbial sulfate reduction rates.
Is it material?	**No.** However, localised acidification of sediment pore waters potentially affecting redox conditions and the mobilisation of chemical species could impact on infaunal assemblage biodiversity and potentially lead to a decrease in marine biodiversity. The zone of impact associated with migration of CO_2 into the seafloor sediments would be localised and it is highly sediment type dependant.
Can it be monitored?	**Yes.** Impact of pH changes in seawater on marine biota has been investigated: $\Delta pH > 1$: potential harmful impact is uncertain as each biological assemblage will be impacted differently and currently there is insufficient information to be able confidently assign thresholds of impacts of CO_2 for all biota types.
Could it be mitigated?	**No.** Once a CO_2 leak has reached the seabed and changed the pH of the porewater, it is difficult to avoid or mitigate any impact on the marine life.
Could it be remediated?	**Yes.** Natural recovery of small, impacted areas should be relatively quick (i.e., within one year), at least for nematodes. Bacterial communities appear to recover more slowly suggesting that effects of large CO_2 leaks on sediment properties may last for a long time after the disturbance is ceased, with consequences on benthic biodiversity that may vary according to the size and ecology of organisms (e.g., dispersion, sessile/motile) and to the scale of the impacted area (Molari et al., 2019).
Summary	**Possible but not material.**

Will carbon dioxide leakage into the ocean result in a decrease in marine biodiversity?

Key Questions	Answers
Is it possible?	**Yes.** The leaking CO_2 will dissolve in seawater, which will lead to a decrease in pH (acidification). This can result in an increase of microphytobenthos productivity and a decrease in faunal biomass and trophic diversity. It can also affect bacterial communities by reducing the composition of heterotrophs and microbial sulfate reduction rates. Excess CO_2 may also lead to retention of inorganic nitrogen adding to the pressures of increasing coastal eutrophication (Vopel et al., 2018). Changes in pH can impact on the growth of organisms such as shellfish, calcareous algae, and corals and therefore decrease marine biodiversity.
Is it material?	**No.** Dependant on the particular marine setting small single-well leaks will have impact length scales, where changes in pH will be detectable, over the order of metres to 10s of metres from the leakage point. For example a simulated leakage of <55 t yr^{-1} of CO_2 in well mixed coastal waters are only detectable in a small area around the leak within the lower 2 m of the water column due to rapid CO_2 bubble dissolution and dispersion. Leakage from wells (in the subsurface) would likely be expressed on the seafloor as a number of small seepages and therefore dispersion and dilution would be enhanced. Only prolonged leakage along numerous wells into poorly mixed waters might compromise long-term CO_2 storage and may adversely affect the local marine ecosystem.
Can it be monitored	**Yes.** Impact of pH changes in seawater on marine biota: ΔpH > 1: potential harmful impact this is uncertain as each biological assemblage will be impacted differently and currently there insufficient information to be able confidently assign thresholds of impacts of CO_2 for all biota types.
Could it be mitigated?	**No.** Once a CO_2 leak has reached the water column and changed the pH, it is difficult to avoid or mitigate any impact on the marine life.
Could it be remediated?	**Yes.** On cessation of any leakage faunal assemblages will repopulate areas previously affected by CO_2 leakage.
Summary	**Possible but not material.**

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5.4 Plant growth

5.4.1 Definition

Hypothetically, leaking CO_2 could accumulate in the root zone of plants and cause plant death. While there is no evidence of this occurring at CO_2 storage sites, there is some evidence from natural analogues on the nature and scale of the impact.

5.4.2 Description

The leakage of CO_2 into the root zone, and thence into the atmosphere, is known to affect plant growth. The dominant effect is due to processes in the root zone, not “fertilization” of the adjacent atmosphere by CO_2. Early studies of the effect of CO_2 leakage into the shallow subsurface used the natural analogues of volcanic areas, for example Laacher See in Germany (Krüger et al., 2011) and Latera in Italy (Beaubien et al., 2008). These early studies quickly confirmed that soil gas concentrations of more than 20% - 40% CO_2 resulted in plant stress and eventual death. The stress manifested as yellowing of the foliage (chlorosis). Generally, in these volcanic areas, the CO_2 emissions are restricted to spatially small areas (~ metres). Because these seeps have lasted a long time, vegetation has adapted and there are distinctive rings of more or less CO_2 tolerant plants around a seep.

Later reviews (West et al., 2015; Jones et al., 2015) integrated this evidence with results from early experiments making controlled releases of CO_2 in the shallow subsurface. From this it was clear that the volcanic models were good parallels for hypothetical leakages from storage sites. Further work confirmed the following key features:

1. High CO_2 concentrations in the root zone will kill plants. The mechanism is simple asphyxiation, as the CO_2 displaces the O_2 (Zhang et al., 2016).
2. The symptoms of plant stress due to excess CO_2 in the root zone are not specific; drought or indeed excess water will result in the same symptoms (Jones et al., 2015).
3. The soil type is not relevant, except to the extent that its permeability will affect the steady-state concentration of CO_2 (Lake and Lomax, 2019).
4. The affected regions are spatially small (Jones et al., 2015)

Further research has expanded the number of plants that have been tested for CO_2 tolerance, but (unsurprisingly), no plants can survive without O_2 being available in the root zone, although there are differences in detailed supportability. Ko et al. (2016) have provided detailed summaries of this work. Controlled release experiments (primarily ZERT, Spangler at al., 2010; and Ginninderra, Feitz et al., 2014, with the full range of experiments reviewed by Roberts and Stalker, 2017) have confirmed the spatially patchy nature of the impact. This will reflect the generally very heterogeneous nature of soil near the surface. Leakage will overwhelmingly favour the highest-permeability path.

Excessive CO_2 in soil gas will also adversely affect bacterial diversity and seed germination (West, Ko et al., 2016; He et al., 2016; Chen et al., 2017; Fernández-Montiel et al., 2015) but how this might feed into impact on plants is not known in detail.

The practical summary, for risk assessment purposes, is that should CO_2 concentrations in the root zone exceed a few tens of per cent, adverse consequences for thriving plant life will be obvious but spatially restricted. If plants are not actively growing, the effects may be less obvious or delayed. The spatially limited nature of natural and simulated CO_2 seeps suggests that the overall impact may be rather small.

5.4.3 Assessment

Will carbon dioxide leakage to the atmosphere result in a decrease in plant growth?

Key Questions	**Answers**
Is it possible?	**Yes**. Natural analogues and numerous experiments show that excess CO_2 in the atmosphere will kill plants. Such excesses can also be associated with dangerous levels of CO_2 in hollows, cellars, and creek beds.
Is it material?	**No**. The areas affected by "leakages", either natural (mofettes) or induced (controlled release experiments) are both small and obvious.
Can it be monitored?	**Yes.** Direct observations of unexplained localised plant death. Remote sensing.
Could it be mitigated?	**No**. Locating and stopping the source of exogenous CO_2 is the remedy for impact on vegetation. Little can be done to help plants recover unless this is done.
Could it be remediated?	**Yes.** CO_2 is a natural consistent in the atmosphere and is not persistent
Summary	**Possible but not material.**

Will carbon dioxide leakage into soils result in a decrease in plant growth?

Key Questions	**Answers**
Is it possible?	**Yes**. Natural analogues and numerous experiments show that excess CO_2 in soil gas will kill plants. Such excesses can also be associated with dangerous levels of CO_2 in hollows, cellars, and creek beds.
Is it material?	**No**. The areas affected by "leakages", either natural (mofettes) or induced (controlled release experiments) are both small and obvious.
Can it be monitored?	**Yes.** Direct observations of unexplained localised plant death. Remote sensing.
Could it be mitigated?	**No**. Locating and stopping the source of exogenous CO_2 is the remedy for impact on vegetation. Little can be done to help plants recover unless this is done.
Could it be remediated?	**Yes.** CO_2 is a natural consistent of soil gas and is not persistent
Summary	**Possible but not material.**

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5.5 Usable water

5.5.1 Definition

Groundwater is used for a range of purposes including drinking water, irrigation, stock watering and industrial water use. Depending on its use different water quality limits apply, and these limits are set by the respective environmental regulator in a state, province or country. At the highest level, the possible use of groundwater is determined by its salinity and an example of acceptable salinity ranges for different applications are shown in Table 15. Other quality indicators, for example critical levels of contaminant concentrations, further constrain possible groundwater usage.

The US EPA through their Underground Injection Control (UIC) program requires the protection of underground sources of drinking water (USDWs), which are defined as “an aquifer or its portion which supplies any public water system; or which contains a sufficient quantity of groundwater to supply a public water system; and currently supplies drinking water for human consumption; or contains fewer than 10,000 mg/L total dissolved solids; and which is not an exempted aquifer.”

5.5.2 Description

Potable water is also known as drinking water. It is supplied from surface reservoirs or dams and also from groundwater sources (that is from underground formations or aquifers). The water from dams or groundwater are usually treated to levels that meet state and federal standards for human consumption. Lower quality waters can be used for stock (sheep and cattle etc.) or for irrigation purposes. Many parts of the world rely on groundwater as an important source of potable water, especially in regions with limited surface water availability. Therefore, there is concern that in the case of geological carbon storage potential migration of CO_2 into overlying aquifers and groundwater supplies could contaminate potable water and thereby constitute a risk to human health.

When CO_2 is introduced into an aquifer, water and CO_2 form carbonic acid which can then react with minerals to change water chemistry.

Carbon dioxide occurs naturally in groundwater and, by itself, is not regarded as a pollutant or contaminant. While pH is considered an important operational water quality parameter, there is no guideline water quality value for pH because it is not deemed to be of health concern at levels found in drinking-water (WHO, 2022). However, secondary standards have been set in several jurisdictions for aesthetic, cosmetic or technical effects and, for example according to the US EPA, acceptable ranges of pH are between 6.5-8.5 for the human consumption of water.

Water-rock interactions due to an increase in CO_2 concentrations may result in the mobilisation of metals in concentrations considered harmful to human consumption. For reference, drinking water maximum contaminant levels and secondary standards from the US EPA are listed in Table 15 and Table 16, respectively. These standards may be different in other jurisdictions.

Table 15. Maximum contaminant levels (MCLs) for inorganic chemicals according to the US national primary drinking water standards.

Contaminant	MCL (mg/L)	Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)
Antimony	0.006	Increase in blood cholesterol; decrease in blood sugar
Arsenic	0.010	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer
Asbestos (fiber > 10 micrometers)	7 million fibers per liter (MFL)	Increased risk of developing benign intestinal polyps
Barium	2	Increase in blood pressure
Beryllium	0.004	Intestinal lesions
Cadmium	0.005	Kidney damage
Chromium (total)	0.1	Allergic dermatitis
Copper	1.3	Short term exposure: Gastrointestinal distress
		Long term exposure: Liver or kidney damage
		People with Wilson's Disease should consult their personal doctor if the amount of copper in their water exceeds the action level
Cyanide (as free cyanide)	0.2	Nerve damage or thyroid problems
Fluoride	4	Bone disease (pain and tenderness of the bones); Children may get mottled teeth
Lead	zero	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities. Adults: Kidney problems; high blood pressure
Mercury (inorganic)	0.002	Kidney damage
Nitrate (measured as Nitrogen)	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.
Nitrite (measured as Nitrogen)	1	Infants below the age of six months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.
Selenium	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems
Thallium	0.0005	Hair loss; changes in blood; kidney, intestine, or liver problems

Table 16. Secondary MCLs according to the US national primary drinking water standards. The only value directly impacted by CO_2 leakage is the pH values (highlighted in grey).

Contaminant	Secondary MCL	Noticeable Effects above the Secondary MCL
Aluminum	0.05 to 0.2 mg/L*	colored water
Chloride	250 mg/L	salty taste
Color	15 color units	visible tint
Copper	1.0 mg/L	metallic taste; blue-green staining
Corrosivity	Non-corrosive	metallic taste; corroded pipes/ fixtures staining
Fluoride	2.0 mg/L	tooth discoloration
Foaming agents	0.5 mg/L	frothy, cloudy; bitter taste; odor
Iron	0.3 mg/L	rusty color; sediment; metallic taste; reddish or orange staining
Manganese	0.05 mg/L	black to brown color; black staining; bitter metallic taste
Odor	3 TON (threshold odor number)	"rotten-egg", musty or chemical smell
pH	6.5 - 8.5	low pH: bitter metallic taste; corrosion
		high pH: slippery feel; soda taste; deposits
Silver	0.1 mg/L	skin discoloration; greying of the white part of the eye
Sulfate	250 mg/L	salty taste
Total Dissolved Solids (TDS)	500 mg/L	hardness; deposits; colored water; staining; salty taste
Zinc	5 mg/L	metallic taste

Many laboratory, controlled-release experiments and modelling studies on the potential impacts of CO_2 on groundwater resources have been conducted during the past 20 years (see Section 4.1), which have been reviewed multiple times (e.g., Lemieux, 2011; Harvey et al., 2013; Lions et al., 2014; Jones et al., 2015; Fischer et al., 2016; Varadharajan et al., 2019). Generally, these studies conclude that the environmental impacts of CO_2 leakage into groundwater appear to be low. While most of the reviewed studies observed some change in pH and ion chemistry in response to increased CO_2, only in very rare circumstances and for very specific mineralogies did these changes exceed safe drinking water limits. These rare cases involve aquifers that are naturally rich in trace elements in which CO_2 is able to mobilize these trace elements (e.g., Fe, Mn, Ni, As, Ba, U) and increase concentrations up to or exceeding threshold values (Lions et al., 2014). However, the mobility of trace elements is reversible and trace elements in solution can be precipitated if pH values return to initial conditions beyond the CO_2 plume; all depending on reaction kinetics (pH buffer effect, mineral dissolution and precipitation of secondary phases) in time and space along the flowpath of the potential plume.

5.5.3 Assessment

Will carbon dioxide leakage to shallow aquifers result in a decrease in usable water?

Key Questions	Answers
Is it possible?	**Yes.** Increased CO_2 concentrations due to leakage from a storage complex could reduce the pH of groundwater, i.e., increase its acidity, and thereby enhance geochemical reactions between groundwater and aquifer sediments, potentially resulting in release and mobilisation of toxic trace metals
Is it material?	**No**. Carbon dioxide itself is not considered a pollutant or contaminant in groundwater and is not considered as a parameter for water quality in most groundwater jurisdictions. Acceptable ranges of pH are between 5-9 for the human consumption of water and 6.5-9 for aquatic life (e.g. US EPA: www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table). Many laboratory controlled-release experiments and modelling studies on the potential impacts of CO_2 on groundwater resources have been conducted during the past 20 years, which have been reviewed multiple times (e.g., Lemieux, 2011; Harvey et al., 2013; Lions et al., 2014; Jones et al., 2015; Fischer et al., 2016; Varadharajan et al., 2019). Generally, these studies conclude that the environmental impacts of CO_2 leakage into groundwater are low. While most of the reviewed studies observed some change in pH and ion chemistry in response to increased CO_2, only in very rare circumstances and for very specific mineralogies did these changes exceed safe drinking water limits.
Can it be monitored?	**Yes.** The of water in most jurisdictions requires water chemical analysis to ensure that water quality follows regulated guidelines. **Cautionary:** CO_2 concentration/pH/salinity above background **Target:** pH < 6.5; salinity > 1000 mg/l; may differ depending on jurisdiction **Critical**: health limits for water constituents, e.g. heavy metals, organics (dependant on drinking water quality guidelines in responsible jurisdiction)
Could it be mitigated?	**Yes.** The already low risk of impacts on potable groundwater due to CO_2 leakage can be further minimised by early leakage detection before reaching groundwater wells; timely stop of injection and mitigation. Selecting an appropriate groundwater monitoring scheme is critical for CO_2 leakage detection. However, quantifying leakage, particularly in cases of small and/or diffuse leaks is challenging (Jenkins et al., 2015).
Could it be remediated?	**Yes.** Groundwater remediation technologies (i.e. pump and treat) are available and mature. Water treatment is commonly applied in public water grids.
Summary	**Possible but not material**

Will carbon dioxide leakage into surface water result in a decrease in usable water?

Key Questions	**Answers**
Is it possible?	**Yes.** Increased CO_2 concentrations due to leakage from a storage complex could reduce the pH of lake or river water, i.e., increase its acidity, and thereby enhance geochemical reactions between water and sediments, potentially resulting in release and mobilisation of toxic trace metals
Is it material?	**No**. Carbon dioxide itself is not considered a water pollutant or contaminant and it is not considered as a parameter for water quality in most jurisdictions. Acceptable ranges of pH are between 5-9 for the human consumption of water and 6.5-9 for aquatic life (e.g. US EPA: www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table).
Can it be monitored?	**Yes.** The use of water in most jurisdictions requires water chemical analysis to ensure that water quality follows regulated guidelines. **Cautionary:** CO_2 concentration/pH above background Target: pH < 6.5; may differ depending on jurisdiction Critical: health limits for water constituents, e.g. heavy metals, organics (dependant on drinking water quality guidelines in responsible jurisdiction)
Could it be mitigated?	**Yes**. The already low risk of impacts on surface water due to CO_2 leakage can be further minimised by early leakage detection before reaching critical values and timely stop of injection. Selecting an appropriate monitoring scheme is critical for CO_2 leakage detection. However, quantifying leakage, particularly in cases of small and/or diffuse leaks is challenging (Jenkins et al., 2015).
Could it be remediated?	**Yes.** Water treatment is common practice for ensuring water quality of drinking water.
Summary	**Possible but not material**

5.5.4 References

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5.6 Air Quality

5.6.1 Definition

Public health has been defined as "the science and art of preventing disease, prolonging life and promoting health through the organized efforts and informed choices of society, organizations, public and private, communities and individuals" (Winslow, 1920), before being refined by The United Nations' World Health Organization to include "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." (WHO, 1946). Further detail can be found in Gatseva and Argirova (2011).

5.6.2 Description

In acknowledging changes to the global climate, the impact on public health, through rising temperatures and more extreme weather events, is wide ranging and likely to amplify existing health problems. It may introduce new risks with respect to clean air, safe drinking water, nutritious food supply and safe shelter (https://www.who.int/health-topics/climate-change#tab=tab1). In addition, climate-anxiety or eco-anxiety are additional stress factors on top of any potential physical or chemical risks from industrial activities which may combine to increase the overall impact to the health of individuals and community groups. Therefore, doing nothing to mitigate emissions may have a major impact on public health.

Introducing a range of mitigation technologies to reduce emissions presents other potential risks to public health. Defining these potential risks and their impacts is important to deployment of, and in developing societal trust and acceptance of CCS.

What might be the impacts of CCS on public health? The literature is currently incomplete and reference to CCS and public health aspects are limited or lack detail. This may be a contributing factor to observations that "the public appears to be less concerned about how the technology works and more concerned about the unknown processes linking CCUS' potentially negative impacts on the natural environment and public health" (Nielsen et al., 2022). This is compounded by a general lack of knowledge and/or technical understanding of not only CCS but also ecosystem and processes that occur in the natural environment (Nielsen et al., 2022). It might be difficult to deconvolute the cause of an environmental change when there may be multiple impacts, not all of which may be attributable to a leakage event. Some communities have therefore recognised that due to the varying complexities of the CCS value chain, and processes in the natural environment, there is always some form of risk, and that this complexity is acknowledged and to some degree accepted.

Studies of the public health impacts of industry impacts from coal seam gas (CSG) have provided some indicators the sorts of health risks that could be relevant to investigate for equivalent risks in CCS activities. These include air, water and soil quality impacts with respect to toxicity and biological risks (Keywood et al., 2018; Huddlestone-Holmes and Dunne, 2023; Huddlestone-Holmes et al., 2023). While in the aforementioned reports concerns were often related directly to chemical and physical hazards, others related to local stressors and mental health effects.

Social stressors and mental health effects such as uncertainty, especially over long-term risks and effects of any co-existing materials in CSG and hydraulic fracturing fluids may result in further stress in managing relationships between landholders and communities who may feel powerless to manage potential or perceived impacts on environmental and human health impacts (Keywood et al., 2018). Cumulative or confounding effects can amplify concerns and stressors. Keywood et al. (2018) adds that infrastructure (e.g., pipelines, compression stations, well pads), over other land use areas, and with the addition of personal challenges (e.g., heavy workloads, land management, loss of spouse, low socioeconomic issues, or poor health town related issues, worries about boom and bust effects) can all compound stress and amplify perception of risk resulting in further mental health issues. There are potential benefits however, where increased monitoring of soil, water and air quality, and other activities could improve health outcomes for regions hosting CCS.

While CCS does remain an important technology for mitigation, there are multiple steps in the value chain (capture/DAC, transport, compression and injection deep underground on/offshore) that are not without a range of risks including that of public health.

Specific risks – Physical - Chemical - Psychosocial

The chemical and physical behaviour of CO_2 is summarised in Table 17. CO_2 is non-toxic. While oxygen depletion is often cited as a major risk factor for human health, cold burns due to the Joule-Thomson effect are a more frequent risk. As the CO_2 expands at an exit point, the throttling process results in a reduction in temperature (e.g., refrigeration). This can be to the extent that cold burns could occur at valve or leakage points in pipelines or tubing. It would be anticipated that this may only occur in restricted areas that exclude the general public.

In terms of the most immediate risk to public health, abbreviated safety data sheet (SDS) data are presented in Table 17, and fuller information can be found online e.g., http://docs.airliquide.com.au/msdsau/AL062.pdf.

Secondary effects such as pH changes may impact physical or chemical processes, so that there could be concern associated with changes to groundwater, soil contamination, marine pollution, or biodiversity impacts, which is covered elsewhere.

In terms of public health impacts and soil contamination, the most likely contaminant would be the CO_2 itself acting as an asphyxiant to plants – thus limiting plant growth and if at sufficient scale, could impact cropping and plant health (section 5.4).

Identifying potential co-contaminants (i.e., incidental substances) that could be entrained in different processes that produce CO_2-rich gas streams can be evaluated in terms of effects to the atmosphere by reviewing the global warming potential of material that may be released to the atmosphere.

Drilling of wells introduces a variety of materials that have been assessed for potential environmental and human health impacts (Huddlestone-Holmes et al., 2023 and references therein). Examples of the sorts of additional chemicals used in cement compositions (Figure 60) and components from drilling fluids (Figure 61), are highly water dominated. Any additional additives may also be utilised, but the amount and type of material used is very much based on the geological environment encountered or for specific operational purposes. The chemistry of fluids used are not considered further in this study, as 99.55% of fracturing fluids contain water and quartz sand and will not harm the atmosphere. The remaining 0.45% of chemicals used and their health impacts are discussed in Huddlestone-Holmes et al. (2023) and related reports and not discussed further here.

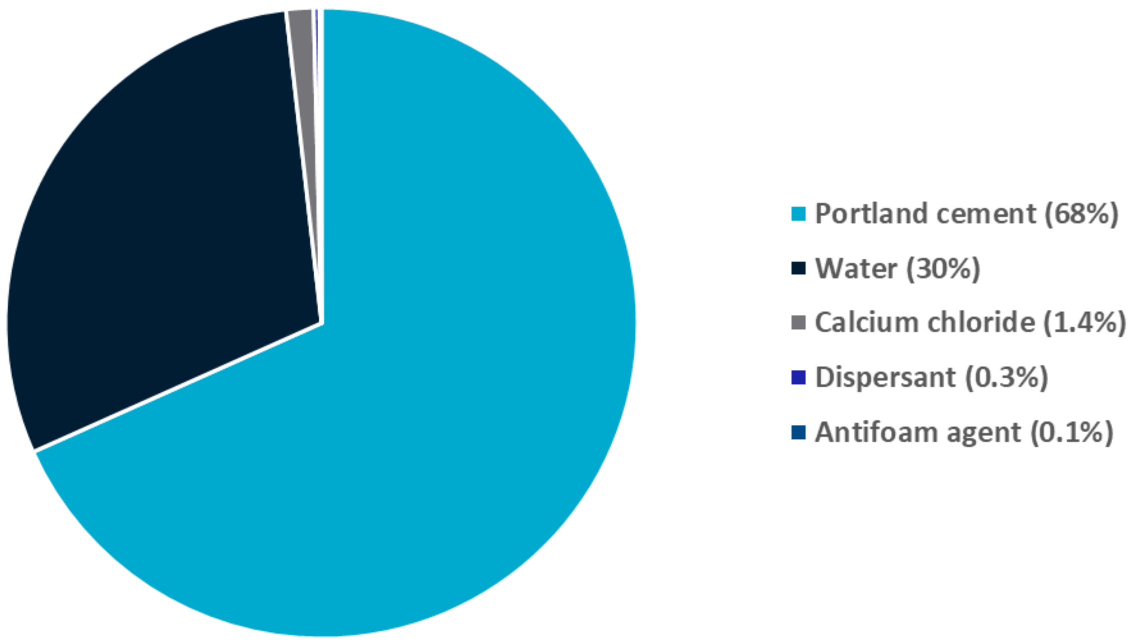

Figure 60. Components used in cement composition for drilling and casing for coal seam gas wells. Example provided by Origin Energy to GISERA (Huddlestone-Holmes et al., 2023).

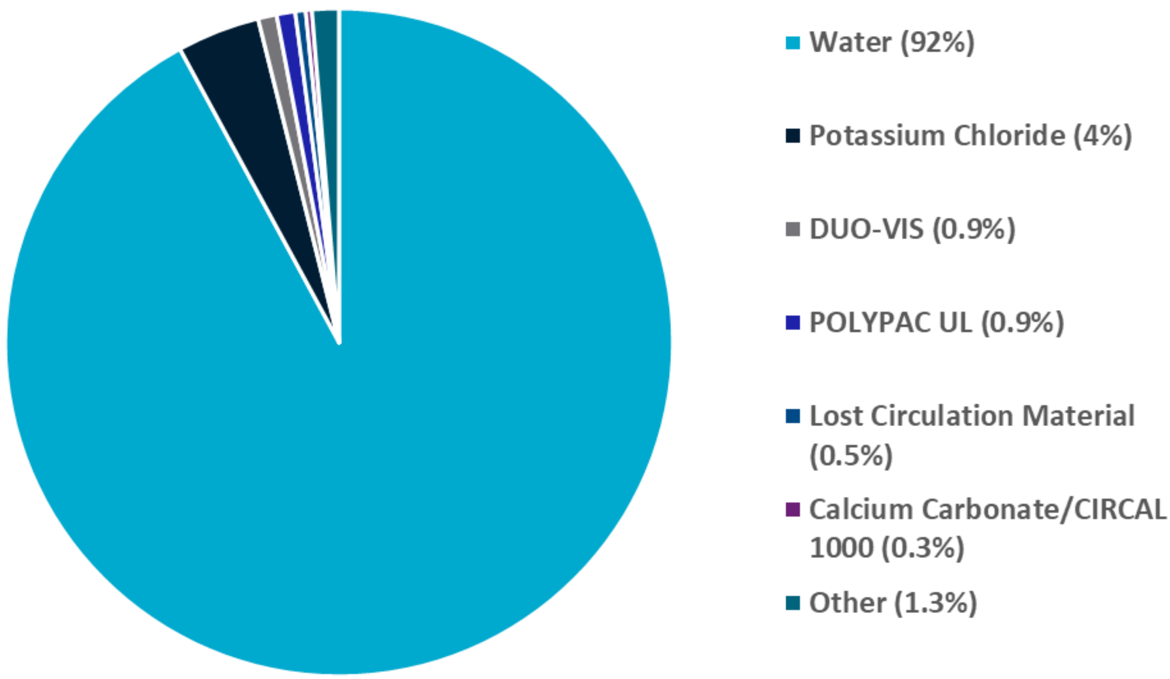

Figure 61. Components found in drilling fluids used in coal seam gas wells. Example provided by Origin Energy to GISERA (Huddlestone-Holmes et al., 2023).

Table 17. Key risks in handling carbon dioxide as noted in various SDS documentation (e.g., http://docs.airliquide.com.au/msdsau/AL062.pdf).

Classifications	Behaviour
Chemical name	Carbon Dioxide
Substance formula	CO_2
Molecular weight	44.01g/mol
CAS-No	124-38-9
EC-No	204-696-9
Risk	Often stored under pressure. Managing pressure vessels. Contact with liquid may cause cold burns/frostbite. Asphyxiant in high concentrations. In high concentrations CO_2 causes rapid circulatory insufficiency even at normal levels of oxygen concentration. Symptoms are headache, nausea and vomiting, which may lead to unconsciousness and death. The substance/mixture has no endocrine disrupting properties.

Case Study – Weyburn, Canada

The IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project, in Saskatchewan, Canada was an early example of using an enhanced oil recovery location for long term CO_2 storage. The claim of CO_2 leakage made at a farm overlying the area, where a local landholder raised concerns about a series of observations, summarised in Romanak et al. (2014) as "unusual bubbling, foaming, algal growths and an oily sheen on a pond surface and dead animals in and around the ponds". The landholder commissioned a series of soil gas surveys over 2010 and 2011, due to concerns that the ponds and the animal deaths were due to leakage of the injected CO_2. This potential public health situation was initially investigated by one company who believed that the impact was due to leakage of CO_2 from the storage site. However, the results and interpretations were questioned by a number of different academic institutions and new sampling and data acquisition activities were conducted. It was acknowledged that it could be possible, but using stable carbon isotopes alone was not a suitable determinator of source or attribution of the CO_2 without analysing many other gases including radiogenic isotopes and noble gases (Romanak et al., 2014; Gilfillan et al., 2017). As a result of the detailed work by several researchers, it was concluded that the observations at this location were not evidence of CO_2 leakage and as such not a risk to public health.

Case study – Barendrecht, Netherlands

In 2007, a potential CCS demonstration project was under consideration at the town of Barendrecht. The proponents, Shell, were considering how to capture and store CO_2 from the nearby oil refinery. The storage sites were two depleted natural gas fields, located under the

Barendrecht township. Significant debate on CCS and the location of this site escalated and the project did not take place (see Feenstra et al., 2010). It resulted in significant polarisation between objectors, mainly local stakeholders from the municipal government and project proponents such as the project developers and national government. Such was the level of debate, discussion and dissent, new opponents developed coordinated groups to respond, whilst researchers were brought in to demonstrate scientifically that the project would be safe.

After a pause, attempts to continue with the project from a government perspective increased objection and the media attention increased such that the project ceased. Conclusions that a lack of mutual trust between stakeholders and those committed to the project resulted in broad disagreement and significant stress in the community. Approaches that would be more commonplace today, looking at community consultation and engagement appear to have been lacking. Questions were raised about the health issues (among other questions) in parliament, and external experts were sought to provide information in response. Some of the health-based questions related to risk related to pipelines as well as the overall long-term safety of the process.

Requests for further research included human health, especially psychosomatic effects (such as fear) on the local residents. This was difficult to execute as no baseline data were available for this location, and there were at that time no comparable studies globally (Feenstra et al., 2010). Barendrecht is a case study that demonstrates difficulties of being “first-of-a-kind” and many lessons have been learned through studies of the activities at this project. The conclusions of studies on human health were that there were no risks to health, but many other factors had by this time contributed to a wholly negative view of the project and it was never conducted.

5.6.3 Assessment

Will carbon dioxide leakage to the atmosphere result in a decrease in air quality?

Key Questions	**Answers**
Is it possible?	**Yes.** CO_2 is considered to be minimally toxic by inhalation. The primary health effects caused by CO_2 are the result of its behaviour as a simple asphyxiant as it reduces or displaces the normal oxygen in breathing air.
Is it material?	**No.** Material levels of CO_2 in the atmosphere (>5,000 ppm) only occur in very rare circumstances that require high leakage rates and accumulation of CO_2 in a constrained environment (e.g. closed room, caves, excavations with poor ventilation, stratification in a stagnant water body).
Can it be monitored?	**Yes.** Monitoring methods have been developed for the detection of direct leakage into the atmosphere (e.g. Lewicki et al., 2009; Humphries et al., 2012; Luhar et al., 2014). An example for critical CO_2 limits with respect to human health are listed below: 5,000 ppm (0.5%): Permissible Exposure Limit for 8-hour exposure 10,000 ppm (1.0%): Typically no effects, possible drowsiness 15,000 ppm (1.5%): Mild respiratory stimulation for some people 30,000 ppm (3.0%): Moderate respiratory stimulation, increased heart rate and blood pressure 40,000 ppm (4.0%): Immediately Dangerous to Life or Health 50,000 ppm (5.0%): Strong respiratory stimulation, dizziness, confusion, headache, shortness of breath 80,000 ppm (8.0%): Dimmed sight, sweating, tremor, unconsciousness, and possible death (https://www.osha.gov/)
Could it be mitigated?	**Yes**. Monitoring of high-risk areas and ventilation.
Could it be remediated?	**Yes.** Ventilation
Summary	**Possible but not material.**

5.6.4 References

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6 Summary and conclusions

In recognising the potential for environmental and public health implications of CO_2 migration or leakage to the surface or shallow subsurface, this report attempts to frame the risks and consequences using a causal network. In doing so, the report provides a structure with which to interrogate those risks for four successive levels from a Driver (emissions reduction) to various Endpoints (climate change mitigation, air quality, biodiversity, plant growth and beneficial groundwater use). The nature of the risks, their impacts and whether they are (or are not) material were assessed from a general perspective and not at a geographic or site- specific location (Figure 62). It is important to note that while CO_2 geological storage is considered to be a form of waste disposal, CO_2 itself is not regarded as a pollutant in ground or surface water.

From this general perspective, it was found that there is the possibility of material leakage of CO_2 to the atmosphere, the ocean or shallow aquifers through compromised wells or geological pathways like faults. Compromised well integrity can be mitigated through adequate well design and construction of injector wells that meet designated standards. Identification, sealing and monitoring of abandoned wells are other relevant activities to reduce risks. CO_2 leakage through compromised wells can lead to a direct pathway to a locally material change in CO_2 concentrations in aquifers, soils, surface waters, oceans, benthic sediments or the atmosphere. As such leaks are likely localised, they are relatively easy to identify and be remediated using a variety of available tools and techniques.

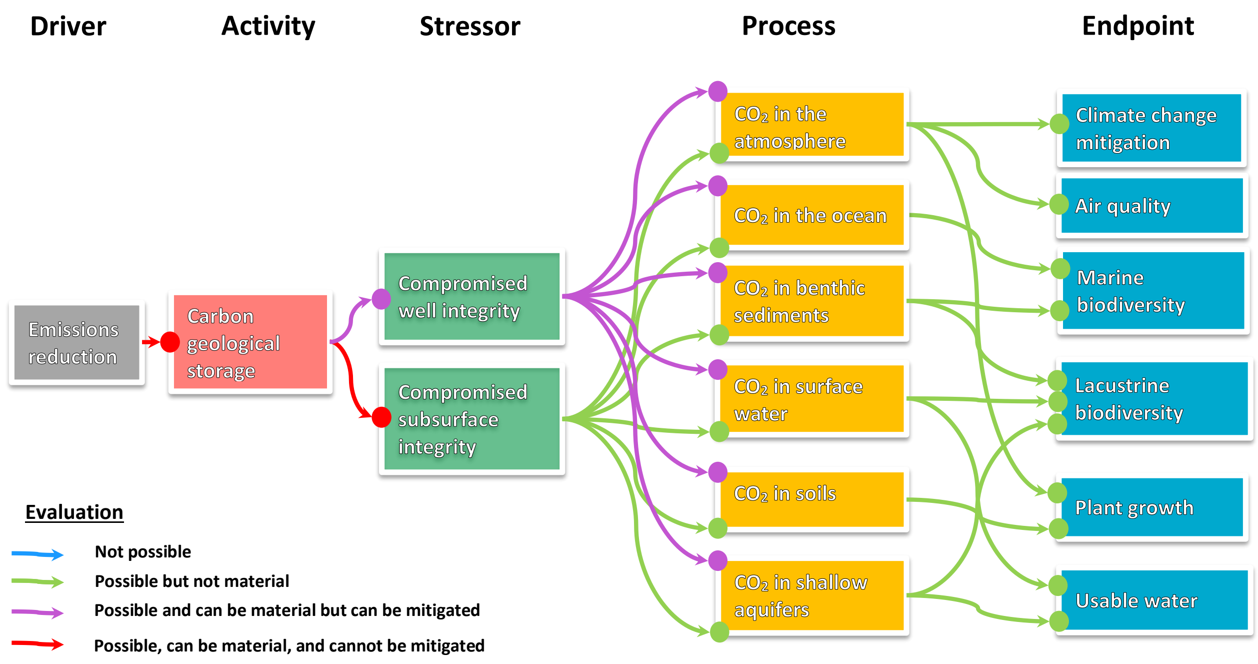

Figure 62. Causal network structure for the global assessment of environmental and public health implications of CO_2 migration to the surface or shallow subsurface. **See Page 34 for the interactive navigation tool.**

The lack of cases of leakage from commercial operations means that it is challenging to characterise what a geological leak might look like, determine the rates of leakage, or quantify the leakage impacts. Targeted monitoring and leakage detection in this case will be difficult because leakage would most likely occur at a location that had not been identified during site characterisation. Leakage rates are expected to be small and diffuse or patchy.

Multiple barriers and migration within intervening aquifers, chemical buffering, dissolution, and residual saturation will retard CO_2 migration and reduce volumes ending up in the shallow subsurface environment or the atmosphere, so that the impacts to Endpoints are deemed 'possible but not material'. While the effects of increased CO_2 on air quality, marine biodiversity, lacustrine biodiversity, plant growth and groundwater (surface or aquifer) is well-established, the leakage rates estimated to be possible, are not expected to exceed thresholds associated with these endpoints. Therefore, the general conclusion is that CO_2 migration from geological storage to the surface or shallow subsurface has a low risk to having material adverse effects on the environment and public health.

It is impossible to completely avoid the risk of CO_2 entering a shallow aquifer, the ocean or the atmosphere, but the role of site characterisation and M&V techniques should limit or eliminate secondary migration into these environments. Thus, site selection is key. Should a leakage pathway be established however, mitigation and remediation can be staged. This is likely to be through efforts such as ceasing injection and re-equilibration of pressure or use of pressure relief wells which will reduce over time the driver for CO_2 to escape its primary container.

Climate mitigation is the only Endpoint in the causal network for which the impact from CO_2 leakage can be solely assessed at a global level because it needs considering the combined potential CO_2 leakage from storage projects worldwide. Recent studies (Alcade et al., 2018; Postma et al., 2019; Hoydalsvik et al., 2021; Daniels et al., 2023) agree that the rare case of a single project experiencing material leakage would not have material impacts on climate mitigation efforts. Indeed, when accepting that CCS is required as part of a larger climate change mitigation portfolio, the biggest risk of CO_2 geological storage for the climate is not doing it at all. It is worth noting that even these recent CO_2 leakage estimations are compared to the Hepple and Benson (2005) suggested 'climate thresholds' of 0.1 – 0.01 % and we would argue that these should only be used in a global context and are not useful for regulating an individual storage project.

Although considered a rare occurrence, a material leak may still have severe consequences to the local environment and leakage thresholds that have direct environmental and health implications should be used in the impact assessment of all other endpoints but climate mitigation. Where available, examples were provided in the relevant sections for water quality limits and toxicity levels in groundwater and surface water, and for human health CO_2 limits in the air. However, performing a detailed risk assessment for a specific site is far beyond the scope of the project and the general causal network developed.

Local causal networks can be built from this general network to include spatial information, jurisdiction-specific regulatory thresholds, and nodes and data relevant to a specific storage project. For example, an offshore storage project would not require any nodes or linkages involving lacustrine biodiversity or plant growth. On the other hand, the local network would need to be extended by including 'assets' that are important to a specific region, for example specific endangered fish species or marine mammals. Also, with local knowledge and defined thresholds it would be possible better quantify leakage and specific environmental risks.

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