Recommendations for safety and performance analyses of storage pilot in the Paris Basin

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WP Leader	Thomas Le Guénan	TLG	20/05/26
Project Coordinator	Isaline Gravaud	IG	12/06/26

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Non-technical summary

This report assesses the safety and performance of a possible small-scale CO_2 storage pilot in the Paris Basin, in Seine-et-Marne. The purpose of the study is to identify what could happen, estimate how likely it is, and define what should be done to prevent, monitor and manage potential issues.

CO_2 geological storage consists of injecting carbon dioxide deep underground into a porous rock formation, where it can be stored instead of being released into the atmosphere. In this project, the target reservoir is located around 1,800 to 2,000 metres below ground, far below drinking-water resources. The reservoir naturally contains salty water, which is not suitable for drinking or agriculture. Above it, several layers of low-permeability rocks act as natural barriers and help keep the CO_2 underground.

The pilot considered in this report is limited in size. It would involve injecting up to 100,000 tonnes of CO_2 over a short period of a few months. This is much smaller than a potential commercial-scale storage project. The role of the pilot is therefore to test the behaviour of the underground reservoir, measure pressure changes, observe how the CO_2 moves, and collect data before any larger project could be considered.

The risk assessment considered several types of possible events: CO_2 moving farther than expected, leakage through old wells, leakage through the natural sealing rocks, induced seismicity, small ground movements, possible effects on other underground activities, and risks related to surface operations such as drilling, construction and CO_2 handling.

The results are generally reassuring for the pilot scale. According to the simulations, the CO_2 plume remains in all scenarios limited in size and does not reach the identified old wells in the area. The pressure increase caused by the pilot injection is also limited and remains too low to damage the sealing rocks above the reservoir under the assumptions considered. The probability of CO_2 leakage through the caprock is therefore assessed as negligible for the pilot case.

The risk of induced seismicity was also studied. The Paris Basin is a region with very low natural seismic activity, and no major fault has been identified in the immediate study area. The analysis indicates that the probability of induced seismicity remains low for the pilot. If very small seismic events were to occur, they would most likely be too small to be felt at the surface. Predicted ground movements are also very small, in the order of millimetres, and remain well below levels expected to affect buildings, infrastructure or land use.

The study also considered whether the project could affect groundwater. The target storage reservoir is much deeper than freshwater aquifers. For the pilot, the pressure changes are not expected to be sufficient to push salty water upwards through old wells towards shallower aquifers. However, the report recommends that groundwater and soil-gas monitoring should be considered around relevant old wells, especially to establish a good environmental baseline.

Risks at the surface, such as those related to drilling, construction, pressure equipment or CO_2 handling, are similar to risks already managed in other industrial activities. They can be managed using standard safety rules, appropriate engineering design, emergency procedures, gas detection systems, exclusion zones and compliance with existing regulations. Particular attention should be paid to the final location of the wellhead, the proximity of existing industrial facilities, and the way CO_2 would be supplied to the site.

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The main technical uncertainty identified for the pilot is injectivity, which means the ability of the reservoir to accept the planned CO_2 flow rate without exceeding pressure limits. This is more an operational question rather than a public safety issue. Most simulations show that the target injection volume can be reached or nearly reached, but in some of the less favourable cases injection could be limited by pressure constraints. This is one of the reasons why a pilot is useful: it allows the real behaviour of the reservoir to be measured before any larger project is considered.

The report also looks beyond the pilot and sketches what could happen if a larger commercial-scale project were developed in the future. Some issues that are very limited for the pilot could become more important at larger scale, simply because more CO_2 would be injected over a longer period. This includes the possible extension of the CO_2 plume, pressure effects on neighbouring underground activities, interactions with old wells, and long-term injectivity. Further studies, monitoring and careful design would therefore be necessary before any commercial development.

Public information and engagement are also essential. Trust cannot rely only on technical studies. It must also rely on transparency, dialogue, and the ability to answer legitimate questions and integrate views from local communities.

In conclusion, this assessment shows that a small CO_2 storage pilot in the Paris Basin can be designed and monitored in a way that keeps risks under control. It also highlights the value of starting with a limited pilot phase: the data collected during the pilot would help verify the behaviour of the underground reservoir, improve confidence in the assessment, and support transparent decisions about any possible future development.

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Executive Summary

The PilotSTRATEGY project aims to support the development of CO_2 geological storage pilots in several European regions by improving site characterisation, assessing storage performance, and evaluating safety conditions prior to potential pilot injection. This report presents the safety and performance risk assessment carried out for the proposed CO_2 storage pilot in the Paris Basin, France. It synthesises the work performed within Work Package 5 and builds on geological characterisation, reservoir modelling, preliminary risk screening, and probabilistic analyses developed throughout the project.

The proposed pilot targets the Dogger carbonate reservoir in the Paris Basin, with the Oolithe Blanche Formation as the main storage unit and the Callovo-Oxfordian marls and Oxfordian limestones forming the primary and secondary sealing system. The study area is located onshore, approximately 55 km southwest of Paris, in a region with a long history of subsurface use, including hydrocarbon exploration and production, geothermal operations, and wastewater injection. This regional context makes the assessment of legacy wells, pressure interactions and other subsurface uses particularly important.

The risk assessment was conducted in two main stages. A first preliminary assessment identified the main safety, performance and project risks and used simplified analytical or semi-analytical approaches to screen the most relevant scenarios. This preliminary work concluded that the pilot concept was broadly favourable from a safety perspective, while highlighting significant uncertainties that required further quantification. A second, more detailed assessment was then carried out using an ensemble of reservoir simulations and risk-specific models to quantify the likelihood and potential consequences of selected risk scenarios.

At pilot scale, the reference scenario considers the injection of 100 kt of CO_2 over approximately four months, followed by a long post-injection period. The probabilistic modelling framework propagates uncertainties related to reservoir properties, permeability distributions, relative permeability and capillary pressure functions, injection conditions, fracture pressure constraints, caprock properties, geomechanical parameters and the operational status of a nearby water disposal well. The resulting simulation ensemble provides the basis for the quantitative assessment of both performance and safety risks.

From a performance perspective, the pilot-scale results are generally favourable. The CO_2 plume remains spatially limited and does not exceed the considered permit area in any of the simulations. The risk of lateral migration beyond the expected storage area is therefore assessed as very low at pilot scale. Storage capacity is also generally sufficient to accommodate the target injection volume, although some scenarios show reduced injected volumes under less favourable subsurface conditions. The main performance concern is injectivity: pressure constraints and uncertainty in reservoir properties may limit the ability to sustain the target injection rate in some cases. Injectivity is therefore identified as a key uncertainty to be tested and constrained during the pilot.

The safety risk assessment also indicates a low level of risk for the pilot scenarios. Numerical simulations show that the CO_2 plume does not reach the identified pre-existing wells closest to the injection area. As a result, leakage through legacy wells is not expected to materialise under pilot-scale conditions. Leakage through the caprock is also assessed as negligible, as overpressure at caprock level remains well below the thresholds associated with the considered failure mechanisms, including intact caprock failure, leakage through undetected defects and fracture propagation.

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Induced seismicity was assessed through several scenarios, including the reactivation of sub-seismic faults in or near the reservoir, basement fault reactivation and diffuse microseismicity. For the pilot case, the combined probability of induced seismicity remains low, and the probability of events reaching magnitudes of concern is very limited. Surface ground movement is also predicted to remain very small, with uplift values well below the thresholds considered relevant for infrastructure or environmental impact. Brine leakage is not expected to occur at pilot scale, as the pressure footprint is insufficient to generate sustained upward flow through abandoned wells under the assumptions considered.

Risks related to drilling, well construction and surface handling of CO_2 were assessed qualitatively. These risks correspond mainly to conventional industrial and HSE hazards associated with drilling operations, construction activities, pressure systems, CO_2 handling and, depending on the retained development option, rail delivery or proximity to existing industrial facilities. No unmanageable scenario was identified, provided that standard engineering design, regulatory requirements, emergency planning and HSE practices are properly implemented. Particular attention should be paid to the final site configuration, potential interactions with the nearby Seveso-classified industrial facility, and the logistics of CO_2 supply if rail delivery is selected.

The report also touches upon the implications of scaling up from the pilot to a possible commercial-scale storage project. The commercial-scale simulations do not identify immediate showstoppers, but they show that several risks become more relevant at larger injected volumes and longer injection durations. These include lateral plume extent, storage capacity, long-term injectivity, interaction with pre-existing wells, brine leakage, and pressure effects on neighbouring petroleum concessions and other subsurface uses. These risks are therefore considered high-priority topics for further investigation before any commercial development.

For a commercial scale project, the CO_2 plume may reach some pre-existing wells in a small fraction of simulations, with the highest estimated probability associated with the active SEIF1 well. Pressure perturbations may also extend into neighbouring concessions, although CO_2 migration into these areas remains a low-probability outcome. The analysis suggests that any future commercial-scale project would require a broader area of review, refined modelling of plume and pressure evolution, improved characterisation of legacy wells, and careful definition of pressure management rules.

Pilot project risks were assessed qualitatively. Delays and cost overruns are considered significant risks, particularly because the economic rationale of a pilot depends strongly on its relationship with a potential commercial-scale project. Political and legal risks are considered more limited at national level, given the existence of an established regulatory framework for CO_2 storage in France, but local political support remains dependent on the perceived benefits and acceptability of the project. Social acceptance is identified as a key project risk, requiring early, transparent and sustained engagement with local stakeholders and communities.

Overall, the assessment supports the technical feasibility of a well-designed and properly monitored CO_2 storage pilot in the Paris Basin. No major safety concern has been identified for the pilot-scale scenario under the assumptions considered. However, the analysis also shows that the pilot should be designed as a structured learning phase, with monitoring and data acquisition explicitly targeted at reducing the uncertainties that matter most for future decisions. Key priorities include pressure monitoring, plume tracking, injectivity testing, improved geomechanical characterisation, legacy well assessment, and the evaluation of possible interactions with other subsurface uses.

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The main conclusion of this report is therefore that the proposed pilot represents a valuable and necessary step towards reducing uncertainty and informing evidence-based decisions on the future of CO_2 geological storage in the Paris Basin. If implemented with appropriate operational limits, monitoring systems, HSE provisions and stakeholder engagement, the pilot can provide critical information for assessing the feasibility, safety and performance of a potential commercial-scale development.

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1. Introduction

1.1 Context and project background

The PilotSTRATEGY project aims to advance subsurface characterization at several sites in preparation for potential pilot CO_2 injection operations. The work focuses primarily on three regions— in France, Spain, and Portugal—while two additional regions, in Poland and in Greece, are currently at earlier stages of development.

This deliverable is part of Work Package (WP) n°5 "Safety and Performance", which applies risk assessment methods to provide recommendations in terms of safety and performance aspects of the pilot.

For reference, the other WPs of the project are[1]:

- WP1: Management
- WP2: Geo-characterisation
- WP3: Simulation
- WP4: Pilot Development
- WP6: Social Acceptance
- WP7: Communications & Impact

1.2 Objectives and scope of the deliverable

The main objective of this report is to present the results of risk assessment for the French region. As the final report of the WP, it will also synthetize previous work within the project.

1.3 Regulatory framework

The work carried out within the PilotSTRATEGY project takes place upstream of any application for an exploration permit. However, the legislative and regulatory framework for CO_2 storage pilots is already established: it is based on the European CCS Directive and its guidance documents. In France, the Directive has been fully transposed into national law. Although there is no specific regulatory category for a "pilot", injection tests of up to 100 kt can be conducted under an Exploration Permit (PER).

More details of the French regulatory framework are given in Bouet *et al.* (2022).

1.4 Report structure

Section 2 describes the regional context of the study area. It introduces the location and geological setting of the site, the main characteristics of the storage reservoir and sealing formations, the structural framework, the presence of legacy wells and other man-made features, and the baseline conditions relevant to the assessment.

Section 3 summarises the preliminary risk assessment performed during the first stage of the project. It presents the initial risk identification, the simplified analyses carried out for the main safety and

[1] https://pilotstrategy.eu/about-the-project/work-packages

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performance risks, and the preliminary conclusions that informed the definition of the pilot implementation plan.

Section 4 presents the updated risk assessment. It first describes the modelling framework and the simulation ensemble used to propagate subsurface and operational uncertainties. It then provides the results of the performance risk analysis, covering lateral extent, capacity and injectivity, followed by the safety risk analysis, covering surface operations, injection well integrity, pre-existing wells, caprock integrity, induced seismicity, surface ground movements, brine leakage and interactions with other subsurface uses. For several risk categories, the implications for a possible commercial-scale development are also discussed.

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2. Overview of regional context

2.1 Site location and geological setting

The study area of the PilotSTRATEGY project in France is situated onshore within the Paris sedimentary basin, approximately 55 km southwest of Paris in the Île-de-France region. The area of interest lies in the southeastern portion of the Brie plateau, encompassing and adjacent to the Grandpuits-Bailly-Carrois commune, near Nangis. The Brie region is bounded to the north by the Marne River valley (e.g., the city of Meaux) and to the south by the Seine River valley (e.g., the city of Melun) (Mathurin et al., 2023).

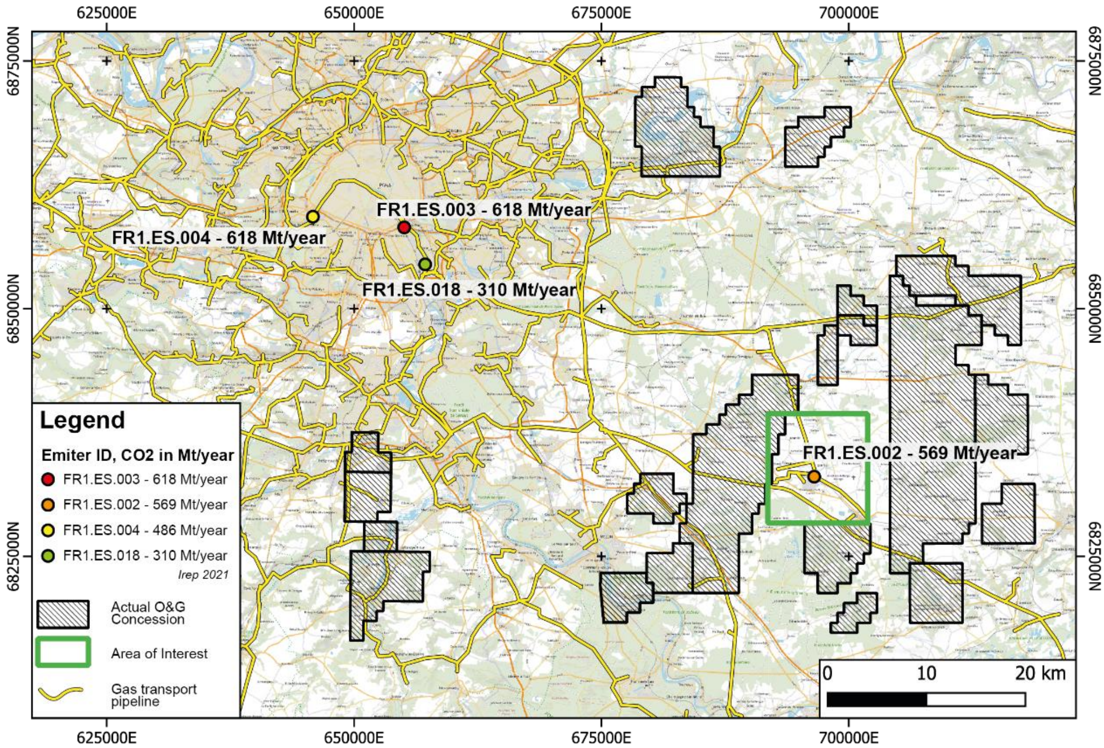

Figure 1: Location map of the area of interest with principal emitters (> 300ktCO2)

The Paris Basin constitutes a large intracratonic sag-type sedimentary basin, exhibiting a maximum thickness of approximately 3 km of indurated sediments in its central region (Bordenave & Wallendorff, 2023). It is underlain by a Paleozoic Variscan basement, subdivided into multiple structural blocks shaped by ancient collisional events (Mathurin et al., 2023). The basin's tectono-sedimentary evolution is characterised by eleven major cycles spanning from the Triassic to the Tertiary periods, predominantly driven by regional geodynamic processes such as the opening of the Atlantic Ocean and the Alpine orogenies (Bordenave & Issautier, 2024). Presently, the region is marked by tectonic quiescence.

A major regional emitter lies near the centre of the area of interest: a fertilizer plant which emitted until recently more than 300 kilotons of CO_2 per year. The ammoniac production process outputs high quality CO_2 which was liquefied and sold to industry. This emitter was a major factor in the choice of location for the French site and was thus considered as the main source of CO_2 for the studies. In

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March 2026 however, the plant management announced that it would no longer operates, after several months of reduced activities. The question on alternative sources of CO_2 needs therefore to be considered (see e.g. Lachen et al. (2025) for a discussion on the topic).

Another characteristic of the chosen site is the history of hydrocarbon exploration and exploitation as demonstrated by the current oil and gas licenses in the area (Figure 1). This ensured a good knowledge of the targeted reservoir, and access to existing data, particularly from logs and samples collected in the existing nearby wells. In addition, 3D seismic data was acquired during the first half of the project (Bordenave & Issautier, 2024).

2.2 Storage reservoir properties

The prospective reservoir is composed of the following lithostratigraphic units: Dalle Nacrée formation (Reservoir-2); Calcaire du Comblanchien formation (Comblanchien) (Semi-Permeable 1); and Oolithe

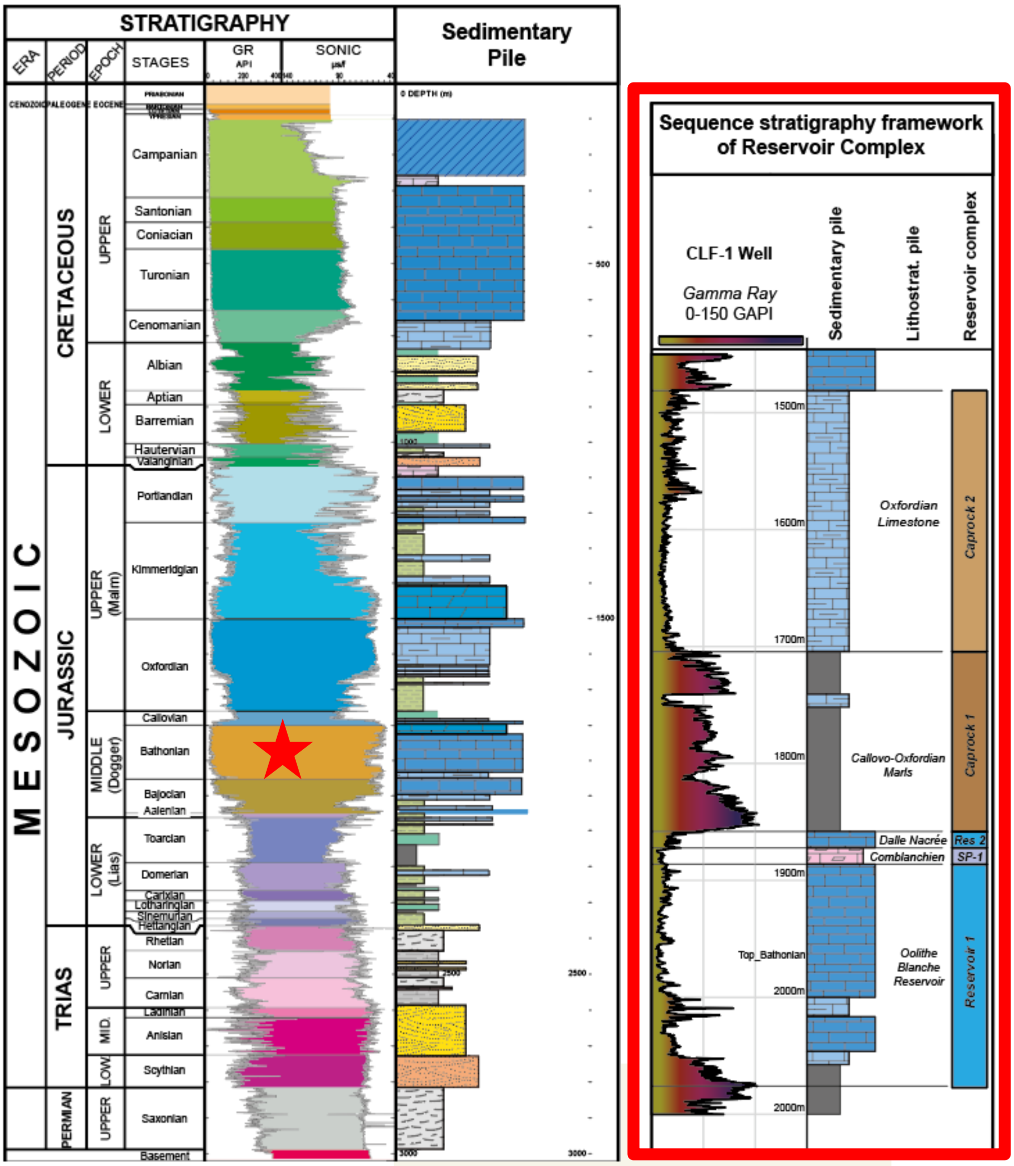

Figure 2: geological section of the Paris Basin (left) and reservoir complex section (right)

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Blanche Formation (Reservoir-1). The Oolithe Blanche Formation corresponds to the primary target for the CO2 storage which is part of the Dogger carbonate platform. The reservoir is primarily composed of grain-supported limestones (Bordenave & Issautier, 2024). The Oolithe Blanche has an average thickness of 100 to 150m and exhibits an average porosity of 10%. Permeability is highly heterogeneous and ranging from 0.1mD to 200mD.

2.3 Caprock / Seal description

The storage complex is bounded by a multilayered sealing system composed of Oxfordian Limestone (Caprock-2) and Callovo-Oxfordian Marls (Caprock-1) (Figure 2). The Callovian marls, also noted as Massingy marls or Marnes de Massingy, are considered as the first caprock interval above the reservoir section, with the thickness approximated between 100 and 130m. The secondary caprock is the Oxfordian limestones and constitutes a secondary barrier above the marls.

2.4 Structural/Stratigraphic traps and fault framework

The storage complex for the French site is considered an open saline aquifer. The seismic interpretation has identified two distinct structural traps: Charmotte fold and Clos-Fontaine fold.

The site of interest represents an absence of major faults intersecting the reservoir. However, major regional sub-vertical faults, such as the Bray and Bouchy/Malnoue faults, exist at distances of 15 km or more from the storage site and divide the basin into several blocks. The study area is on the central block of the basin delimited to the North by the Bray – Vittel fault zone, to the west by the Seine – Sennely fault zone and to the East by the Sillon Houllier – Saint-Martin-de-Bossenay fault zone (Mathurin et al., 2023).

2.5 Legacy wells and man-made features

The region has a dense history of underground resources exploitation. Since late 1950's, oil & gas and geothermal prospecting in the area. The Brie area counts more than 103 boreholes connected to the Dogger and Triassic formations (Mathurin et al., 2023). Although, since the hydrocarbon's activity has slowed down, the geothermal interest in that area contributed into further deep drilling, reaching 110 boreholes. The exploited fields located at the North, East and West of the studied zone are in the Trias below the targeted Dogger formations; but the South oil field, named Charmottes, have production/injection wells in one of the Dogger layers, named the Dalle Nacrée, above the Oolithe Blanche (Alavoine, Bouquet, Estublier, Fornel, Meiller, et al., 2024). In the study area, surrounded by several petroleum concessions, we count 6 legacy wells and a disposal well of the fertilizer plant. Only three are located within a 3-kilometre radius from the CO_2 emission plant and one on the CO_2 emission plant premises (Canteli et al., 2024).

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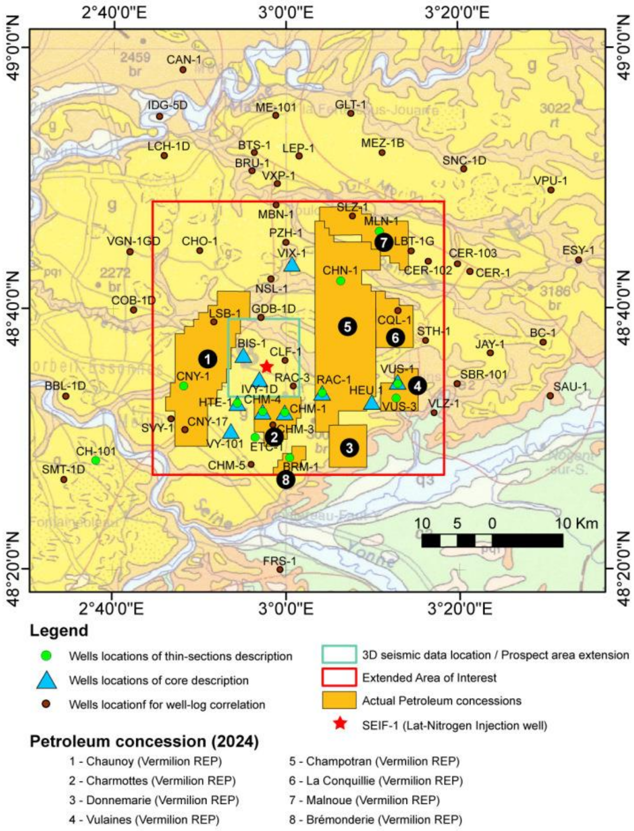

Figure 3: Data distribution in the Area of Interest (red square)

2.6 Environmental conditions

A comprehensive assessment of the environmental and social baseline is provided in D4.8 (Canteli, 2026). The hydrodynamic properties of the aquifers in the Area of Interest, including of the Dogger formation, are reviewed in Mathurin et al. (2023). The relevant properties of the reservoir (e.g. pressure and temperature) are provided is the paragraphs describing the numerical models used in this report (e.g. 4.2.1)

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3. Preliminary risk assessment and pilot implementation plan

3.1 Initial risk identification

The preliminary risk scenarios for the Paris Basin storage presented in this section were identified based on expert insights, through structured workshops, technical meetings, and comprehensive review of analogous CO_2 storage projects. This approach ensured the consideration of several potential technical and non-technical risk scenarios associated with CO_2 injection and storage operations. The methodology followed a structured framework consisting of three main types of risk:

- Safety risks:
    - Drilling / construction / handling at surface
    - Injection well: For new or converted injection wells, risks are associated with well design, cementation and long-term performance under long exposure to CO_2
    - Pre-existing well: When CO_2 reaches legacy wells, there can be a potential leakage through the wellbore due to casing or cement degradation over time. There is a significant risk related to the uncertainties in cementation quality and abandonment procedures.
    - Caprock / fault: the integrity of the sealing could be compromised in case of fracturing or fault reactivation. The loss of the mechanical integrity of the caprock could present a leakage path for the stored CO_2.
    - Induced seismicity: The injection can alter the initial stress in the reservoir. The resulted overpressure if exceeds the fracturing pressure during injection operation, could trigger microseismic events. While the Paris Basin is characterized by tectonic quiescence, the risk of induced seismicity cannot be entirely eliminated.
    - Surface ground movements.
    - Brine at surface: Displacement of formation brines into overlying aquifers due to pressure propagation.
    - Other uses: The storage operation may interact with other subsurface resources or activities in the region
- Performance risks:
    - Lateral extent: Surpassing the expected lateral extent and exceeding the predefined permit area
    - Capacity: The economic and technical viability of the storage operation depends on achieving the expected storage capacity and injection rates.
    - Injectivity
- Project risks: those are risks from the point of view of the project success, i.e. the project is able to inject and store CO_2.
    - Delays and costs: higher delays and costs than anticipated can alter the economic viability of the project
    - Politics / Legal: changes in the political and/or legal framework can affect the project viability
    - « Social »: the project cannot proceed due to strong oppositions from various stakeholders

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The listed distinct risk events were ranked and divided into two priority levels. Few risk events were qualified critical and required preliminary risk analysis using influence diagrams and simplified quantitative models based on expert assessment, before uncertainty reduction through better data and/or better models. Other risks were esteemed less critical and were assessed through expert elicitation.

3.2 Preliminary risk analysis

3.2.1 Plume modelling

As risks are deviation from an expected normal scenario (that meets the project's objectives), a first step in risk analysis is to be able to describe this scenario. Ideally, this description should include: the positioning and design of injection well, the probable plume and overpressure extension, expected stress modifications and thermal effects. Those results were not yet available at the time of the first round, so the risk analysis relied on hypotheses.

In designing a pilot project, we considered the following characteristics:

- A rate of 300 kt / yr for a duration of up to one year (i.e. maximum of 300 kt injected)
- Injection well location close to the plant so near the centre of the zone covered by seismic

We used a semi-analytical tool (Vilarrasa et al., 2013), in order to give a first order estimate of plume extension and pressures. The input data are displayed in Table 1.

Table 1: input data for the simulation using the semi-analytical tool

Input data	Value
Aquifer data	
Permeability	10 or 100 mD
Aquifer thickness	130 m
Porosity	0,15
Temperature	343 K
Capillary entry pressure	0,1 MPa
Residual water saturation	0,42
Depth top	1722 m
Young's modulus	40 Gpa
Poisson ratio	0,3
Brine data	
Brine density	1021 kg/m^3
Brine viscosity	0,0005979 Pa.s
Brine compressibility	$4{,}5.10^{-10}$ Pa^{-1}
CO_2 data	
CO_2 density at P_0	601,51 kg/m^3
Constant for CO2 density	376 kg/m^3
CO_2 compressibility	0,148 MPa^{-1}
Reference pressure P_0	18 MPa
CO_2 viscosity	$4{,}75.10^{-5}$ Pa.s
Well data	
Well radius	0,05 m
Injection data	

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Flow rate	9 kg/s (approx. 300kt/y)
Duration	1 year

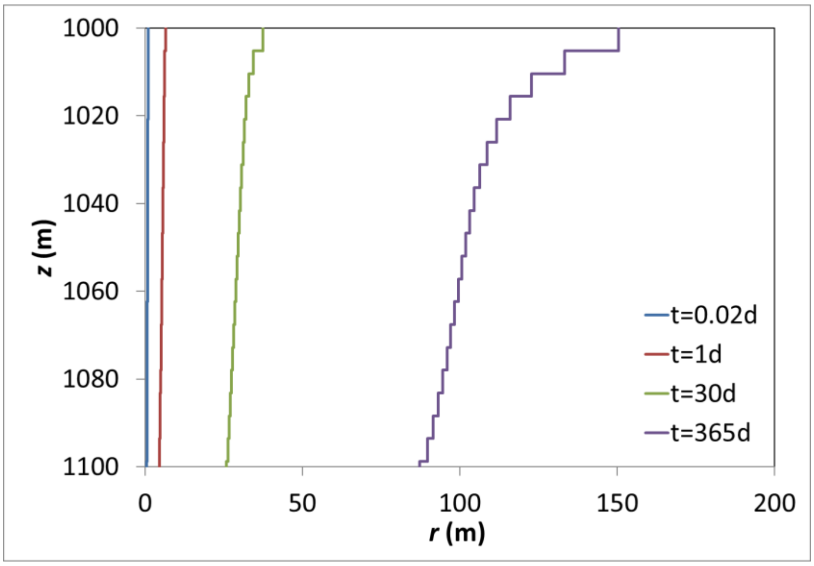

Figure 4: position of the CO2/water interface at different time for the 10 mD case

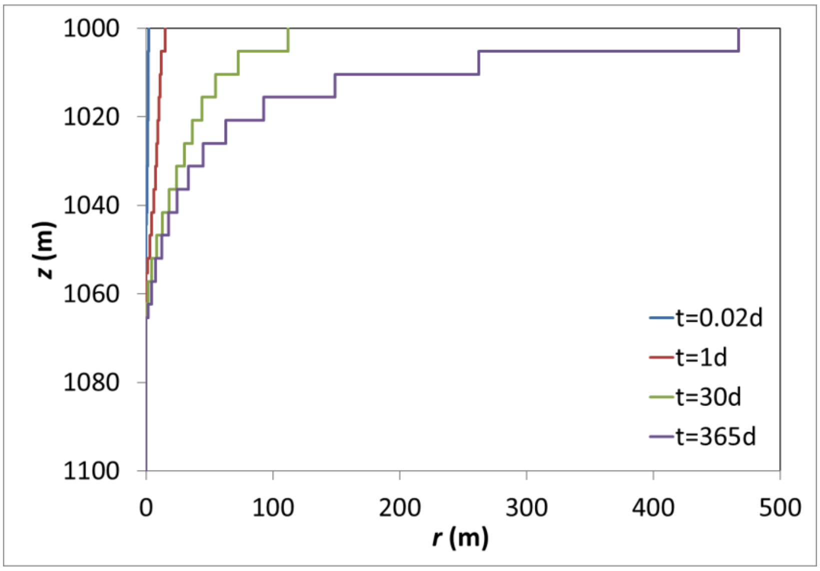

Figure 5: position of the CO2/water interface at different time for the 100 mD case

The results for both case (average aquifer permeability of 10 mD or 100 mD respectively) are displayed in Figure 4 and Figure 5. It shows that after one year and 300 kilotons of CO_2 injected, the radial extension is limited and well under 1 km.

The overpressure at the well at the end of injection is estimated to be 33.9 bars and 6.7 bars respectively. This first value is high as it is in the order of magnitude of fracture pressure. However, notwithstanding the large uncertainty of this simple simulation, if the pressure would reach a value close to the limit, then the operator would be forced to limit the flow of CO_2. Therefore, the risk is not of fracturing the caprock but of not being able to inject the desired quantity of CO_2. This case is studied in more details in round 2.

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3.2.2 Safety risk analysis:

For this first round, the work focused on the anticipated main risks:

- Leakage via pre-existing wells
- Leakage through caprock
- Induced seismicity

With respect to the result of the first round of risk identification, the following risks were not studied in detail. A short justification is provided:

- **Leakage via new well** (injection, monitoring): at this stage, the design of the new wells was not set. It is believed that dedicated CO_2 storage wells have a very low risk of leakage.
- **Impact on other subsurface uses**: the chance of this happening is not negligible. But it is difficult to say anything at this point without dedicated numerical modelling. In particular, the main aspect is the interaction between CO_2 injection and wastewater injection in the area. This is studied in more details during round 2.
- **Surface displacement**: this risk needs an estimation of the pressure increase in the reservoir, which requires numerical modelling.

3.2.2.1 Pre-existing wells

At this stage, without knowing the exact location of the injection well, the analysis consisted in a qualitative appraisal based on knowledge of each identified wells in the area.

The list of wells that reach the reservoir close to the potential injection zone are listed in Table 2 and depicted in Figure 21.

Table 2 provide a summary of the knowledge available during this first qualitative analysis for each well. We use three categories, similar to the method from Metcalfe *et al.* (2009):

- Green: knowledge that provide evidence in favour of safety
- White: lack of knowledge creating uncertainty about the risk
- Red: knowledge that provide evidence against safety

Note that the exact location of the injection was not known at the time, so we assumed a location close to the centre of the study area.

Table 2: Qualitative analysis of leakage risk through the existing wells in the area

SEIF-1		
Regular well logs: • Casing in good state • Cement Bond Log (CBL) show good cementing Geological barrier provided by creeping of shales (L. Cretaceous and U. Jurassic)	Operating plant: water injection should prevent CO_2 plume to reach the well	Close to injection point No CO_2-resistant well material: • Casing carbon steel • Cement Portland
BIS-1		
Geological barrier Cemented casings 7 plugs	CO_2 plume and pressure impact extension	Carbon steel casing (K55)
CLF-1		

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Geological barrier 7 plugs	CO_2 plume and pressure impact extension	Potentially no cementation below Albian (937m)
	IVY-1	
Geological barrier Cemented casings	CO_2 plume and pressure impact extension No info about plugging	Carbon steel casing (K55)
	RAC-3	
Potentially far from injection Geological barrier Cemented casings 7 plugs		Carbon Steel casing (K55)
	RAC-2	
Far from injection Geological barrier Cemented casings	Plugs are not mentioned	
	CHN-55	
Potentially far from injection Geological barrier		No Information about well
	GDB-1	
Potentially far from injection Geological barrier 6 plugs		No casing & cementation below 1277 m
	HTE-1	
Far from injection Geological barrier 5 plugs		7” casing partially cemented, esp. In Dogger

In conclusion of this initial assessment, there is some knowledge about these wells, and some of it gives evidence of safety. The focus of the second round (presented in section 4) is to gain more detailed insights into the possible movements of the plume in order to assess the probability of contact with these wells.

3.2.2.2 Leakage through caprock

Risk scenarios are deviation from a normal, expected scenario. This baseline scenario is the following:

The caprock is unfractured, has a low permeability, a high capillary pressure, is homogeneous and can withstand variations due to CO_2 injection. It is sufficiently thick as to guarantee this remains true even with uncertainties.

From this baseline, we considered three deviated scenarios (Song & Zhang, 2013):

- **Breakthrough pressure exceeded by CO_2**: this can be caused by high heterogeneities in the caprock and a too high pressure at the interface.
- **Re-activated fault act as a conduit**: this is caused by a too high stress due to pressure as well as geochemical, geomechanical and thermal effects. It also requires the presence of faults and fractures, which are unidentified in this case (no known faults or fracture in the caprock according to present data).

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- **Tensile fracturing of the caprock**: this is caused by a too high stress due to pressure as well as geochemical, geomechanical and thermal effects.

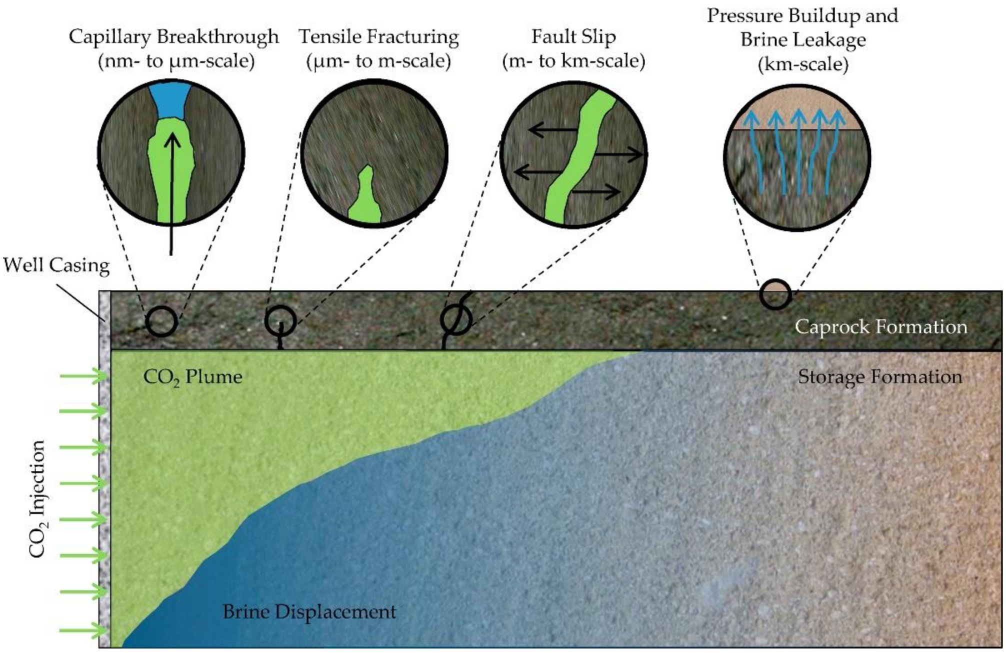

Figure 6: scheme of the various risk scenarios regarding caprock (Hannon & Esposito, 2015a)

Regarding the risk of CO_2 breakthrough by diffusion in the caprock, the thickness of the caprock system and likely values of (low) average permeability makes this risk very low. We did not provide any computation regarding this scenario. However, a previous work performed tests on plugs from potential caprocks in the Paris basin noted low capillary entry pressure (Carles et al., 2010a), meaning the CO_2 may not have a pressure barrier to penetrate the caprock. But the risk of CO_2 moving across the caprock is still very low as the absolute permeability is likely very low.

Regarding the other two scenarios, we followed the equations in Hannon *et al.* (2015). The results are shown in 7.1.2.

Those preliminary results tend to show that relatively high pressure – higher than estimated in 3.2.1 – can be admissible without re-activating faults or opening new fractures. However, there is high uncertainty attached to these models; not only regarding the input variables, but also regarding the models themselves. Rohmer *et al.* (2010) show that analytical models tend to overestimate the admissible pressure with respect to numerical models. Hydro-mechanical 3D models are thus needed to get more accurate estimates of admissible injection pressures.

A synthesis of the overall risk is provided in the table below.

Table 3: synthesis of risk analysis for leakage through caprock

Leakage through caprock		
More than 300m of caprock system Flat shape, meaning low risk of fractures	Stress measurement only at Bure (> 150 km distance) No caprock plug at this stage	Low capillary pressure measurements of top reservoir (Carles et al., 2010b).

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No detected fault		

3.2.2.3 Induced seismicity

Regarding induced seismicity risk, the mechanisms associated is that injections induce a change in the subsurface stress distribution. This change of stress, whether due to pore pressure change or poro-elastic effects has the possibility to trigger fault slip.

The hazard thus depends on the magnitude of stress change: this will be better estimated in round 2 with dedicated hydromechanical models from WP3.

The hazard also depends on the existence and status of existing faults. Again, there was no detected fault in the area. An analytical model is provided by Wu *et al.* (2021) to assess induced seismicity risk, but it supposes the existence of a fault crossing the reservoir. Consequently, we cannot use this model, and we only rely on qualitative analysis. However, the presence of nearby oil and gas fields could be an indication of nearby faulted structures.

A good indication of the status of existing faults is the recorded (natural) seismic activity. Masson *et al.* (2019) provide a map of historical and instrumental seismicity for France (Figure 7). The studied area is in a zone with very low historical and instrumental seismicity which means that there is not any active fault in the area and that inducing seismicity by injecting CO_2 is very unlikely. There is geothermal water reinjection as well as natural gas injection for seasonal storage in the Paris Basin, and there is no evidence of induced seismicity by either activity.

Moreover, the reservoir is located far from the basement (above approximately 800 m of sediments), which is an additional safety factor, as injection close to basement is believed to be more hazardous (Zhai et al., 2019).

Table 4 synthesizes this qualitative analysis.

Table 4: synthesis of risk analysis for induced seismicity

Induced seismicity		
Zone of very low activity Injection far from basement (~ 800m of sediments) No detected fault in the pilot zone	3D seismic resolution about 20 m	Neighbouring oil reservoirs are probably faulted

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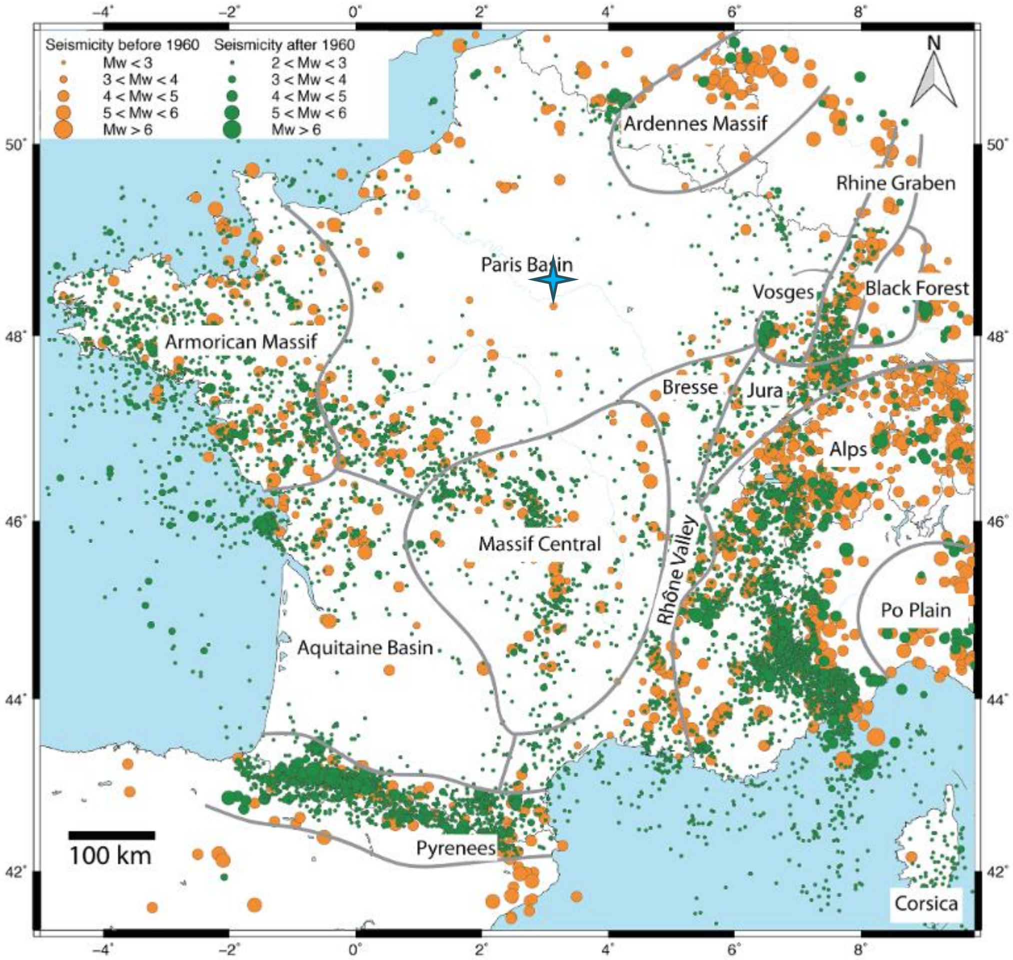

Figure 7: map of instrumental (in green) and historical (in orange) seismicity in France (Masson et al., 2019). A blue cross indicates the approximate location of the storage area.

3.2.3 Performance risk analysis

No specific risk analysis was conducted at this stage. See paragraph 3.2.1 for early modelling of plume displacement and pressure increase during the pilot operations.

3.3 Preliminary risk evaluation

At this stage, given the site configuration and modelling results using analytical models, the main conclusion is that the risk for safety and performance is low; however the uncertainties are large.

The main effort in the following stage is thus to reduce uncertainty, including by quantifying risk as much as possible, as prescribed by deliverable 5.1 (Le Guenan et al., 2024). A prerequisite of quantification is a more detailed identification of risks, i.e. detailing each risk category in sub-scenarios.

3.4 Pilot implementation plan

Following this first round of risk assessment, a task in the project was dedicated to performing modelling work for optimizing the choice of well location taking into account several criteria, including both surface and subsurface criteria. This work is presented in deliverable 3.3 (Alavoine, Bouquet, Estublier, Fornel, Meiller, et al., 2024).

Building on this work, the complementary techno-economic analysis made in WP4 (Canteli et al., 2025), combined with input from the French project partners, informed the final decision on well placement within the reservoir. The concept of the project was also validated: the next section thus focuses on the risk assessment of a pilot project injecting a maximum quantity of 100 kt of CO_2 at a rate close to a full-scale commercial project of about 300 to 350 kt/ year.

This choice is justified as a pilot project is a necessary first step before a larger project can be developed.

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4. Risk assessment synthesis

4.1 Risk identification update

Following the completion of Round 1, the French partners convened a workshop to review the risk register. The objective was to update the register in light of knowledge acquired throughout the project, and to examine how deliverables from other work packages could inform the risk assessment. The initial risk categories were kept identical, although some were judged as less relevant for a quantitative analysis, mainly because some risks are not adapted to being modelled numerically (ex: construction risks, project risks). In the case of “brine at surface”, the risk was studied with existing analytical models but was not considered a fully quantitative analysis. This reflects both resource constraints and a lower prioritisation from stakeholders and in the literature. Table 5 present the list of risk categories and indicates whether the category is studied quantitatively or not. In the case of a qualitative analysis, the goal is to detail the possible scenarios for each category, and to provide recommendations, without performing the analysis. As a reminder, the register considers three categories:

- **Safety risks** are risks from the operations to health, environment and goods.
- **Performance risks** are risks due to geological uncertainties to the project main objectives (i.e store a target quantity of CO_2)
- **Project risks** are risks due to external uncertainties to the project viability.

Table 5: list of risks considered in the second round of risk assessment

Risk category	Quantitative analysis
Safety risks	
Drilling / construction / handling at surface	NO
Injection well	YES
Pre-existing well	YES
Caprock / fault	YES
Induced seismicity	YES
Surface ground movements	YES
Brine at surface	NO
Other uses	YES
Performance risks	
Lateral extent	YES
Capacity	YES
Injectivity	YES
Project risks	

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Delays and costs	NO
Politics / Legal	NO
« Social »	NO

4.2 Risk analysis

Building on the preliminary risk assessment, for the risks studied quantitatively, probabilistic risk models were developed to characterise both the likelihood and magnitude of potential consequences. The core of this workflow relies on an ensemble of reservoir simulations, specifically designed to span the range of plausible subsurface behaviours under uncertainty. Hydrodynamic simulations were carried out using OPM Flow (Rasmussen et al., 2021) and executed on a High-Performance Computing (HPC) cluster.

To systematically capture the effect of subsurface uncertainties, twenty input parameters were varied across the simulation ensemble. These include reservoir permeability distributions, relative permeability curves, injection rates, and the operational status of a nearby water disposal injection well (see Appendix 7.2.1).

The pilot scenario considers the injection of 100 kt of CO_2 over a 4-month period, followed by 1000 years of post-injection monitoring. Building on the pilot scale analysis, the modelling scenarios were scaled up to commercial scale scenarios (300kt/year over 30 years), where the uncertainties were propagated to assess a range of identified risks.

Simulation outputs are then processed through risk-specific models tailored to each risk event and its associated sub-scenarios. For the pilot-scale scenarios, results are expressed as loss distribution curves, from which key percentiles (P10, P50, and P90) are extracted to characterise the range of potential consequences. The outcomes of the commercial-scale simulations are subsequently analysed to derive risk-specific recommendations, supporting scale-up strategies and informing future decision-making.

4.2.1 Dynamic model description

The risk analysis is grounded in a three-dimensional grid model covering a 20 km × 20 km × 2.5 km domain, constructed from seismic interpretation and well marker data. At the available seismic resolution of approximately 20 m, no fault was identified within the sector. From this structural framework, three static realisations were derived. While all three share the same geometry and petrophysical properties, they differ in the porosity field assigned to the Oolithe Blanche Formation, the target CO_2 storage formation, reflecting uncertainty in pore volume estimates. These realisations are designated P10, P50, and P90, representing pessimistic, base-case, and optimistic storage capacity scenarios, respectively.

For the pilot scenarios, these three porosity realisations form the base of the 2016 simulations, from which permeability distributions were derived through a porosity-permeability (k-ϕ) relationship, alongside the remaining uncertain parameters sampled across their defined ranges. Whereas for the commercial case, 3464 realisations were conducted. For both scenarios, dynamic simulations were performed on a coarse 500 × 500 m grid (51 × 51 cells in the X–Y direction). Embedded local grid refinements were excluded to reduce computational cost and as consequence of the current tool limitations (Christ et al., 2024). Both heat transfer and the geothermal gradient were accounted for,

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with temperature profiles derived from depth-referenced measurements (Mathurin et al., 2023). Rock compressibility was held constant per layer, assigned as a mean value.

At the model boundaries, regional saline aquifer flow was not represented, and surrounding petroleum activities were similarly excluded. One notable exception is the water disposal injection well operated by a nearby fertiliser plant, which was explicitly incorporated into the model and constrained by the estimated fracture pressure (Alavoine et al., 2024). The injection well geometry, including its location, radius (0.069 m), and perforation interval (60 m thick), was directly inherited from (Christ et al., 2024).

In the following subsections we will be based on the previously described model and input uncertainties results to perform risk analysis on the safety risk events and the performance risk analysis and present the results.

4.2.2 Performance risk analysis

4.2.2.1 Lateral extent

4.2.2.1.1 Risk description

This risk event addresses the probability that the CO_2 plume, in its gas phase, migrates laterally beyond the boundaries of the permitted storage area. Such an exceedance would constitute a performance failure, potentially triggering regulatory penalties for permit violation and raising broader concerns over storage feasibility. As illustrated in the influence diagram (Figure 8), the spatial evolution of the plume is governed by a combination of operational and geological factors, primarily the injection rate, temperature, and duration, alongside the geological model, petrophysical properties, CO_2 stream composition, the operational state of the nearby water injection well, and the geometry of the permit area itself.

4.2.2.1.2 Key data and assumptions

In this study, the permit area and the boundary geometry are treated as a fixed decision inputs (though they can be updated if required) and are defined as the seismic acquisition square of 10km x 10km (Veloso et al., 2021). The CO_2 pilot injection scenario assumes the injection of 100kt of pure CO_2 over 4 months period, which represents the maximum quantity authorized under the French regulatory framework for CO_2 injection tests. The injection rate was determined to meet the commercial target of 300kt/year, corresponding to the estimated CO_2 flow rate available from the capture process in the fertilizer plant, if operational. The injection well location is inherited from Lachen et al. (2025).

The injection rate and temperature are considered as uncertain parameters. Porosity uncertainty is represented through the three static realisations (pessimistic, median, and optimistic), from which permeability distributions are derived via the k-\phi relationship described in the Appendix 7.2.1. CO_2 migration is assessed in the gas phase only, and a conservative gas saturation cutoff equal to 0.01 is applied to ensure that residual plume migration is captured.

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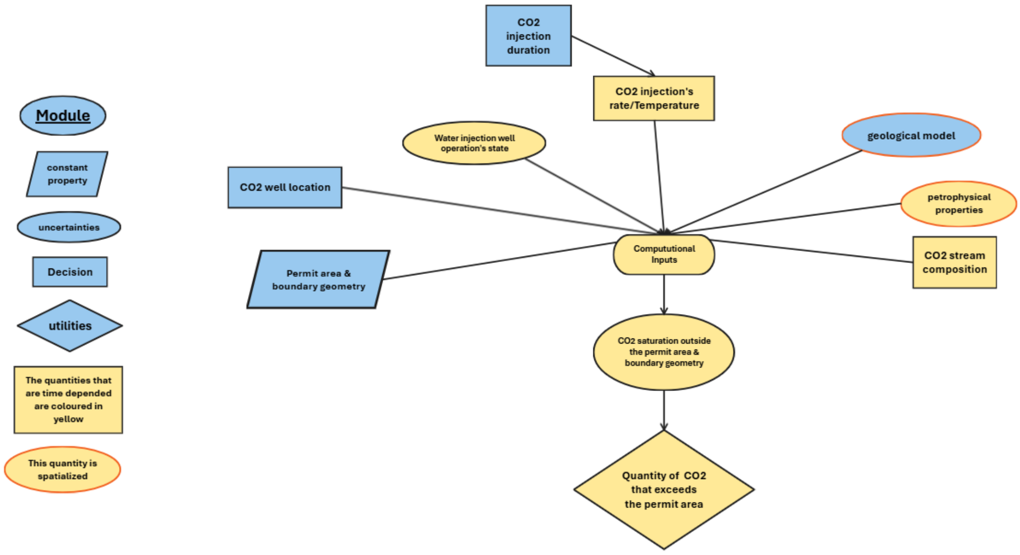

Figure 8: Influence diagram of the risk event: lateral extent

4.2.2.1.3 Modelling approach

The lateral extent of the CO_2 plume is assessed by tracking the spatial distribution of gas saturation across all simulations and over all timesteps. For each grid cell, a cell is considered part of the plume if its gas saturation exceeds the defined threshold. A vertical projection is then applied, such that a column is flagged if any cell within it has exceeded the threshold at any point in time throughout the simulation period. By assembling results across all the simulations, the probability of CO_2 occurrence is computed spatially.

4.2.2.1.4 Results

The previous modelling allows us to characterize the plume exceedance map that indicate the likelihood of CO_2 presence at any given location within the model domain (Figure 9).

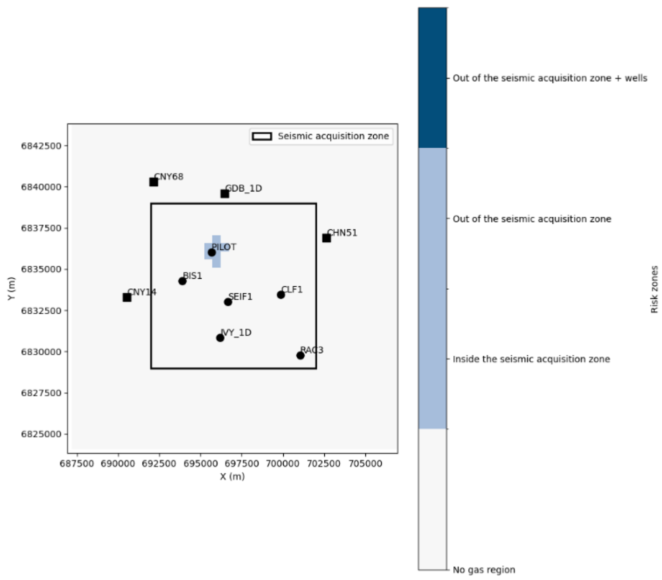

Figure 9: Spatial map of the probability occurrence of the cell to have gas (Pilot scale)

4.2.2.1.5 Scale-up to commercial scenario and recommendations:

For the commercial-scale case, a total of 3464 realisations were generated to explore the uncertainty space. Figure 10 illustrates the lateral extent of the CO_2 plume, projected along the Z-axis, and highlights the cells in which free-phase CO_2 is present across the different simulations. The colour coding distinguishes three spatial zones: inside the seismic acquisition area, outside the seismic acquisition area, and outside the seismic acquisition area while intersecting an existing well.

The figure shows that, in a limited number of realisations, the CO_2 plume migrates northward beyond the seismic area and may reach a well (GBD_1D) located outside the seismic zone. These specific cases are analysed in more detail in the following two figures. The Figure 11 left presents the exceedance probability curve, indicating that the probability of CO_2 mass extending beyond the lateral boundary of the permit is only 1.8 %. The Figure 11 right shows that only 61 realisations exhibit a CO_2 mass exceeding 1 kt outside the permit area. For these cases, the mass of CO_2 located outside the permit ranges between 0 and 1938.9 kt, with a P50 value of 189.1 kt and a P90 value of 1516.4 kt.

Overall, these results indicate that while plume migration beyond the seismic area is possible under conservative assumptions, such occurrences remain low-probability events and are limited to a small set of the simulated realisations.

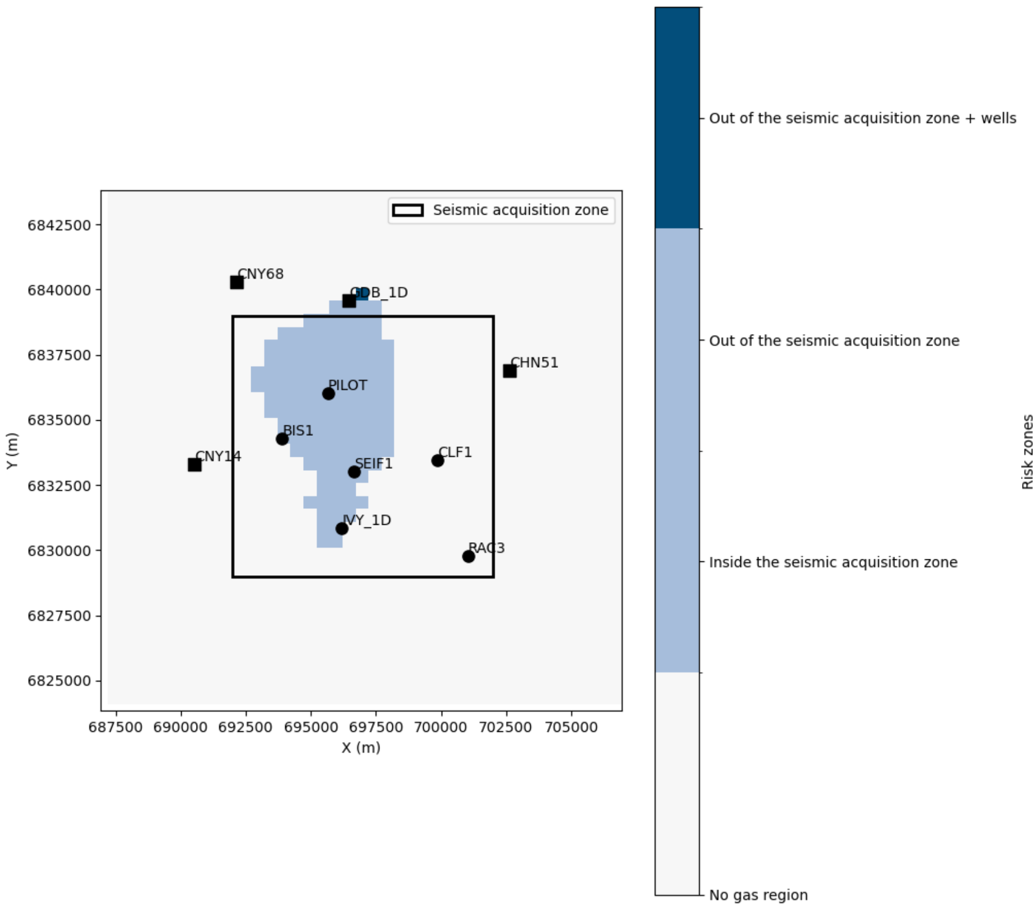

Figure 10: Lateral extent of the CO_2 plume for the commercial-scale scenarios compared to the seismic acquisition area.

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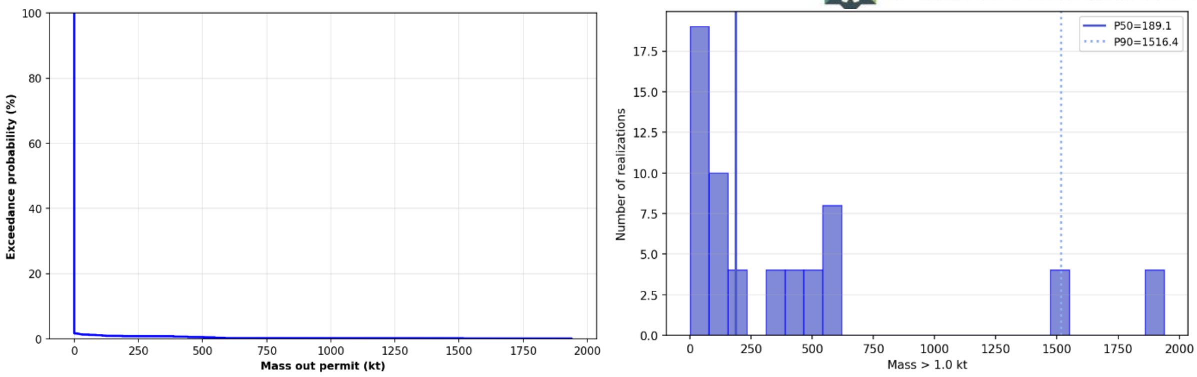

Figure 11: left: Exceedance probability of CO_2 mass extending beyond the lateral boundary of the seismic area (commercial scale), right: Distribution of CO_2 mass > 1kt located outside the seismic acquisition area for the commercial-scale simulations

A key recommendation that follows from these results is that, in the absence of additional information and constraints, acquiring and exploiting data from the larger permit area - beyond the current seismic acquisition zone- would provide more conservative and risk informed decision for commercial scale storage deployment.

4.2.2.2 Capacity

4.2.2.2.1 Risk description

This risk event addresses the probability that the predicted injection capacity is inferior to the storage target, thereby constituting a performance failure. In the context of this pilot project, the target is defined as the injection of 100 kt of CO_2 over the 4 months. At this scale, this risk is generally considered low, as the injected volume represents a modest quantity. However, failure to achieve this target may result in regulatory penalties. In fact, beyond the purely operational dimension, this risk event represents a financial component: when the operator is contractually obligated to inject a specific quantity of CO_2 any shortfall in reservoir capacity translates directly into an economic loss.

As illustrated in the influence diagram (Figure 12), the injected CO_2 quantity is governed by a combination of operational and geological factors, including injection rate, temperature, duration, the geological model, petrophysical properties, CO_2 stream composition, and the operational state of the nearby water disposal injection well. In addition to the previously mentioned parameters, economic parameters are incorporated to convert the quantity shortfalls into financial consequences.

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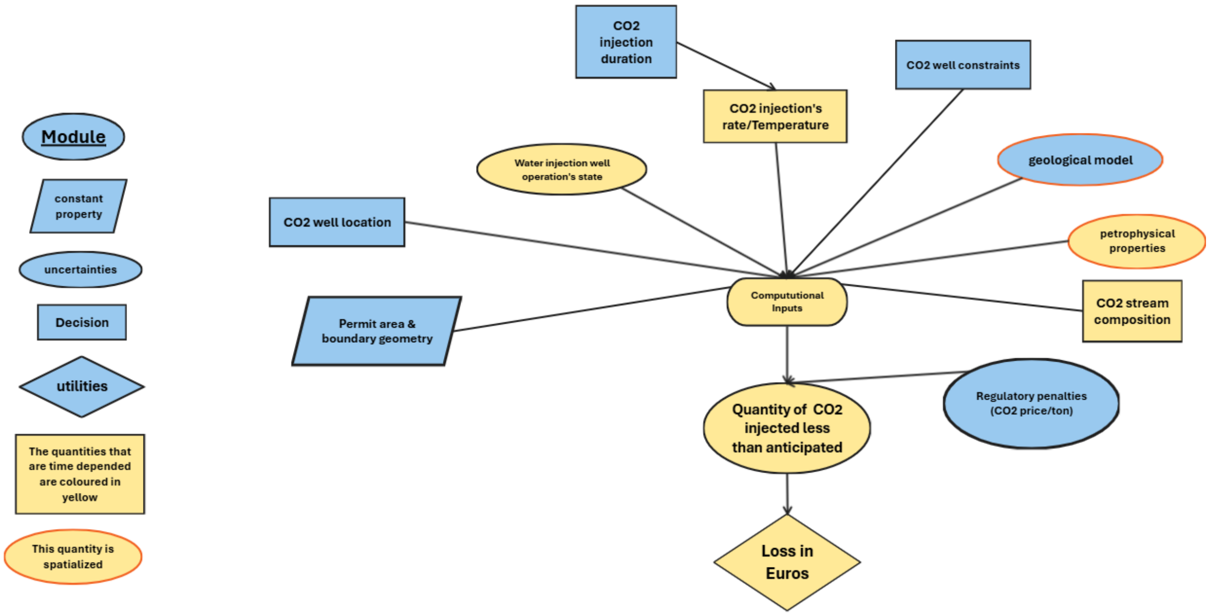

Figure 12: Influence diagram for the capacity risk event

4.2.2.2.2 Key data and assumptions

The storage target is treated here as a fixed decision input and is defined as the injection of 100 kt of pure CO_2 over a 4-month period, representing the maximum quantity authorised under the French regulatory framework for CCS pilot-scale projects. The injection well location and the injection rate are inherited from task 3.2. A penalty of 75 €/t of uninjected CO_2 is assumed to represent physical shortfalls into financial consequences.

4.2.2.2.3 Modelling approach

The risk metric is expressed as the cumulative quantity of injected CO_2 across all simulations and at the end of the injection phase. For each simulation realisation, the total quantity of CO_2 injected successfully by the end of the injection period, is recorded and compared against the target of 100 kt. A shortfall is noted if the cumulative quantity is below this threshold, and the non-injected quantity is retained to track the capacity risk. Note that in this study, this may occur when the bottom-hole pressure constraint is reached before the target volume is achieved.

By assembling results across all simulations, a distribution of the capacity distribution and a loss exceedance curve was constructed, reporting the P10, P50, and P90.

4.2.2.2.4 Results

At the pilot scale, the loss exceedance curse is expected to remain concentrated near zero, reflecting the low probability of significant capacity limitations under the modelled conditions. However, the capacity analysis reveals that achieving the full injection target of 100 kt is not guaranteed across all realisations. Here, P10, P50, and P90 refer to the 10th, 50th, and 90th percentiles of the achieved injected volume distribution across the ensemble (Figure 13, Left). The P50 and P90 injected volumes are 98.63 kt and 98.65 kt respectively, indicating that in most cases the target is nearly met. The P10 value of 79.05 kt indicates that 10% of the realisations the injected volume does not exceed this value. This highlights that under the most unfavourable subsurface conditions, the shortfall of up to ~21 kt can be noteworthy.

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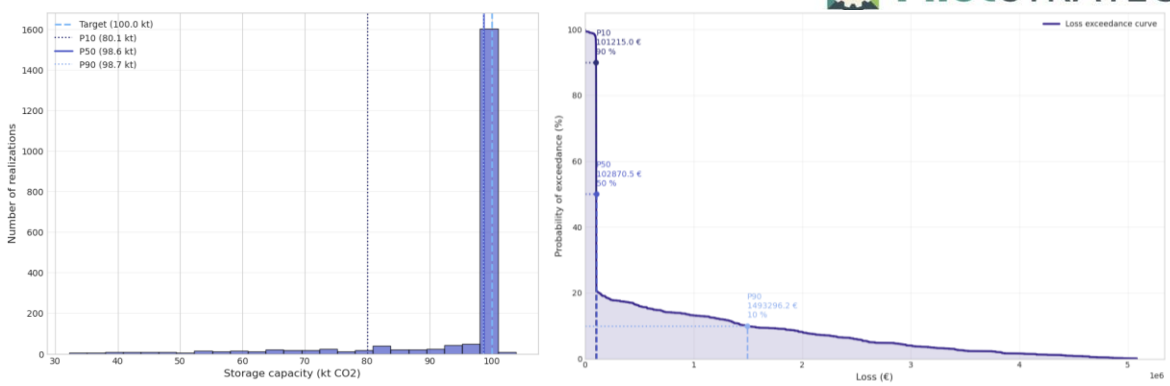

Figure 13: Storage distribution across the simulation ensemble: achieved capacity (P10, P50, and P90) and Loss exceedance curves for the capacity risk event.

The close values between P50 and P90 values confirms that the capacity shortfall is a low-probability event, largely confined to a narrow tail of unfavourable subsurface conditions. This is further reflected in the financial assessment (Figure 13, right): applying a penalty rate/t of uninjected CO_2, the mean expected loss across the ensemble is €, fully consistent with the low risk level expected at pilot scale. The P10 loss stands at ~101 k€, meaning that half of all simulations result in a financial loss below this value, while the P90 loss reaches ~1,493k€. The theoretical maximum loss of ~5,083k€ corresponds to the worst-case scenario.

Overall, these results are reassuring: the capacity risk remains a low-probability event in most realisations, and the financial consequences are bounded. The analysis does however highlight the sensitivity of injection performance to subsurface uncertainty mainly under pessimistic conditions.

4.2.2.2.5 Scale-up to commercial scenario and recommendations:

The Figure 14 left shows the distribution of CO_2 storage capacity (in Mt) obtained from the commercial-scale simulations. The target storage capacity is aiming at 9 Mt. The results indicate a P10 capacity of 2.8 Mt, a P50 capacity of 8.9 Mt, and a P90 capacity of 9 Mt, demonstrating that the target capacity is achievable for some cases. The Figure 14Figure 13 right presents the exceedance probability curve of economic loss (in M€) associated with the capacity risk due to non-injection of the total quantity. The results show a P10 loss of 2.4 M€, a P50 loss of 9.5 M€, and a P90 loss of 464.5 M€, with a maximum simulated loss of 635 M€. These values quantify the range of potential financial consequences for the commercial case.

These results indicate that, while the target CO_2 storage capacity of 9 Mt is reached in the median to upper scenarios, significant variability remains at the lower end of the distribution. The loss exceedance analysis shows that high-impact economic losses are low-probability events, but their magnitude can be significant. This behaviour highlights the importance of uncertainty management when scaling up to commercial operations.

These findings support the need for additional site-specific data, in order to increase confidence in both storage capacity and economic performance.

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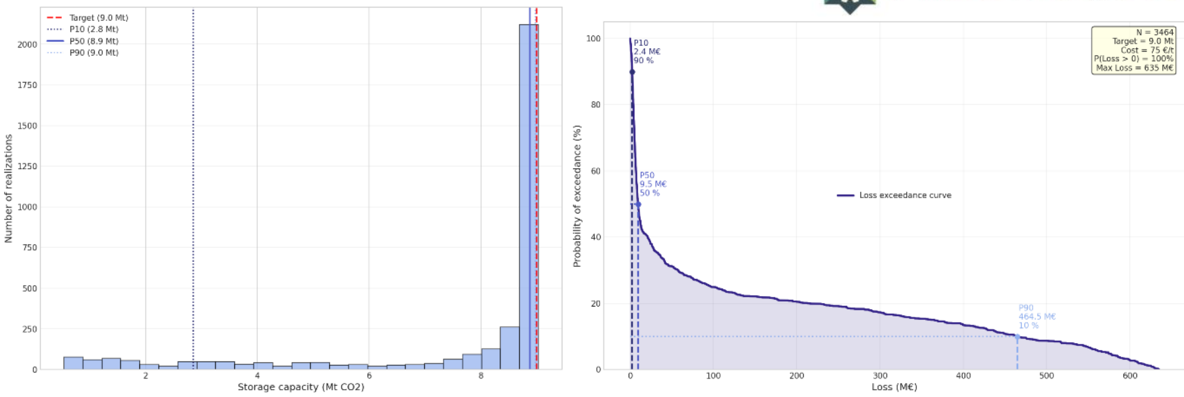

Figure 14: left: Distribution of CO_2 storage capacity for the commercial scale simulations, right: Exceedance probability of economic loss in M€ (for commercial scale)

4.2.2.3 Injectivity

4.2.2.3.1 Risk description

This risk event treats the probability that the achieved injection rate is below the target value, thereby constituting a performance failure. In the context of this pilot project, the target is defined as the injection of 100 kt of CO_2 over the 4 months. The injection rate was determined to meet the commercial target of 300 kt/year, corresponding to the estimated CO_2 flow rate available from the capture process at the nearby fertiliser plant. The risk at the pilot scale could be relevant at commercial scale, since the target rate is unchanged and only the injection duration differs. However, failure to sustain the target rate may result in a range of financial and regulatory consequences, including contractual penalties, alternative storage costs, and losses related to carbon credits. As per the capacity risk, the financial dimension is quantified: any shortfall in well injection rates translates directly into an economic loss.

As illustrated in the influence diagram (Figure 12), the governing parameters are closely similar to those identified for the capacity risk event.

4.2.2.3.2 Key data and assumptions

The injection rate target is treated here as a fixed decision input and is defined as 415100 sm^3/day. The injection well location is inherited from task 3.2. A penalty of 75 €/t of uninjected CO_2 is assumed to represent physical shortfalls into financial consequences. A critical additional uncertainty concerns the fracture pressure of the formation and constitutes a constraint that limits the injection operations. When the simulated bottom-hole pressure approaches this limit, injection is stopped to prevent formation damage.

4.2.2.3.3 Modelling approach

For this risk analysis, the injectivity risk is quantified using the mean injection rate over the injection period. For each simulation realisation, the injection rate time series and the corresponding bottom-hole pressure (BHP) values are extracted. The mean injection rate is adopted as a simplifying assumption; an approximation that is acknowledged as a potential source of uncertainty given the central role of injection rate variability in operational performance assessment.

The BHP profile serves a diagnostic purpose: it allows to distinguish if the injection rate was ensured when the BHP remains below the fracture pressure threshold throughout the injection period. In this case, the shortfall relative to the target rate is attributed to reservoir performance limitations. When the BHP reaches or exceeds the fracture pressure, injection is stopped and an effective reduced rate

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is computed. The annual rate shortfall is calculated as the difference between the target rate and the mean achieved rate and subsequently converted into a financial loss based on the CO_2 price and the project duration.

To propagate the uncertainty on fracture pressure, each porosity realisation (P10, P50, and P90) is assigned its own fracture pressure distribution. In fact, for each porosity realisation, the financial loss is evaluated under three fracture pressure scenarios: optimistic (higher fracture pressure), median estimate, and conservative (lower fracture pressure). This three-scenario framework results in a family of loss exceedance curves that captures the combined effect of reservoir uncertainty and fracture pressure uncertainty on injectivity performance.

4.2.2.3.4 Results

The injectivity risk assessment is presented through loss exceedance curves that represent the financial consequences of injection rate shortfalls across the full simulation ensemble (Figure 15). Several simulation scenarios lead to non-negligible financial losses, particularly under pessimistic subsurface conditions.

The following Table 6 represents the results of the average loss for the three porosity scenarios (P10, P50, P90) and the three operational scenarios were considered: optimistic, base, and conservative, defined by decreasing fracture pressure threshold, defined for each of the cases. At low porosity (P10), the system remains relatively stable, with moderate losses and limited variability. For the porosity P50, results are similar but slightly more pronounced with slight increase of constrained cases. At porosity P90, the system becomes significantly more sensitive to operational conditions.

Table 6: Summary of fracture pressure scenarios, average financial losses, and constraint levels for the P10, P50, and P90 porosity cases.

Porosity percentile	Realizations	Fracture pressure		Average loss (M€)	Constrained cases (%)
P10	672	Optimistic	270	0.79	35.1
		Base	262	0.90	40.2
		Conservative	250	1.06	47.0
P50	672	Optimistic	260	0.80	37.2
		Base	252	0.92	42.3
		Conservative	240	1.10	49.3
P90	662	Optimistic	230	0.69	35.8
		Base	219	0.93	48.3
		Conservative	210	1.23	64.8

However, the exceedance probability curves (Figure 15) provide additional insight into the distribution of financial losses across the three porosity scenarios. It is notable that at low loss values (around 1-1.2 M€) exceedance probability is significantly higher for P90 (~48%) than for P50 (~43%) and P10 (~40%). Then, the curves gradually decrease, reflecting the probability of exceeding higher loss levels. In the intermediate range (~1.5-2.5 M€), the three scenarios show relatively similar behaviour. However, clearer differences emerge in the high-loss tail. The P10 case exhibits higher exceedance probabilities above ~3 M€, meaning that large losses are more likely in low-porosity conditions. In contrast, the P90 curve drops more rapidly, indicating a lower probability of extreme losses. This behaviour highlights a trade-off between constraint occurrence and loss severity.

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Additionally, these results demonstrate the significant influence of fracture pressure uncertainty on the loss distribution. As illustrated here, for each porosity realisation, the uncertainty bands associated with the three fracture pressure scenarios span a considerably wide range, with each scenario represented by a distinct colour envelope. Under conservative fracture pressure assumptions, the loss distributions shift towards higher values, especially for the porosity P90 cases. This demonstrates that the fracture pressure threshold is a substantial manager of injectivity risk, underlining the importance of improving the mechanical characterisation of the formation.

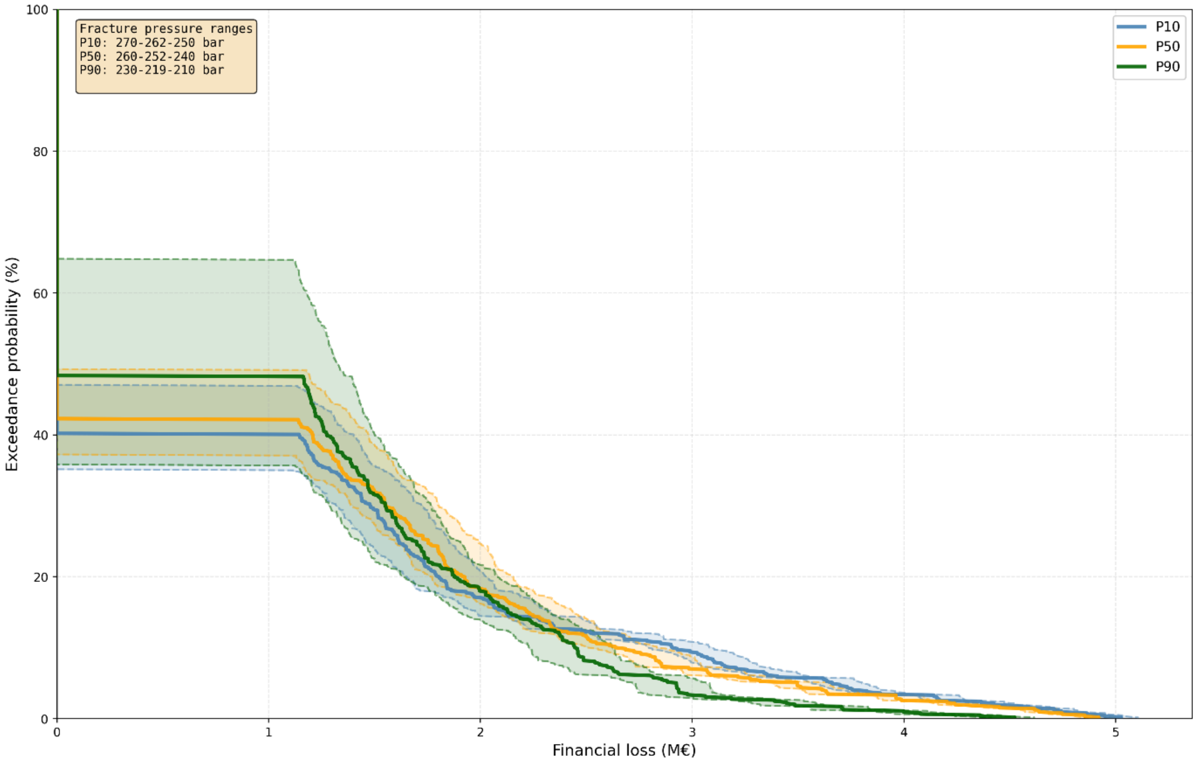

Figure 15: Loss exceedance curves for the injectivity risk event: financial losses associated with injection rate shortfalls under combined porosity and fracture pressure uncertainty.

4.2.2.3.5 Scale-up to commercial scenario and recommendations:

A total of 3358 commercial-scale simulations were analysed to assess injectivity performance, with BHP evaluated against fracture pressure constraints for different porosity scenarios. Results are reported for low (P10), medium (P50), and high (P90) porosity cases, and for optimistic, base, and conservative fracture pressure assumptions.

Table 7: Summary of fracture pressure scenarios, average financial losses, and constraint levels for the P10, P50, and P90 porosity cases (for commercial case).

Porosity percentile	Realizations	Fracture pressure		Average loss (M€)	Constrained cases (%)
P10	1118	Optimistic	270	194.07	66.9
		Base	262	205.42	70.0
		Conservative	250	225.36	76.2
P50	1164	Optimistic	260	186.26	64.6
		Base	252	199.31	69.1
		Conservative	240	217.72	73.5

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P90	1076	Optimistic	230	161.49	58.6
		Base	219	184.20	67.8
		Conservative	210	214.31	82.9

The summary presented in Table 7 highlights a similar overall behaviour to the previous analysis for the pilot scenario, but with significantly higher loss levels and a stronger impact of operational constraints.

Across all commercial-scale realisations, the expected economic loss ranges from 102.67 M€ to a maximum simulated loss of 598.85 M€. The exceedance probability curves (Figure 16) show the impact of long-term operations on the losses and constraint levels. For low loss values (around 120-150 M€), a clear classification can be distinguished, and it differs from the pilot case: P10 cases reach the highest exceedance probabilities, followed by P50 and then P90 curves. This indicates that for long injection periods, low porosity scenarios are more associated with losses exceeding this threshold. This section reflects the dominant role of fracture pressure limitations through the large-shaded uncertainty bands indicating large variability in probabilities within each porosity case, most notably for P90.

The curves progressively converge during the intermediate range (around 150-250 M€), where the difference becomes less noticeable. This convergence is reinforced by the reduced uncertainty bounds indicating comparable variability. However, the classification reappears in the high loss region. The P10 curve remains above the others, indicating higher probability for higher losses, while P90 shows lower exceedance probabilities.

Overall, the results of the commercial case suggest that the low porosity scenarios are more likely associated with higher exceedance probabilities across most of the loss range, whereas higher probabilities tend to decrease the likelihood at the high-loss tail. These results reflect a shift in the distribution compared to the pilot case and especially for the low loss values and outline the more direct impact of petrophysical properties on the magnitude of losses on the long-term operations.

These results indicate that injectivity is strongly controlled by porosity and fracture pressure assumptions, with low-porosity and conservative fracture pressure cases leading to higher pressure constraints and increased economic losses. Higher-porosity scenarios improve injectivity and reduce average losses but remain sensitive to fracture pressure uncertainty. Therefore, it is recommended to constrain the reservoir porosity, refine the fracture pressure estimates through geomechanical studies and calibration with field data, and integrate uncertainty analysis to optimize injection design.

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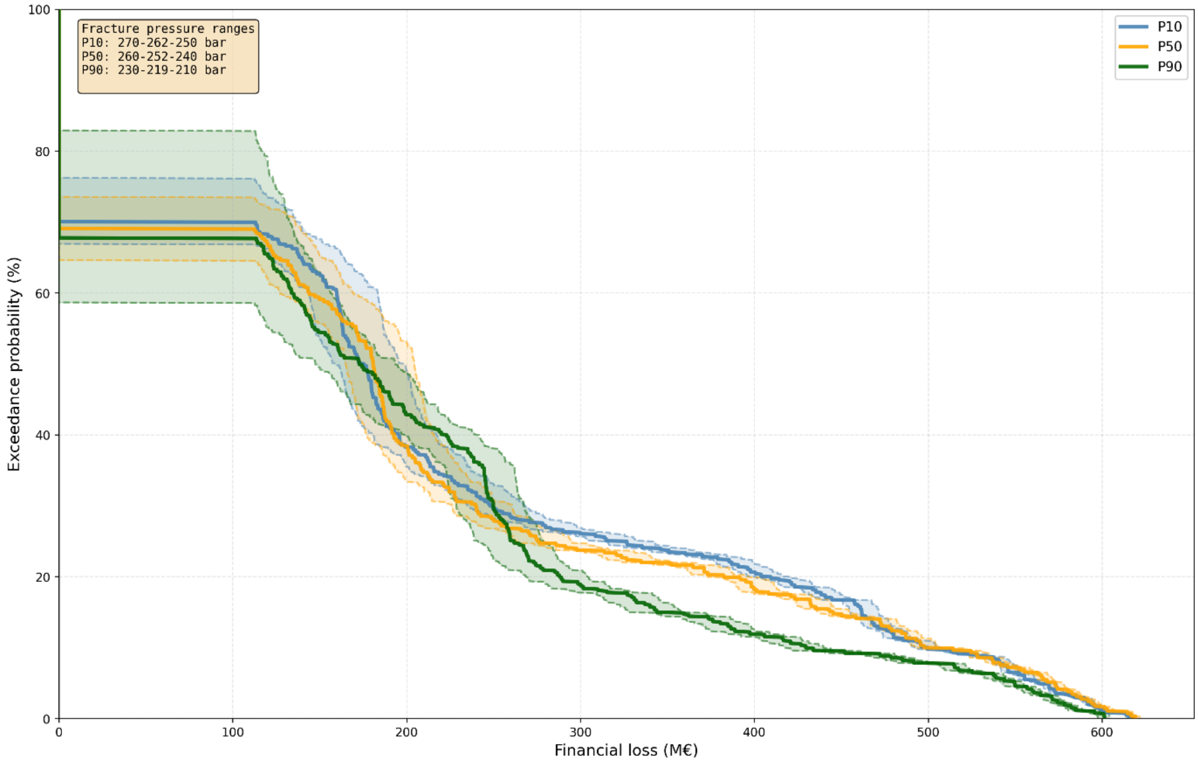

Figure 16: Loss exceedance curves for the injectivity risk event: financial losses associated with injection rate shortfalls under combined porosity and fracture pressure uncertainty (for commercial scale).

4.2.3 Safety risk analysis

4.2.3.1 Drilling / Construction / Handling CO_2 at Surface

4.2.3.1.1 Risk description

This risk category covers **occupational and process safety hazards** associated with the physical operations at the pilot injection site, rather than subsurface containment risks. It groups several scenarios that share a common characteristic: they involve conventional industrial hazards that are well understood and managed through standard HSE (Health, Safety & Environment) practices.

Main Scenarios

We can distinguish three main sub-categories:

1. Drilling and Well Construction Hazards

- **Well control incidents** (kicks, blowouts) during drilling or completion phases
- **Mechanical failures** of drilling equipment (hoisting, rotary systems)
- **Handling of drilling fluids and chemicals** (spills, exposure)
- **Dropped objects, working at height, confined spaces** — standard construction site hazards

2. Surface Facility Construction and Commissioning

- **Construction-phase accidents** during installation of surface equipment (piping, valves, injection skid, monitoring equipment)

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- **Pressure testing incidents** during commissioning (e.g., hydro-test failures)
- **Electrical hazards** associated with instrumentation and power supply

3. CO_2 Handling at Surface (Operational Phase)

- **CO_2 release from surface equipment** (leaks at connections, valve failures, pipeline/hose rupture) leading to a **localised CO_2 cloud** with asphyxiation risk for on-site personnel
- **Overpressure / rupture of surface vessels or lines** due to thermal expansion of liquid/dense-phase CO_2 (e.g., trapped volumes warming up), incorrect valve sequencing, or pressure control failure
- **CO_2 rail delivery incidents** (derailment or collision on the site rail spur, hose/arm disconnection during transfer from rail tank car to buffer storage)
- **Cold exposure / brittle fracture** — rapid depressurisation of CO_2 can cause cryogenic temperatures, risking cold burns to personnel and brittle failure of non-rated steel components

4.2.3.1.2 Key data and assumptions

Surface equipment and planning are described in more detail in D4.6 (Ron Martín et al., 2026) . Here is a summary of the main points.

The pilot project targets the injection of **100 kt of CO_2** over an approximately **4-month** operational period, at a maximum injection rate of **300 kt/year (~822 t/day)**. Four development scenarios are under consideration, differing in two key parameters:

- **CO_2 source**: either a *local industrial source* (a fertilizer plant, CO_2 delivered at atmospheric pressure, 99% purity) or an *external source* transported by rail (food-grade CO_2, delivered in liquid form at ~1.5 MPa, −40 °C, near-pure);
- **Well configuration**: either a *highly deviated well* ("onsite well", ~3.3 km measured depth) allowing the wellhead to be located directly at the CO_2 collection point, or a *slightly deviated well* ("offsite well", ~1.6 km measured depth) requiring a **3 km surface pipeline** between the CO_2 conditioning point and the injection wellhead.

In all scenarios, CO_2 is compressed and conditioned at the surface to supercritical/dense-phase conditions (9.6–12.5 MPa, 39–56 °C at the wellhead) before injection. **No intermediate buffer storage** is planned, and given the short injection period (~3 months), **no specific maintenance campaign** is foreseen during operations.

For the rail delivery scenarios, CO_2 is transported in wagons carrying 50 t of liquid CO_2 each (−40 °C, 15 barg). To sustain the target injection rate, approximately **17 wagons must be unloaded per day**, implying frequent handling operations and a significant logistical footprint at the rail delivery point.

Regarding the site setting, the onsite well scenarios place the wellhead and surface facilities in close proximity to the fertilizer plant, which is itself classified as a **Seveso site**. The rationale is to cluster hazardous activities together and minimise pipeline length, but this configuration introduces a potential for **cascading events** between the CO_2 injection facilities and the existing industrial installation. In the offsite well scenarios, the wellhead is located remotely, in agricultural land, **far from any population centre**.

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The construction and commissioning phase extends over approximately **2 years** after permit approval, comprising civil works (7 months), and CO_2 compression and pipeline installation (~8 months), with some overlap. During this period, personnel are exposed to conventional drilling and construction hazards.

The following **simplifying assumptions** are retained for this surface safety assessment:

- The high purity of CO_2 in all scenarios means that **toxicity of impurities is not a driving concern**; the primary hazard from a surface release is **asphyxiation** (oxygen displacement) and **cryogenic exposure**;
- Standard industrial HSE practices and regulatory requirements (including Seveso regulations where applicable) are assumed to be implemented throughout all project phases;
- The short duration of the injection phase inherently **limits the exposure time** to operational hazards.

4.2.3.1.3 Modelling approach

No quantitative modelling is performed for this risk category. Surface safety hazards associated with drilling, construction, and CO_2 handling are **conventional industrial risks** that are well understood and managed through established HSE frameworks and regulatory requirements (including Seveso regulations where applicable).

The assessment therefore relies on a **qualitative approach** limited to:

- **Identification of the main hazardous scenarios** for each project phase (construction, commissioning, operations);
- **Discussion of the key uncertainties** that may influence the risk level depending on the development scenario retained;
- **Formulation of recommendations** to ensure these risks are adequately addressed in subsequent project phases.

This level of analysis is considered proportionate to the nature of the risk: surface safety hazards are not specific to CO_2 geological storage and will be covered in detail through the **regulatory safety studies** (e.g., DREAL-required hazard studies, Seveso compliance documentation) that are mandatory prior to the start of operations.

4.2.3.1.4 Results

Lachen *et al.* (2025) conducted a complementary HAZID covering all project phases; their findings are consistent with this analysis.

1. Drilling and Well Construction Hazards

Well control incidents, mechanical failures, chemical handling, dropped objects, working at height, and confined space hazards. These are **standard drilling risks** managed through well control procedures and drilling HSE management systems.

- **Likelihood: Very Low.** According to *IOGP Safety performance indicators - 2024 data* (2025), the fatality rate for drilling operations in Europe is under 1 per million working hours. For a single well over a short drilling campaign (~weeks), the total working hours would not exceed

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15,000 hours. Thus, the probability of a fatality due to drilling accident is of order 10^{-3}–10^{-2} per well. Other construction accidents can be more frequent but typically lower severity. *Confidence: good — well-documented in drilling industry statistics.*

- **Consequences: Minor to moderate** with standard barriers in place. A blowout would be the most serious scenario but is very unlikely given the good knowledge of geological conditions in the region. *Confidence: good.*

2. Surface Facility Construction and Commissioning

Accidents during installation of surface equipment, pressure testing incidents, electrical hazards.

- **Likelihood: Low.** Short construction period, limited scope of works. *Confidence: good — standard industrial construction.*
- **Consequences: Minor.** Standard construction site injuries; pressure testing incidents could be moderate but are mitigated by exclusion zones during hydro-tests. *Confidence: good.*

3. CO_2 Handling at Surface (Operational Phase)

This is the most specific risk category for this project. Four sub-scenarios are retained:

a) CO_2 release from surface equipment or pipeline Leaks at connections, valve failures, hose or pipeline rupture, leading to a cold dense CO_2 cloud with asphyxiation and cryogenic hazards.

- **Likelihood: Low to moderate.** Failure frequencies for industrial piping are typically 10^{-4}–10^{-3} per connection per year; however, the large number of rail unloading operations (~17/day) significantly increases the cumulative probability of a release during transfer. *Confidence: moderate — extrapolated from industrial gas statistics, not site-specific.*
- **Consequences: Moderate.** Dangerous CO_2 concentrations (>5%) possible within tens of metres of the release point; potentially serious for exposed personnel. Cryogenic effects and dry ice projections add to the hazard. *Confidence: moderate — no site-specific dispersion modelling performed.*

b) Overpressure / rupture of surface vessels or lines Thermal expansion of trapped liquid CO_2, incorrect valve sequencing, or pressure control failure.

- **Likelihood: Very low** with properly designed relief systems. *Confidence: good.*
- **Consequences: Serious** if it occurs (vessel burst, projectiles), but standard design codes (pressure relief valves, burst discs) make residual risk very low. *Confidence: good.*

c) Rail delivery incidents Derailment or collision near site, hose disconnection during transfer from rail tank car to buffer storage.

- **Likelihood: Low** for a derailment/collision scenario given the short rail spur and low speed. Transfer incidents (hose disconnection) are more plausible, especially given the high unloading frequency. *Confidence: moderate — rail transport of hazardous materials is well-regulated but incident statistics are not CO_2-specific.*

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- **Consequences: Moderate to serious** for a large-scale release from a rail tank car (~20 t); **minor** for a hose disconnection (rapid detection and automatic shutdown expected). *Confidence: moderate.*

d) Cold exposure / brittle fracture Rapid depressurisation causing cryogenic temperatures, cold burns, and potential brittle failure of non-rated components.

- **Likelihood: Low** — occurs only during abnormal depressurisation events, which are themselves low-probability. *Confidence: good.*

- **Consequences: Minor to moderate** — localised cold burns; brittle fracture could escalate to a larger release (links back to scenario 3a). Mitigated by material selection (low-temperature rated steel) and operational procedures. *Confidence: good.*

Key factors influencing the risk

The overall surface safety risk is primarily driven by **CO_2 supply mode** (rail delivery frequency increases handling exposure), **site configuration** (proximity to the Seveso-classified plant introduces potential domino effects), and **duration of operations** (short pilot duration limits cumulative exposure). Detailed engineering design choices (detection systems, exclusion zones, emergency shutdown) will significantly affect residual risk levels.

4.2.3.1.5 Risk evaluation and recommendations

Overall, this risk category groups conventional industrial hazards for which a robust regulatory framework exists. The analysis does not reveal any unmanageable scenario; potential consequences are mainly limited to on-site workers.

Two aspects are somewhat less conventional:

- In the case of the highly deviated well, the wellhead would be located adjacent to the Seveso-classified facility, requiring close coordination with the plant's HSE team to address potential domino effects.
- In the case of external CO_2 supply by rail, the estimated 17 unloading operations per day significantly increases cumulative exposure to handling incidents during transfer.

Consequently, the recommendations are:

1) Finalise the site configuration to enable a more detailed risk assessment:
   a) For the CO_2 source, the preferred option is on-site CO_2 (from the plant), but this depends on decisions external to the project regarding the continuation of plant operations. Should this option prove unfeasible, procuring external CO_2 by rail remains the fallback.
   b) For the wellhead location, the off-site option appears qualitatively less risky, as it would be remote from populated areas and would reduce the potential for cascading events with the Seveso facility.
2) If rail supply is retained: consider measures to reduce unloading frequency (larger buffer storage, larger tank cars) and conduct a HAZOP on the unloading sequence once the detailed design is available.
3) Verify that emergency services can access the injection site independently from the Seveso plant, so that a simultaneous incident at the plant does not hinder intervention at the wellhead (and vice

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versa). If independent access is not feasible, this constraint should be explicitly addressed in the joint emergency response plan.

4) Perform simplified dispersion modelling (e.g. Gaussian plume) for credible release scenarios at the unloading area and at the wellhead, in order to define exclusion zones and confirm that the chosen site layout is compatible with acceptable risk levels.

4.2.3.2 Injection well

4.2.3.2.1 Risk description

This category deals with the risk of CO_2 leakage due to a loss of integrity in the injection well.

There are several mechanisms that can be involved, but the three main scenarios are (Figure 17):

1) Leak in the first annulus due to failure of the tubing or liner
2) Moderate leak due to a lack of integrity in the external cement barrier
3) Major leak due to blowout (loss of pressure control inside the well)

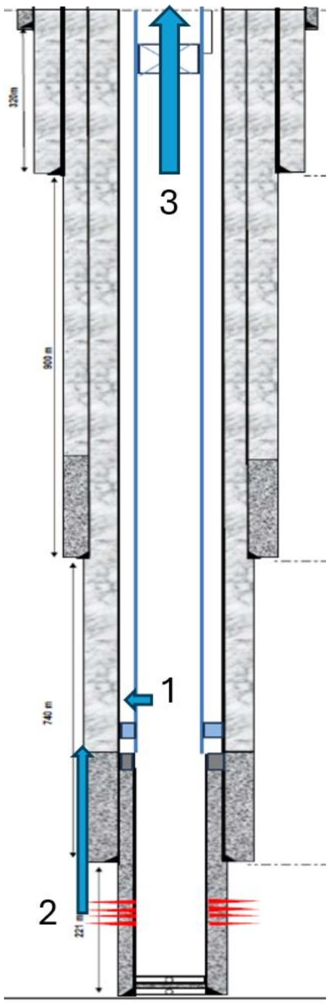

Figure 17: well schematic showing the three main leakage pathways (numbers correspond to the scenarios above, adapted from Lachen et al. 2025)

The tubing (or liner) constitutes the primary barrier in direct contact with the CO_2 stream. A failure of this barrier would allow CO_2 to enter the first annulus (A-annulus), which is normally isolated by the packer and filled with inhibited packer fluid. Potential causes of tubing/liner failure include:

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- Corrosion from wet CO_2 or CO_2-saturated brine, particularly at connections
- Mechanical failure due to thermal cycling, pressure fluctuations, or connection leaks
- Erosion from impurities or particulates in the injected stream

A tubing failure alone would not result in a leak to the formation, as the production casing and cement sheath act as secondary barriers. However, it is considered a risk because it compromises the defense-in-depth philosophy, exposes the casing to a corrosive environment for which it is not designed, and can escalate into a formation leak if the secondary barriers are also degraded. Early detection is provided by annulus pressure monitoring.

In the expected scenario for the external barrier, cement forms an impermeable barrier that sits between the casing of the well and the formation. A leakage could occur if:

- There is a sufficiently large annulus between the cement and the formation, going all the way through the caprock system. Annuli are created during the cement placement and depend on the process used.
- The cement is degrading due to conditions in the storage reservoir:
  a) Chemical stress due to acidification from CO_2
  b) Mechanical stress due to overpressure near the injection well
  c) Thermal stress due to injection of CO_2 colder than the in-situ conditions

If CO_2 were leaking up the well, the most probable pathway would be to leak into the first permeable formation. In the case of this project, this would be the Lusitanian formation, which contains mineralized, undrinkable brine.

The case of the blowout requires a failure of several well components ensuring pressure control. The main equipment in this context is the subsurface safety valve (SSSV). For simplification, we call "surface barrier" the several components at surface ensuring pressure control in the well. This equipment could fail in case of material degradation, mechanical impact (accident) or operational error.

The risk differs according to the phase of the well. It is documented that the risk of blowout is higher during maintenance/workover phases where barrier elements are temporarily displaced or removed to allow access to the well.

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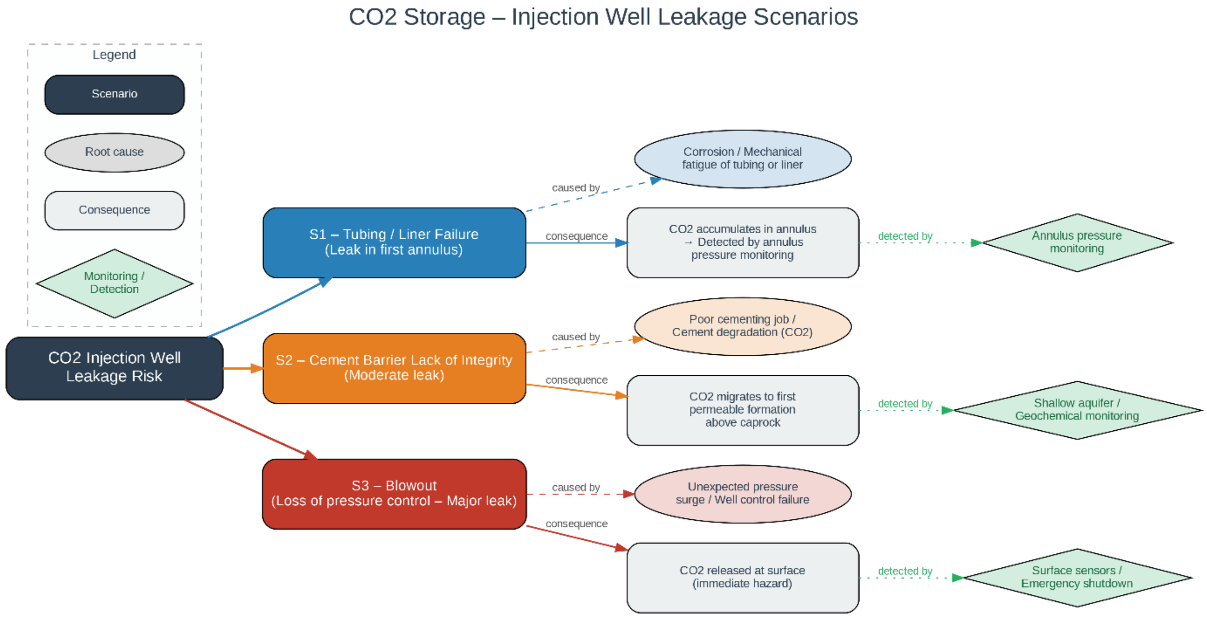

Figure 18: diagram describing the injection well leakage scenarios included in the analysis

4.2.3.2.2 Key data and assumptions

Well design specific for this case have been produced by WP4 (Lachen et al., 2025). In summary, there are two designs, one slightly deviated, and the other highly deviated.

Both have typical CO_2 injection well architecture, with elements of design stemming from the drilling experience in the Paris basin (Hydrocarbons and geothermal wells).

In the case of leakage along the cement, it is unlikely that the CO_2 reaches the surface as multiple cement barriers are present, and it would require a defect in each of those layers independently. If the CO_2 starts moving up the well in an external annulus (between cement and formation), then it will accumulate in the first permeable layer encountered. In this case, it would be the Lusitanian formation, which is a brine aquifer, and not a strategic water resource. This would act as a secondary reservoir (Mathurin et al., 2023).

In the case of blowouts, or any leakage to the surface, in the case of the slightly deviated well, the wellhead is located remotely from other installations. In the case of the highly deviated well, there could be cascading events with high velocity CO_2 blowouts, if the wellhead is close to other equipment.

The numerical model described in 4.2.1 is used to compute a distribution of the pressure at the bottom well in order to assess the magnitude of stress for the well components.

4.2.3.2.3 Modelling approach

For this category, we model the risk by taking generic estimates of well failures, based on the literature. We then attempt to improve the estimates by looking at specific conditions that might affect the initial estimation.

In the recommendations, we propose a full quantitative modelling approach for a potential scaling up to a commercial project.

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4.2.3.2.4 Results

Daniels et al. (2023) provide generic active well leakage probabilities based on both a literature review and modelling work. See Table 8 for the literature review.

Table 8: Leakage probabilities for active wells derived from literature review (Daniels et al., 2023)

Leak category	Leak rate (t/d)	Duration (months)	Probability of defined leak rate occurrence/well Maximum	Probability of defined leak rate occurrence/well Minimum
Seep (continuous)	Less than 1	Continuous	1 in 10	1 in 1000
Minor	1 – 50	Up to 6	1 in 1000	1 in 100,000
Moderate	50 – 1000	Up to 4	1 in 10,000	1 in 100,000
Major	Greater than 1000	Up to 4	1 in 100,000	1 in 1 million

Regarding modelling results, they report a probability of a minor leak rate (between 1 and 50 tonnes per day) of 1 in 500 well/annum.

Considering these numbers come from the experience in the oil and gas industry, which is on average less regulated and stringent than CO_2 storage in Europe, those numbers are pessimistic for a properly designed and constructed CO_2 injection well.

As those numbers are generic, we look at factors from this project that might have an influence on the actual risk. We use the numbering of scenarios as in Figure 18.

For S1, we considered the following mechanisms:

- Corrosion from wet CO_2 or CO_2-saturated brine, particularly at connections
- Mechanical failure due to thermal cycling, pressure fluctuations, or connection leaks
- Erosion from impurities or particulates in the injected stream

Potential factors:

- Maximum deviation of the well can impact connection quality
- Purity of CO_2 impact chemical stress and corrosion rates
- Injection rates and “stop and go” operations impact mechanical stress on the tubing

For S2, there are three main factors:

- Quality of cement placement
- Impact of well deviation on cement placement (e.g. centering issues)
- Mechanical and chemical stress due to CO_2 injection.

The geology is usually a factor, but as there are several oil and gas active licenses nearby, the knowledge acquired in drilling various types of wells can be exploited to design a good cement job, accounting for the specificities of the region.

For S3, the key factor is the overpressure of the gas phase in the well.

The risk of caprock fracturing due to BHP overpressure is addressed in 4.2.3.4 and used here as a proxy for the mechanical loading on the well. Cement integrity under combined hydro-thermo-mechanical and geochemical loading is not modelled in this study; Detailed modelling of the risk of CO_2 leakage along CO_2 injection well is presented in Moghadam & Amiri (2025) and Moghadam & Loizzo (2024). This type of modelling work can improve confidence in the assessment but require precise data about the caprock geology and cement rheology that we lack now.

Regarding CO_2 saturation, modelling results for the pilot scale showed that CO_2 rarely reach the top of the reservoir (Figure 19). Thus, considering the average generic likelihood of 1 in 10,000, it should be pondered by the fact that, according to our model, there is less than 5% of chance that the CO_2 even reaches the top of the reservoir, so a likelihood of 5×10^{-6}. And this does not account for the fact that the well is deviated, and thus the cement / caprock / reservoir interface is horizontally distant from the injection point in the reservoir.

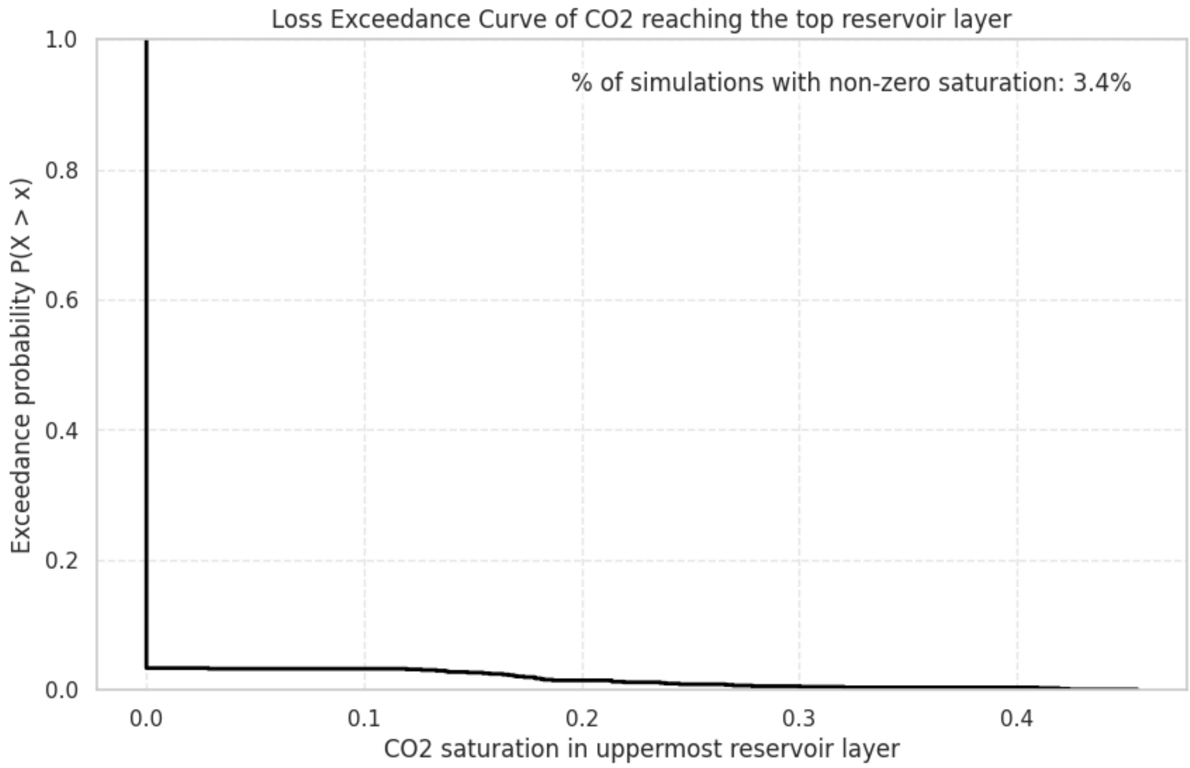

Figure 19: Loss exceedance curve of CO_2 reaching the top reservoir layer

4.2.3.2.5 Risk evaluation and recommendations

This analysis, as well as current experience in operating CO_2 injection storage wells, demonstrate that a well-designed and well-constructed well, in line with best practices, will provide high safety standards and very low probability of failure. Current practices already integrate the recommendations stemming from such analysis. Nonetheless, here is a summary of important points:

- **CO_2 cement type**: there is currently no consensus amongst expert on the best type of cement for CO_2 injection wells. Different groups are developing CO_2-resistant cement, but some argue (IEAGHG Risk Management Network Meeting Report, 2023) that ordinary Portland cement have beneficial reactive properties allowing, under certain conditions, self-healing of small defects. The recommendation would therefore be to first consider ordinary Portland cement unless it is proven

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that it will be a significant point of weakness. The other advantage is that the drilling / cementing team will be more experienced with the cement properties, improving the chance of a good placement.

- **Experienced contractors**: as a lot of the integrity of the injection well rely on a good cement placement, an experienced contractor with impeccable track record should be favoured for supervising the cement job. This is also valid for the whole construction of the well.
- **Cement placement**: best practices should be followed regarding cement placement: control of the hole before cementing, use of rigid centralizers, with sufficient density in the caprock zone.
- **Lessons learned**: make a dedicated review of CO_2 injection well experience, and check for any specificities or challenges requiring a modification in the design.
- **Monitor CO_2 quality at the injection**: in particular to avoid as much as possible wet CO_2 or corrosive impurities.
- **Design procedures** for shut-in / restarting the well in order to avoid frequent and/or extreme mechanical variations.
- **Caprock data:** necessary for improving the modelling of cement bonding and potential for formation creep.

4.2.3.2.6 Scale-up to commercial scenario and recommendations

For the commercial case, the idea is that the well used for the pilot is the same for a commercial scale-up. Here are aspects that can be learned during the pilot that would help for the safety analysis of the commercial scale:

- The main aspect of any injection test is to determine the injectivity by monitoring the trend of pressure build-up for a given injection rate. This observation can allow for adjusting the injection design if necessary, such as perforating new intervals
- Behaviour of CO_2 near the wellbore: observations during injection can inform on the parameters influencing flow and pressure close to the well. This will help reduce uncertainties, allowing more detailed modelling of saturation and pressure dynamics on the well components, particularly the cement.

Additional data is necessary to make the best decisions regarding the choice of materials and components, mainly the quantity and source of CO_2 (Sonke et al., 2022). This has an impact for instance on the best material for casing and tubing. Unfortunately, the pilot cannot directly provide such data. If there is no progress on the commercial scale scenario, then conservative decisions should be made in order to cover for several type of CO_2 streams. An alternative is to make a reasonable guess and then impose CO_2 specifications for CO_2 to be injected in this well.

4.2.3.3 Pre-existing wells

4.2.3.3.1 Risk description

In this category, the scenario is that there are known, pre-existing wells in the area, reaching the Dogger reservoir. If the CO_2 plumes reach the well, since it was not specifically designed for CO_2 storage, there is a possibility that CO_2 can breach one or more of the well barriers and reach shallower layers.

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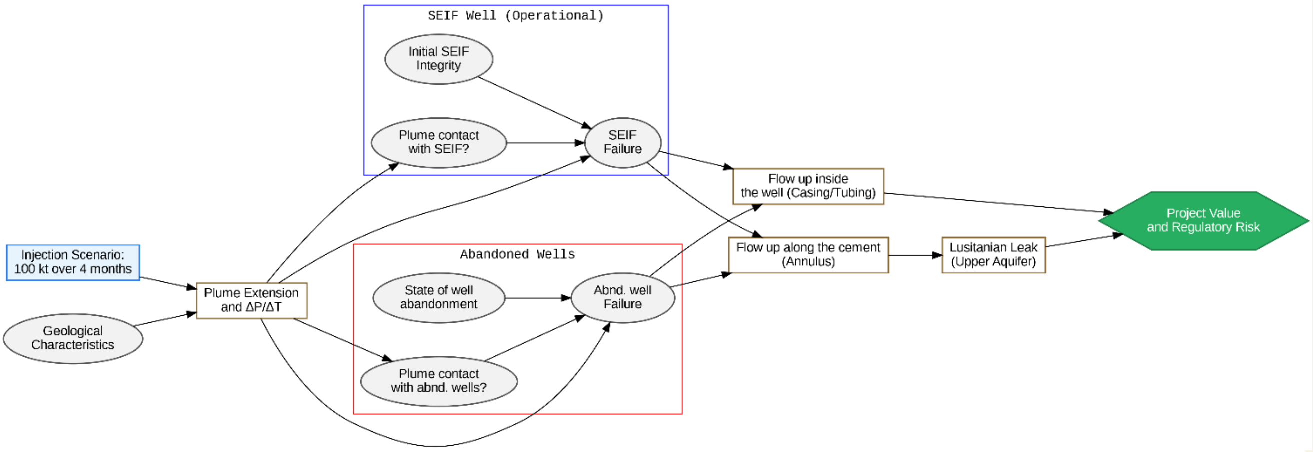

Figure 20: Influence diagram for the risk of CO2 leakage through pre-existing wells

Figure 20 shows an influence diagram for this risk. This risk is simplified in two questions:

1) Under current uncertainties, is there a chance that the plume reaches the other wells in the area?
2) If the plume reaches a well, given the knowledge about the status of these wells, what are the chances that the CO_2 might leak out of the storage complex?

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4.2.3.3.2 Key data and assumptions

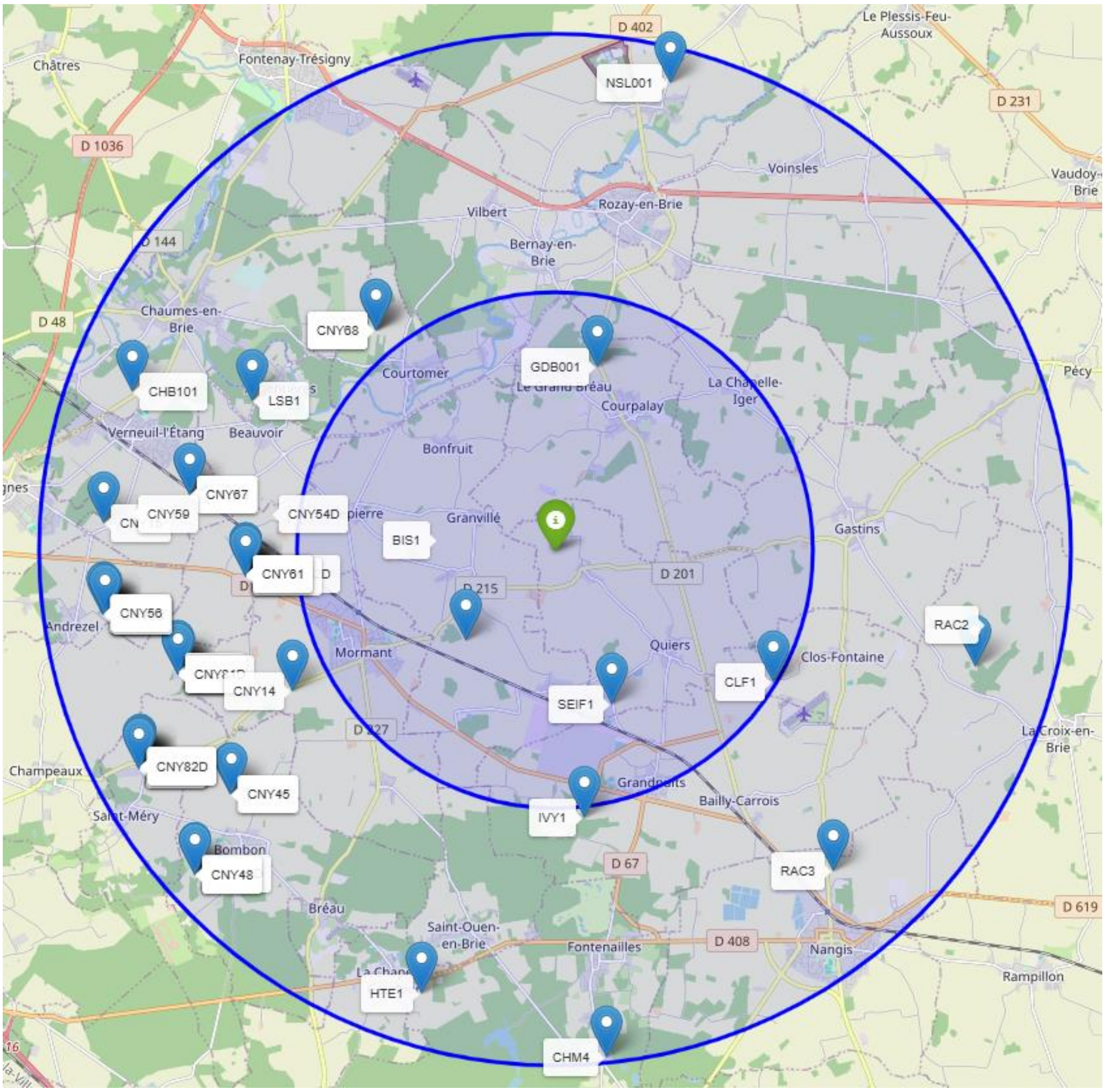

Figure 21: location of potential injection well (in green) and existing wells (in blue). The circles show distance from the injection well of 5km and 10km respectively

From the chosen injection point in the reservoir, the closest existing wells are:

- BIS1
- SEIF1
- CLF1
- GDB001
- IVY1

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SEIF1 is an active wastewater injection well. The other wells are old hydrocarbon exploration wells and are abandoned. Reports and logs about the wells are available on the subsurface databases[2] managed by BRGM.

4.2.3.3.3 Modelling approach

The likelihood of CO_2 reaching the other wells is computed by using the numerical model described in 4.2.1. The probability is computed as the number of simulations where the saturation in CO_2 in the cells containing the well location is over 0 at any time, divided by the number of simulations (2016).

4.2.3.3.4 Results

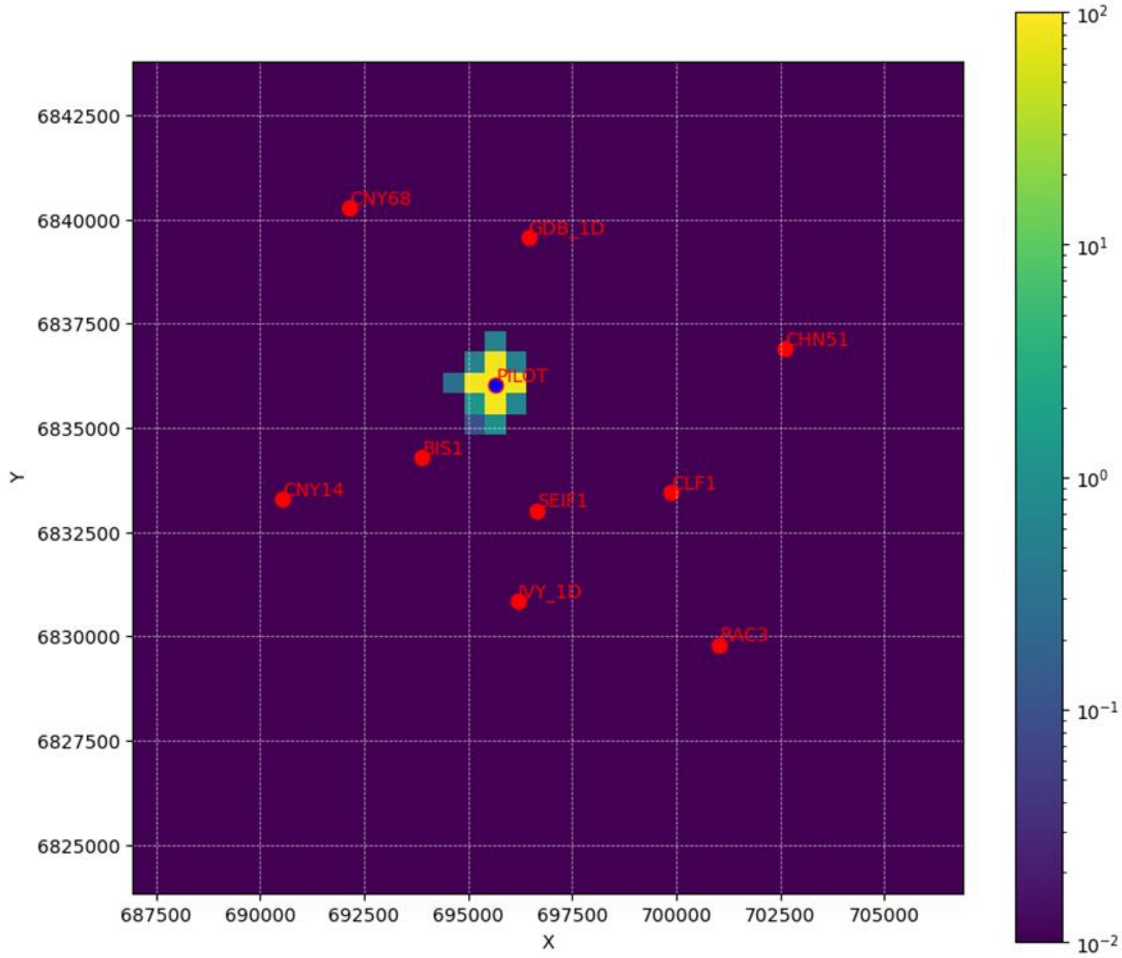

Figure 22: map showing the probability of the CO2 reaching a cell in the model for the pilot case

Figure 22 shows the probability of the CO_2 reaching a cell in the model. Under the current assumptions for the pilot case, considering the geological uncertainty, the CO_2 never reaches the closest well. Consequently, the risk does not materialize according to our simulations.

[2] Infoterre.brgm.fr contains public information about all wells in the database. https://www.minergies.fr/ contains additional public but paying data

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4.2.3.3.5 Risk evaluation and recommendations

For the pilot, as the computed risk is 0, we do not provide any specific recommendation. However, the pilot case can provide invaluable information in order to assess the risk for a commercial application (See next paragraph).

4.2.3.3.6 Scale-up to commercial scenario and recommendations

We run the same model as in the previous paragraphs, with a commercial-scale injection over 30 years. Those simulations show that the CO_2 plume might reach one or several of the wells in the area (Figure 23, Table 9, Figure 24).

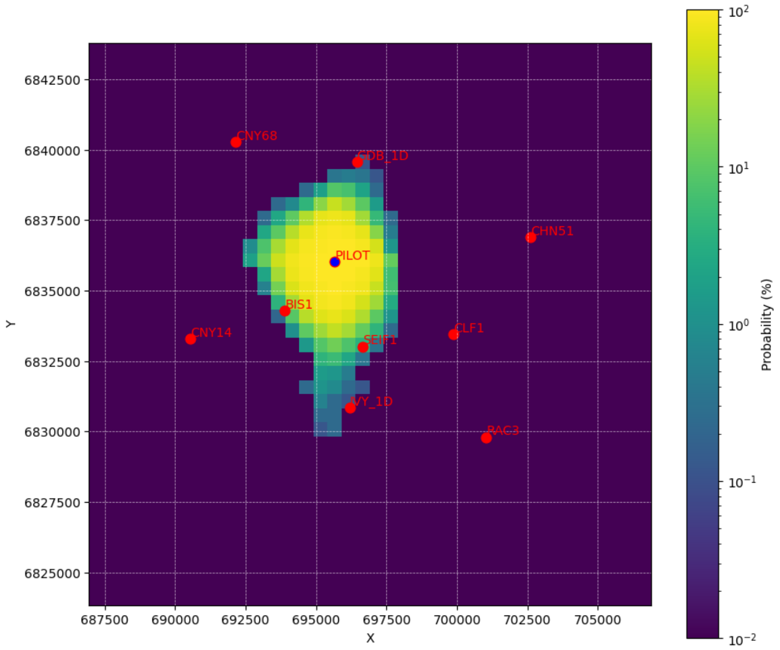

Figure 23: map showing the probability of the CO_2 reaching a cell in the model for the commercial case

Table 9: probability of supercritical CO_2 reaching a given well

Well	P(SGAS > 0)
BIS1	0.21%
SEIF1	3.78%
IVY1D	0.24%
GDB1D	0.21%

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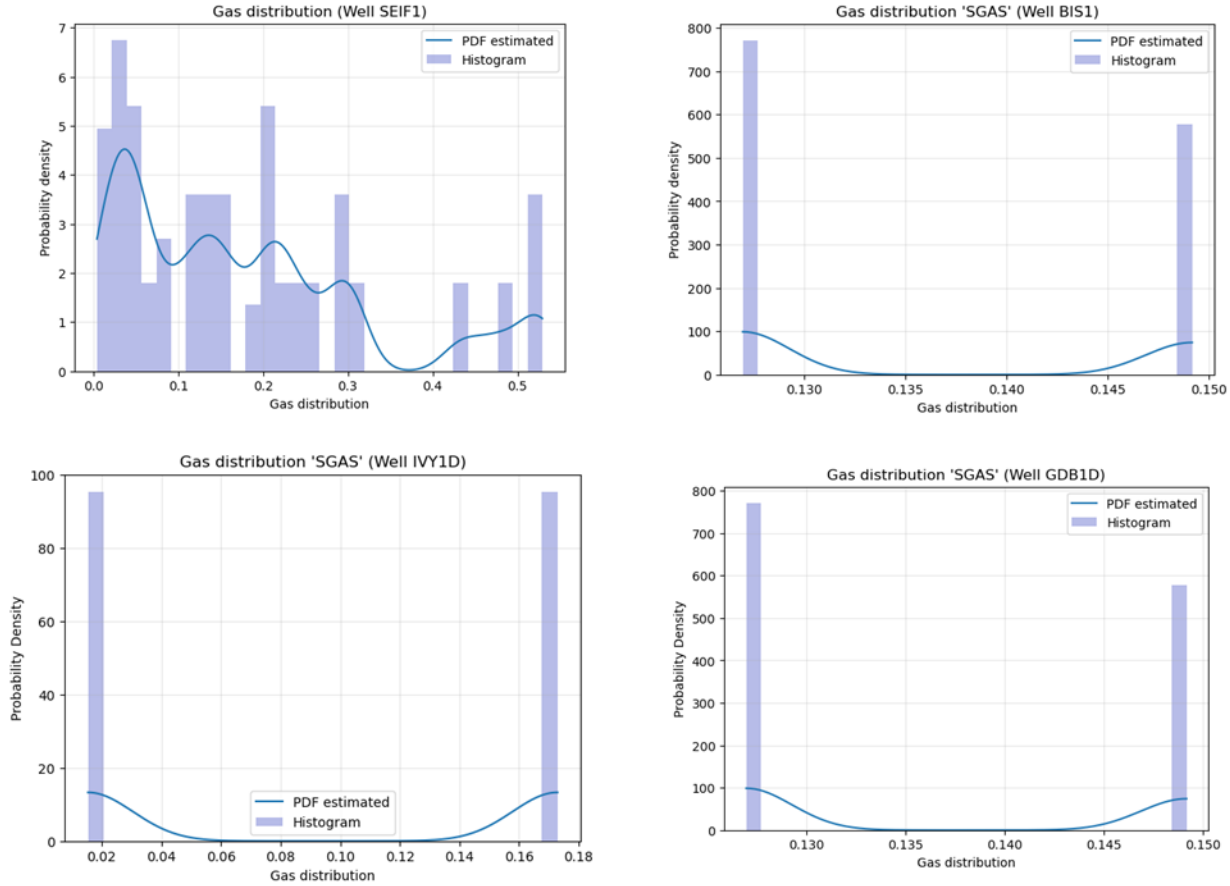

Figure 24: distribution of simulated gas saturation for four existing wells. Only results where saturation is positive are shown

Hence, for the commercial case, the question "is there a chance that the plume reaches the other wells in the area?" is relevant, and the answer depends on the uncertainties.

We tested several approaches to rank the main variables responsible for the uncertainty, in order to improve the recommendations. Here, we present the results from one method, using Value of Information (VOI) analysis.

Briefly, the principle of a VOI analysis is to check if a decision can be improved assuming that a given variable is known with certainty. Here the decision is to go ahead or not with CO_2 injection at commercial case. We model a profit as proportional to the quantity of CO_2 injected. In a given simulation, if more than 100 kg of CO_2 reaches an existing well, then the operator has to re-enter the well and "fix" the integrity. The cost of doing this could "kill a project" (order of magnitude: several million euros). So, averaging over the simulations we can compute if the average profit is over the average mitigation cost: if that is the case, then the best decision is to proceed with doing the project. Then, we separate each variable into a few bins (typically between 5 and 10), and for each bin, we check if the result improves the decision. A drawback of this method is that the result is highly dependent on the probability of the event happening, and thus highly sensible on the assumptions made for the profit and cost. So, the cost of mitigating the well was defined in order to produce a meaningful ranking. In Figure 25, only the relative strength of VOI can be interpreted but not the value of VOI.

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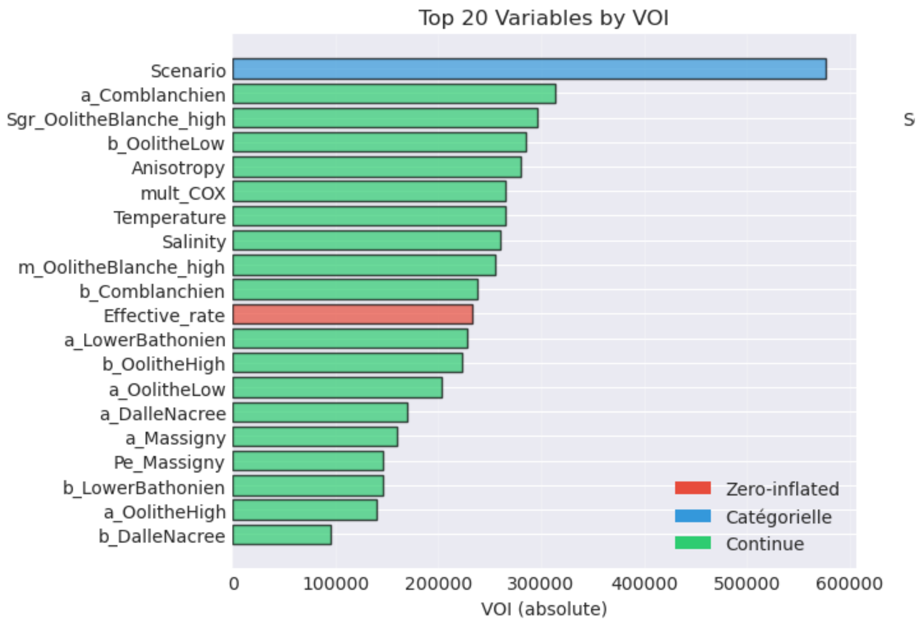

Figure 25: uncertain variables ranked by VOI analysis

Here are some interpretations of this figure:

- The value of knowing the *Scenario* is approximately double the value of knowing the other variables
- All the variables in the model are somewhat valuable

Here *scenario* refers to one out of three porosity distributions we used for the model (it is a categorical variable). In reality, there are an infinite number of "realizations" of the porosity model, so it is probably an artifact of our uncertainty model, and maybe the porosity is not more influential on the result than the other variables.

a_formation and *b_formation* are the coefficients of the K-phi law for the given formation. It shows that not only the value for the Oolithe blanche high (the main target for CO_2 injection) is important, also the other layers have an effect on the movement of the plume.

Other variables are:

- Sgr_OolitheBlanch_high and m_OolitheBlanche_high: parameters for the relative permeability equation
- Anisotropy: the ratio of vertical to horizontal permeability
- Mult_COX: a multiplier for the permeability of the COX layer (caprock)
- Pe_Massingy: Capillary pressure parameter of the caprock
- Temperature: CO2 temperature at injection
- Salinity: salinity of the reservoir
- Effective_rate: rate of water injection in the SEIF well (called "effective" because it is 0 50% on average)

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We also tested other methods. Based on the simulations, we produced a surrogate model with machine learning techniques (i.e. XGboost[3]). Using the surrogate model, we were able to produce various sensitivity analyses (i.e. permutation importance and Shapley values). We tested:

- Sensitivity on reaching the wells or not (binary classification)
- Sensitivity on the quantity of CO_2 reaching the wells (regression on the continuous quantity)
- Sensitivity on large quantities (with a pre-defined threshold – binary classification)
- Interactions effects by considering all pair of variables

None of these techniques showed a clear hierarchy between the variables. We choose to present only the result of VOI because of the originality of the method.

If there is a chance that the CO_2 reaches the well, then the second question becomes relevant:

[3] See https://en.wikipedia.org/wiki/XGBoost

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“Given the knowledge about the status of these wells, what are the chances that the CO_2 might leak out of the storage complex?”

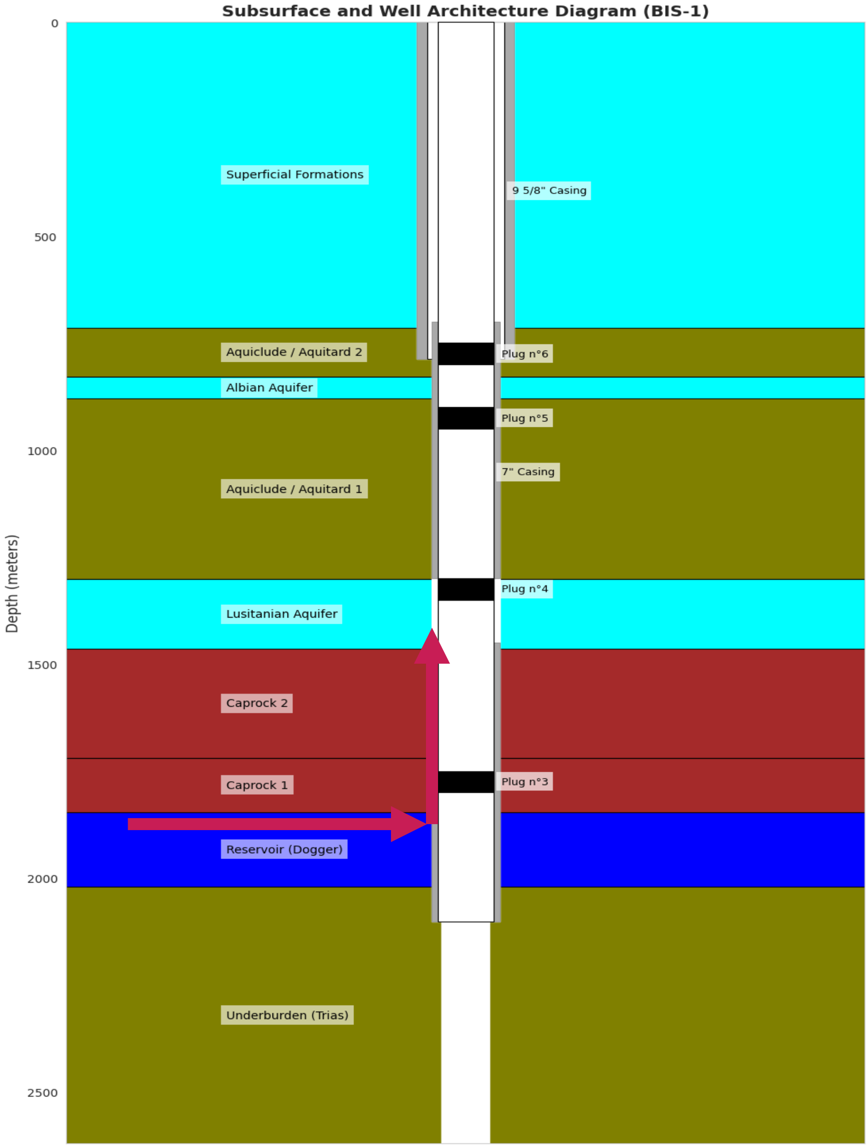

Figure 26 shows the architecture of well BIS1, with the plugs. The most probable scenario for a leak is on the external annulus, if the cement integrity along the caprock is not effective. Then, as it reaches a permeable layer (here, the Lusitanian aquifer, which is not a resource of fresh water), it is “easier” for the CO_2 to migrate in the aquifer than to continue upward, as this would require another defect in the cement.

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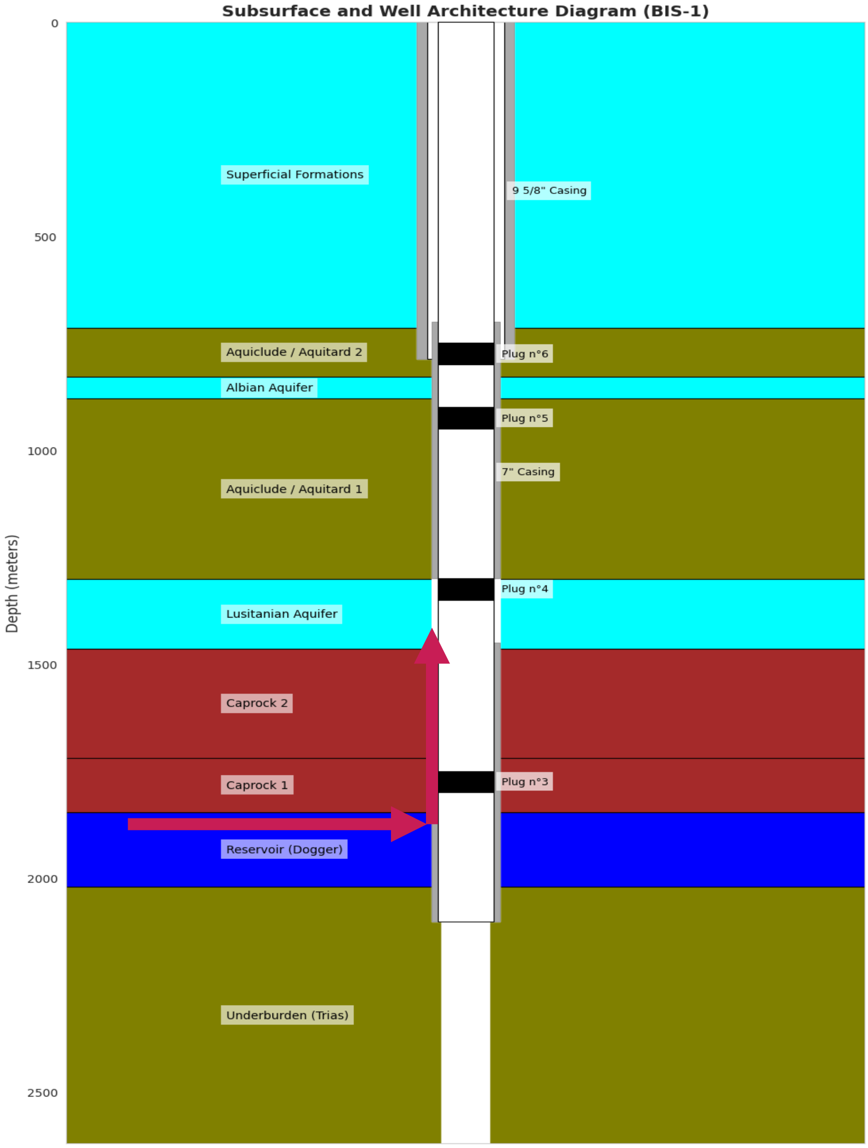

Figure 26: schematic of BIS1 wells with plugs. Red arrows show the most probable leakage scenario

A quantitative analysis of the well integrity was not planned in this work. However, for illustrative purposes, here is an extract from the CBL of BIS1 at the caprock (Figure 26). The bonding index is the graph in the middle. The bonding seems adequate between 1725m and 1650m. However, this CBL was acquired 1/ before the well was abandoned and 2/ nearly 40 years ago (at the time of writing). It is thus hard to be confident in this assessment. Note that the bonding may well improve over time, considering the potential for formations to creep over time (Moghadam & Loizzo, 2024).

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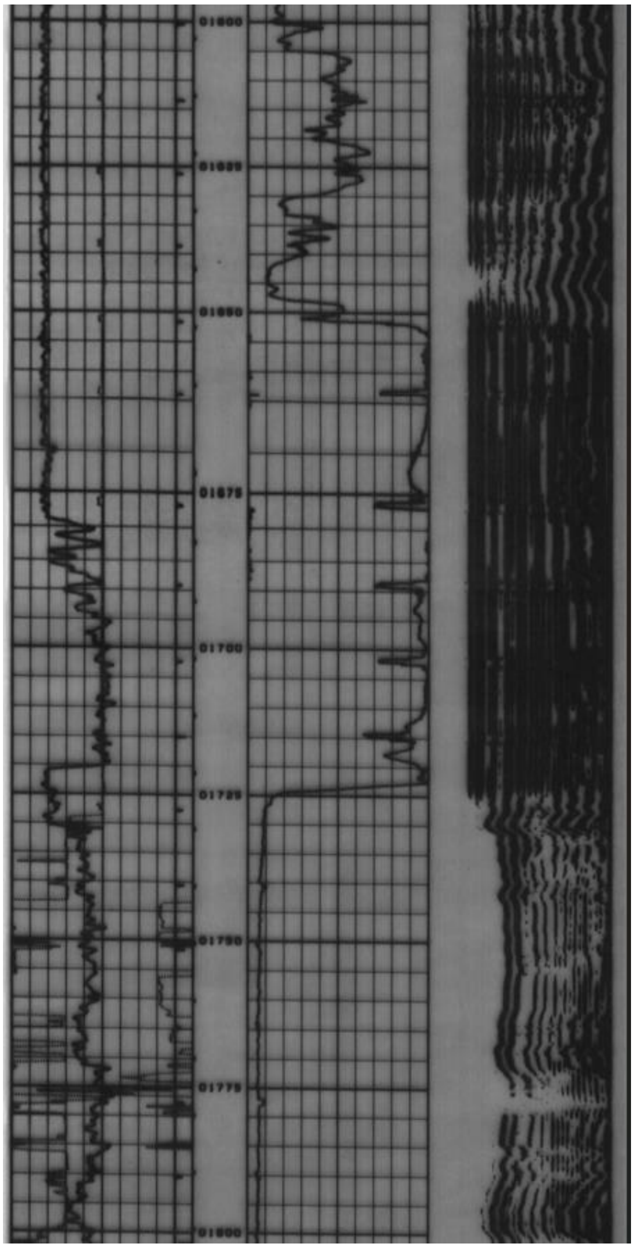

Figure 27: extract from the CBL scan at BIS1 between 1800m and 1600m.

Lastly, we also need to consider the location of the well and the possibility of accessing the well. According to the report, the wellhead of BIS1 is now buried 2m below ground. It is in the middle of an agricultural field. Hence, confirmation of the precise location of the well is necessary in order to analyse or monitor the well. Geophysical methods were used successfully in some case to locate abandoned wells (Lackey et al., 2026).

Considering this, the recommendations for the pilot phase are:

- **Reducing uncertainty regarding the plume movement**: our analyses were not successful in highlighting a reduced set of variables more important than others. It will be key to monitor plume movement during injection (for instance with close well imaging techniques such as DAS-VSP) as well as pressure evolution, and to history-match with a detailed numerical model.

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- **Consider the possibility of monitoring the legacy wells**: re-entering a well can be very expensive, so we cannot recommend doing it, unless there is high certainty about the potential consequences. With high uncertainty, the best option is to monitor soil gas and aquifers around existing wells. As no CO_2 can reach those wells during a pilot test, this would be for environmental baseline monitoring purposes.

4.2.3.4 Leakage through caprock

4.2.3.4.1 Risk description

This risk addresses the probability of CO_2 migration from the storage and leakage through the overlaying sealing formation (the caprock) under realistic injection-induced pressure scenarios, potentially reaching shallower geological formations, freshwater aquifers, or the surface (Section 3.2.2.2). Such substantial failure would compromise the integrity and safety of the storage, with significant consequences for the environmental, regulatory, and commercial dimensions, and may even lead to project shutdown.

For this risk event, three distinct scenarios (S1-S3) have been considered (Figure 28). Each scenario is governed by different physical processes and represents different failure modes:

- **(S1) Failure of intact caprock**: injection operation can induce overpressure that exceeds the combined minimum horizontal stress and tensile strength of the sealing column, causing fracturing of both the Massingy marls and the Oxfordian limestones. This scenario requires substantial high overpressure and assumes the absence of pre-existing structural weaknesses.
- **(S2) Leakage via undetected pre-existing defects**: sub-seismic faults or fractures with throw displacements below the seismic resolution limit reduce the effective sealing thickness and may provide permeable pathways if reactivated. This scenario is structurally undetectable from available seismic data and is treated probabilistically.
- **(S3) Propagation of a new fracture**: a hydraulic fracture initiates at the reservoir caprock interface and propagates vertically through the entire caprock column, governed by fracture mechanics principles rather than simple tensile failure criteria.

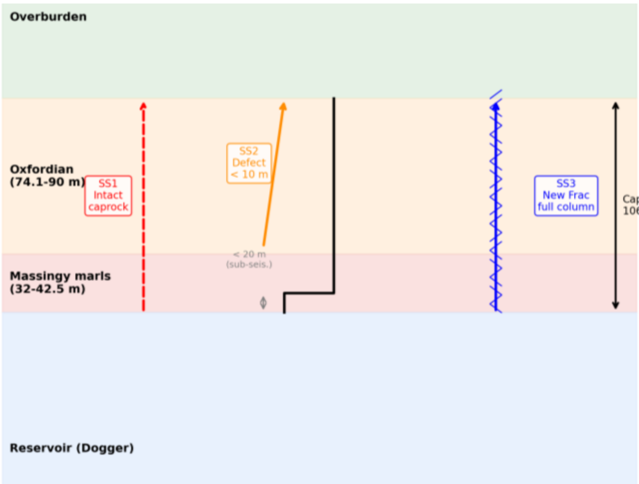

Figure 28: Three distinct scenarios considered for the risk of leakage through the caprock.

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The probability of caprock leakage is primarily controlled by the magnitude and spatial distribution of injection-induced overpressure, the initial stress state of the formation, the presence of undetected sub-seismic faults, and the mechanical properties of the sealing formations.

4.2.3.4.2 Key data and assumptions

The caprock system consists of two distinct formations: the Callovo-Oxfordian marls, with a thickness ranging from 28 to 45 m treated as a uniform uncertain distribution, and the overlying Oxfordian limestones, with a thickness of ~75 m, yielding a total sealing column of 103 to 120 m. The top of the caprock is located at approximately 900 m depth.

The pressure input to the geomechanical assessment is derived directly from the reservoir simulation ensemble of the realisations described in Section 4.2.1. Geomechanical parameters, including the minimum horizontal stress ratio (Sh/Sv), Biot coefficient, tensile strength, and fracture toughness are treated as uncertain parameters for both formations, sampled from distributions informed by literature analogues and available data in (Christ et al., 2024). In the absence of in-situ stress measurements, the stress ratio Sh/Sv represents the most significant source of epistemic uncertainty in this assessment. Monte Carlo sampling is used to propagate these uncertainties and estimate the probability of leakage for each scenario.

The three failure scenarios are treated as mutually independent, with no credit taken for one failure triggering another.

4.2.3.4.3 Modelling approach

For each realisation, the maximum overpressure ΔP at the caprock level is extracted over all timesteps and spatially averaged over the relevant stratigraphic layers, capturing uncertainty in reservoir pressure.

The first scenario (S1) assumes an intact caprock, where leakage occurs only if overpressure exceeds both the effective minimum horizontal stress and the tensile strength across the entire caprock column. The second scenario (S2), leakage may occur either through tensile failure of the residual caprock or via shear reactivation of the fault plane under Mohr-Coulomb conditions. The third scenario (S3) requiring both fracture initiation at the reservoir-caprock interface and sufficient energy to propagate through the full caprock thickness.

4.2.3.4.4 Results

The overpressure distribution at caprock level across the realisations is presented in Figure 29; left. The distribution is right skewed, with a P10 of 0.14 bars, a P50 of 0.56 bars, and a P90 of 2.62 bars. Even under pessimistic realizations, the maximum overpressure calculated at the caprock remains below the failure thresholds associated with any of the three sub-scenarios.

The exceedance probability curves (Figure 29 right) confirm this finding: across the full range of overpressure thresholds considered, the probabilities of triggering the three scenarios are close to zero throughout the ensemble. The injected volume of 100 kt generates no significant overpressure at caprock level capable of activating any failure mechanism under the modelled conditions.

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Therefore, the caprock leakage risk at pilot scale is negligible. This conclusion is consistent with the results of Alavoine et al., (2026).

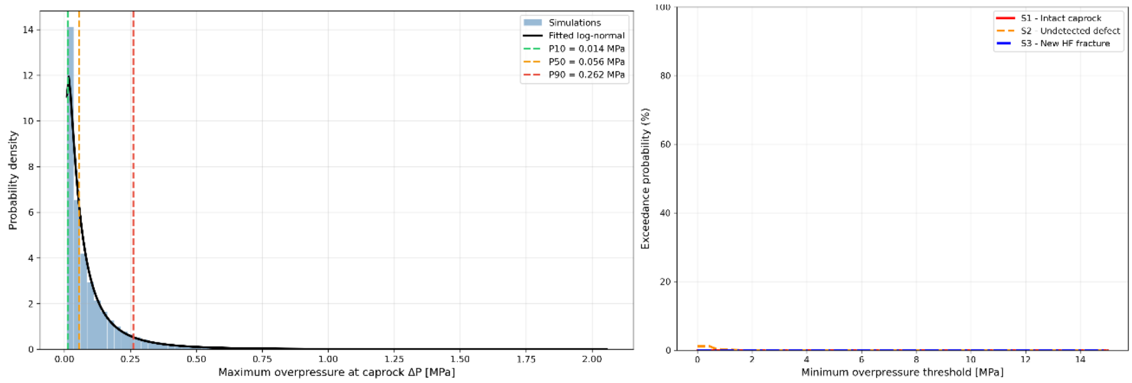

Figure 29: Caprock leakage risk assessment at pilot scale: (left) distribution of maximum overpressure at caprock level across the realisations; (right) exceedance probability curves for the three failure sub-scenarios.

4.2.3.4.5 Scale-up to commercial scenario and recommendations

The analysis of pressure propagation into the caprock for the commercial injection scenario indicates a limited impact on caprock integrity. The distribution of maximum overpressure at the caprock shows relatively low values, with characteristic percentiles of P10 ≈ 0.015 MPa, P50 ≈ 0.056 MPa, and P90 ≈ 0.359 MPa (Figure 30 Left). These values are lower than the overpressures observed within the reservoir, confirming a strong attenuation of pressure across the caprock. The distribution is skewed, with most of the caprock experiencing negligible pressure increases and only few cases reaching higher values. Note that the highest overpressures are expected to be spatially localized, typically within a few hundred meters of the injection well, whereas most of the caprock remains largely unaffected.

The failure analysis further confirms this trend (Figure 30 right). The exceedance probability curves corresponding to the three different failure scenarios remain extremely low. These results indicate that the caprock operates well within its mechanical limits under the considered injection conditions.

Overall, the commercial scenario suggests a high level of containment security, with negligible risk of caprock failure or significant pressure-driven leakage. While uncertainties remain regarding local heterogeneities and potential undetected features, the results provide strong evidence that caprock integrity is preserved under the simulated conditions.

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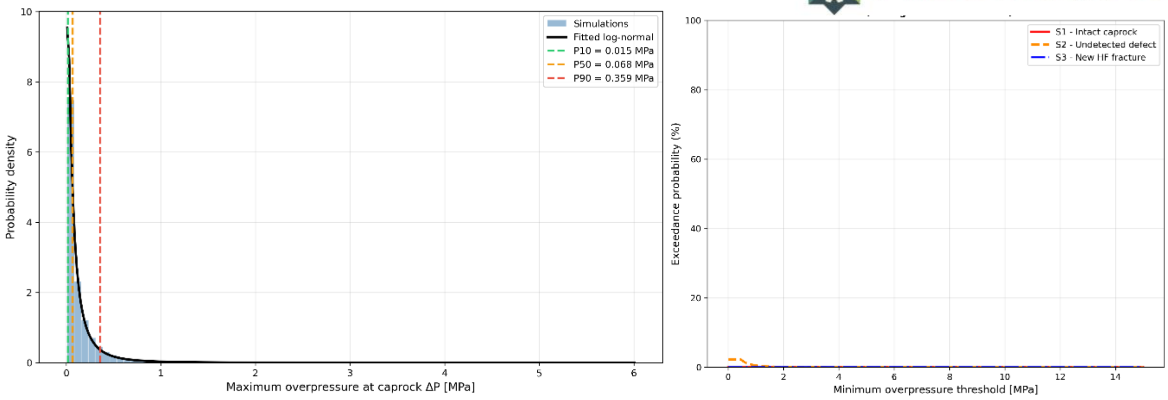

Figure 30: Caprock leakage risk assessment at commercial scale: (left) distribution of maximum overpressure at caprock level across the realisations; (right) exceedance probability curves for the three failure sub-scenarios.

4.2.3.5 Induced seismicity

4.2.3.5.1 Risk description

This risk event treats the probability that the CO_2 injection induces seismic events of sufficient magnitude to cause disrupt to the population, damage to the infrastructures, affect well integrity. This site presents a favourable context: no faults has been identified with the study area according to the 3D seismic data. However, the seismic resolution limit of approximately 20m implies that potential faults with throw displacement below this threshold cannot be detected and their potential reactivation due to injection overpressure must be assessed.

Therefore, three distinct scenarios are considered, as illustrated in Figure 31:

- S1- Fault reactivation near the reservoir: fault located within or immediately adjacent to the Dogger reservoir formation is reactivated under increased pore pressure, evaluated through the Coulomb Failure Stress.
- S2- Fault reactivation in the basement: a fault located in the basement formations, beyond the base of the reservoir, is reactivated through pressure diffusion from the injection zone, also evaluated through the CFS criterion.
- S3- Diffuse micro seismicity: very low magnitude seismic events distributed through the reservoir characterised using the Shapiro index.

The seismic events range from negligible events to felt events. To that due a threshold magnitude at 2.0 was set.

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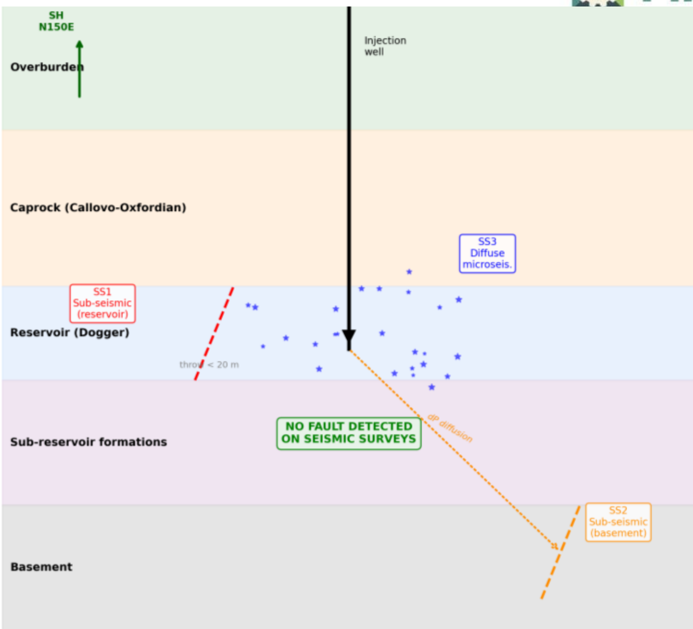

Figure 31: three distinct scenarios considered for the induced seismicity risk assessment

4.2.3.5.2 Key data and assumptions

The induced seismicity assessment workflow is also based on the reservoir pressure ensemble as for the previous risk events. The overpressure at the reservoir targeted is extracted from the simulation realizations. The reservoir is located between 1850m and 2010m depth with the basement situated at ~2500m.

The stress state is based on the geomechanical work in (Christ et al., 2024) and consistent with Alavoine et al., (2026). The maximum horizontal stress oriented N150°E, with $S_H/S_v = 1.0$ and a minimum horizontal stress ratio S_h/S_v treated as an uncertain parameter with a mean of 0.70 and a range of [0.55, 0.85]. The Biot coefficient and Poisson's ratio are also treated as uncertain parameters, sampled as truncated normal distributions. Fault mechanical properties as friction coefficient (mean 0.65, range [0.40, 0.85]) and cohesion (mean 0.5 MPa, range [0.0, 2.0] MPa).

For the S1 and S2, faults are simulated with potential throw uniformly distributed between 0.1 and the seismic resolution limit of 20m. The orientation of the throw is 150°.

For the S3, the seismic index is treated as an uncertain parameter, and the range is determined from analogue sites reported in the literature. Further details are available in the Appendix 7.2.2.

4.2.3.5.3 Modelling approach

For SS1 and SS2, the modelling approach resolves the initial and perturbed stress states (S_v, S_H, S_h, P_0) onto hypothetical fault planes defined by strike and dip, incorporating poroelastic effects (alpha, nu) and pore pressure changes (ΔP). The stress tensor is resolved via Cauchy stress transformation $\sigma_n = l^2 S_H + m^2 S_h + n_d S_v$, $\tau = l^2 S_H^2 + m^2 S_h^2 + n_d^2 S_v^2 - \sigma_{nn}^2$, where ($l$, m, n_d) are direction cosines. Injection induces pore pressure ΔP, perturbing stresses poroelastically. The updated stress states are written as: $S_{H_u} = S_H + \gamma \Delta P$, with poroelastic coefficient $\gamma = \alpha \frac{1-\nu}{1-2\nu}$, where α is the coefficient of Biot and ν is the coefficient of Poisson.

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Coulomb Failure Stress (CFS) is computed as $\Delta CFS = \Delta\tau + \mu(\Delta\sigma_n - \Delta P)$, triggering failure when initial CFS transitions from negative (stable) to an updated non-negative CFS (unstable). SS2 accounts for pressure diffusion to basement depths using distance, diffusivity, and injection duration, delaying pressurization effects.

Afterwards, the magnitudes could be estimated from fault length, shear modulus, and stress drop, capped by McGarr limits as $M_w = \frac{2}{3}\log_{10} M_0 - 6.07$, with M_0 is the seismic moment expressed as: $M_0 = G\,\pi\,r^2 \frac{\Delta\sigma\ r}{C_g G_{shear}}$.

SS3 applies a statistical Gutenberg-Richter model, predicting event frequency N from injected volume Qt, seismicity parameters (σ_seis, b-value), and a Mw=2.0 threshold, with maximum magnitudes from GR scaling and McGarr constraints. $\log_{10} N = \log_{10} Q_t + \sigma_{seis} - b \cdot M_w^{threshold}$.

The seismogenic index approach is based on an empirical relationship proposed by Shapiro et al. (2010), which relates the number of induced seismic events to the injected volume. The seismogenic index (σ_seis) represents the intrinsic propensity of the site to generate seismicity and cannot be derived from first principles. Instead, it is calibrated from analogous sites reported in the literature.

In this study, σ_seis is treated as an uncertain parameter and sampled within a range representative of fluid injection projects, reflecting the variability observed across different geological contexts.

4.2.3.5.4 Results

The following risk analysis, for the pilot injection scenario, indicates a low level of hazard consistent with the limited pressure perturbations observed in the reservoir simulations (Figure 32, left). The distribution of maximum overpressure exhibits a strongly skewed behaviour, with most values remaining below 10 bars and only a limited cases reaching higher pressure magnitudes. The overpressure values span a P10 ≈ 0.5 bars, P50 ≈ 8.1 bars, and P90 ≈ 26.8 bars. These values are the maximum overpressure registered in the reservoir during the simulation this pic is potentially localized concentrated around the injection well.

Through the Figure 32, right the probabilistic study of the occurrence of the three scenarios shows that the overall likelihood of inducing seismicity remains low, with a combined probability of occurrence of approximately 1.5%. Among the different mechanisms considered, the dominant contribution arises from the reactivation of sub-seismic faults located within the reservoir (S1), with a probability of about 1.3%. In contrast, the contribution from basement fault reactivation (S2) is significantly lower (≈0.15%). Similarly, the diffuse microseismicity component (S3) remains marginal (≈0.11%), indicating a limited seismogenic potential of the site under the considered conditions and parameters.

These results suggest that any induced seismicity associated with the pilot injection is likely to be rare. The relatively low overpressure levels, combined with the restricted spatial extent of the pressure perturbation, limit the transmission of stress changes to deeper formations, thereby reducing the likelihood of basement fault activation.

Overall, the pilot scenario can be characterized as presenting a low induced seismicity risk. These findings are consistent with the injected volume during short injection duration. It should be noted that the analysis is based on a probabilistic workflow with simplified representations of subsurface structures and pressure evolution.

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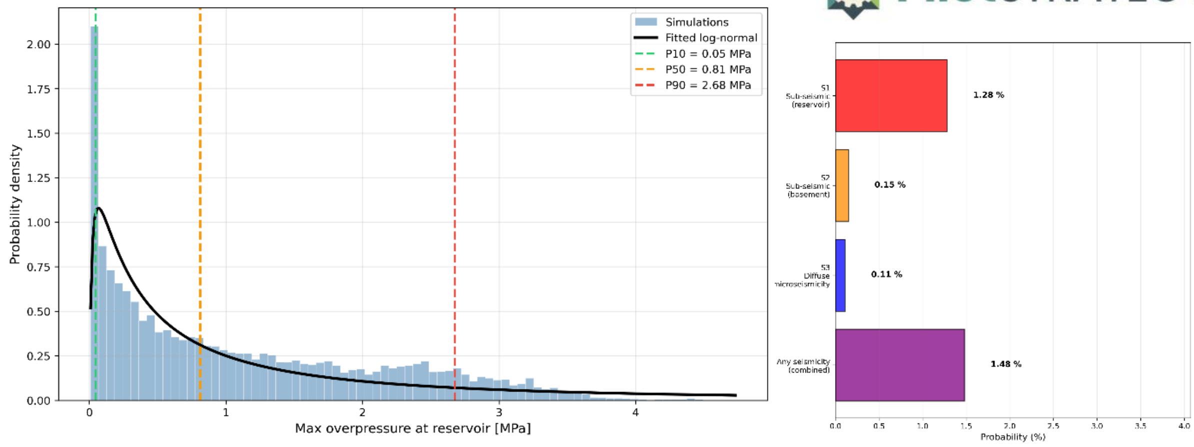

Figure 32: Left: Overpressure distribution in the reservoir, right: probability of induced seismicity for the pilot scenario for the three scenarios and the combined case (pilot scenario).

The magnitude exceedance analysis is provided by the Figure 33. The probability of exceeding a given magnitude decreases with the increasing magnitude for all scenarios. For the scenario 1, the exceedance probability remains around 1% for low magnitudes, drops around magnitude 3 and becomes zero around magnitude 4. The scenario 2, represents probabilities lower than the scenario 1, the probability is around 0.14 across all magnitudes. While the scenario 3 shows higher probabilities at very low magnitudes, translating the possible occurrence of numerous small events. However, the probability decreases rapidly and becomes negligible for magnitudes around 1 and 2. These results indicate that the probabilities of exceeding felt magnitudes remain very low and the probability to reach alert magnitude is close to zero for the pilot case.

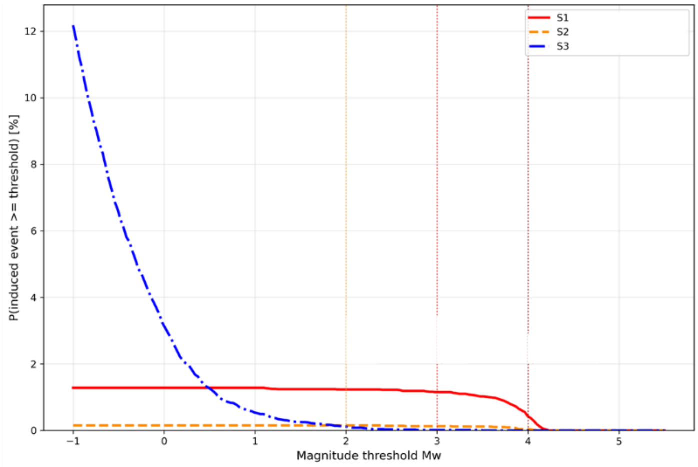

Figure 33: Magnitude exceedance probability for the three considered scenarios, for the pilot injection case.

4.2.3.5.5 Scale-up to commercial scenario and recommendations

The induced seismicity analysis for the commercial injection scenario shows an increase in the pressure perturbation and subsequently the associated seismic risk, compared to the pilot case. The distribution of maximum reservoir overpressure remains strongly skewed, but with a high-pressure tail. The characteristic values of the overpressure registered at the reservoir are approximately P10 of 0.05 bars, P50 of 8. 6 bars, and P90 of 30 bars. This is consistent with the significantly larger injected volume due to longer injection duration, which probably increase both the magnitude and diffusion of pressure within the formation.

The likelihood of inducing seismicity is slightly higher compared to the pilot case, with a probability of 5.2%. The likelihood of the scenario 1 being approximately 1.82%, for scenario 2 is 0.79% and scenario 3 represents 2.95%. Unlike the pilot case, the commercial scenario shows the major seismic probability resulting from diffuse microseismicity. This is once again reflecting the larger injected volume, which increases the number of expected seismic events.

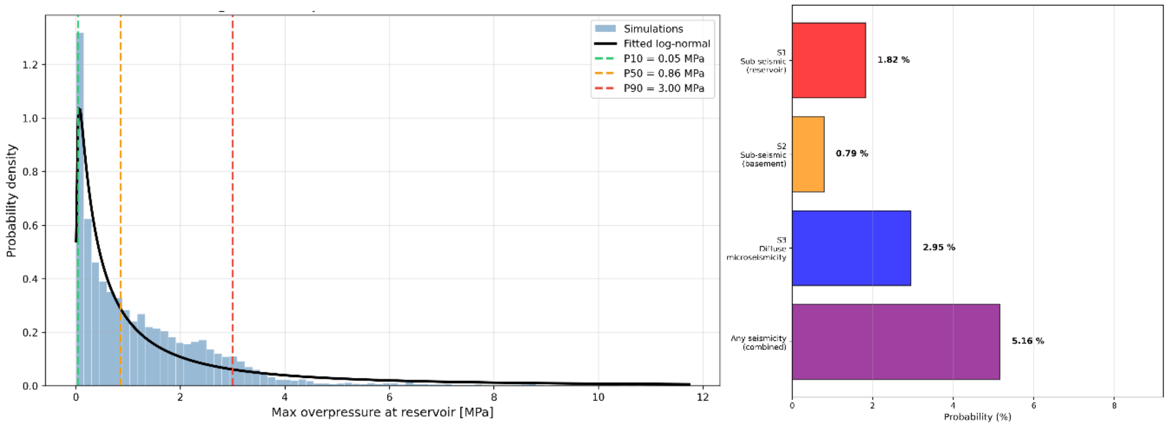

Figure 34: Left: Overpressure distribution in the reservoir, right: probability of induced seismicity for the pilot scenario for the three scenarios and the combined case (commercial scenario).

The magnitude exceedance analysis for the commercial case is provided in Figure 35. This analysis highlights a significant increase in the expected seismic response and particularly for low magnitude events. For instance, the scenario 3 dominates the exceedance probability at low magnitude (mainly negative) and this reflects an expected large number of small seismic events due to the increased injected volume. The scenario 1 remains stable with an exceedance probability around 2% at low magnitudes and a decrease as the magnitude increases. This behaviour indicates that while sub seismic fault reactivation may occur, it is unlikely to generate events of a significant magnitude. The contribution of scenario 2 remains consistently low across all magnitudes, with exceedance probabilities below 1%. This confirms that, even under commercial injection conditions, the likelihood of activating deeper structures capable of generating larger events remains limited.

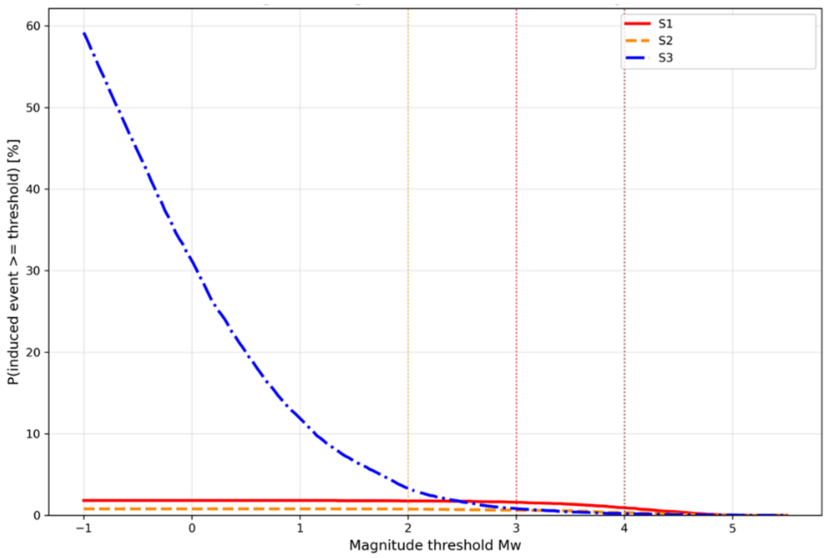

Figure 35: Magnitude exceedance probability for the three considered scenarios, for the commercial injection case

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Overall, the magnitude analysis confirms that the commercial injection scenario is characterized by a higher frequency of small magnitude events, while the likelihood of moderate to large magnitude events remains low. This translates that the number of activated microstructures increases without significantly increasing the potential of large-scale rupture.

It should be noted that the overpressure used in the analysis corresponds to the maximum pressure reached over time, which represents a conservative assumption. In practice, such peak pressures are likely to be spatially localized, mainly in the vicinity of the injection well (Alavoine et al., 2026), whereas the probabilistic framework assumes that these values can be sampled more broadly. In addition, several key parameters are defined based on ranges from the literature rather than site-specific measurements. While this approach ensures robustness and captures uncertainty, it may also contribute to a cautious estimation of the risk. Further reductions in uncertainty could be achieved through improved characterization of reservoir properties, fault distribution, and in-situ stress conditions, as well as by incorporating more spatially resolved coupling between pressure evolution and geomechanical response.

4.2.3.6 Surface ground movements

4.2.3.6.1 Risk description

Surface ground deformation induced by CO_2 injection is assessed using a probabilistic framework combining reservoir simulation outputs with analytical geomechanical modelling.

The increase in pore pressure within the reservoir generates poroelastic deformation, which propagates through the overburden and results in surface displacements. This phenomenon is evaluated using the analytical solution proposed by (Geertsma, 1973), which models the reservoir as a distributed source of deformation embedded in an elastic half-space. The deformation response is driven by the overpressure field derived from reservoir simulations and a set of uncertain geomechanical parameters sampled within a Monte Carlo framework. Overpressure values are extracted from multiple reservoir simulation realizations. For each realization, the maximum overpressure reached over time at each grid cell within the reservoir is computed. This approach assumes that surface deformation is controlled by the peak pressure perturbation, regardless of its timing.

A representative overpressure distribution is constructed through values across all realizations. These values are then sampled and used as input for the geomechanical calculations. This methodology allows the uncertainty in reservoir flow behaviour to be propagated into the assessment of surface deformation.

Three sub-scenarios are defined to capture different aspects of surface ground movement:

- S1 - Surface uplift: This scenario evaluates the risk of excessive vertical displacement at the surface. Failure is defined as the exceedance of a threshold value. Failure if $U_z^{max} > 20$ mm .
- S2 - Differential ground movement: Spatial variations in reservoir pressure induce differential uplift, resulting in surface tilt. This may affect infrastructure stability. Failure if $\frac{dU_z}{dr} > 1$ mm/m.
- S3 - Horizontal displacement: Radial expansion of the reservoir leads to horizontal displacements at the surface. Failure if $U_r^{max} > 10$ mm.

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4.2.3.6.2 Key data and assumptions

The proposed methodology relies on several simplifying assumptions as, the subsurface is represented as a homogeneous and isotropic elastic medium, the pressure field is approximated by a simplified geometry, spatial and temporal correlations of pressure are not preserved, and deformation is assumed to be purely elastic and reversible. These assumptions may underestimate localized effects.

4.2.3.6.3 Modelling approach

Key input parameters are treated here as uncertain variables and sampled using truncated probability distributions. These include reservoir elastic properties (Young's modulus, Poisson's ratio), Biot coefficient, reservoir thickness and depth, extent of the pressurised zone, amplification factor.

A Monte Carlo approach (10000 realizations) is used to propagate these uncertainties through the analytical model. For each realization, surface displacements are computed and compared against predefined threshold. The probability of exceedance is then estimated for each scenario, as well as the combined probability of any surface deformation criterion being exceeded.

The deformation is computed using the Geertsma solution. The maximum vertical surface displacement above the reservoir is given by:

$$U_z^{max} = C_m(1-\nu)\Delta PH\left[1-\frac{D}{\sqrt{R^2+D^2}}\right]$$

where ΔP is the reservoir overpressure, H is the reservoir thickness, D is the depth to the reservoir centre, R is the radius of the pressurised zone, ν is the Poisson's ratio, C_m is the uniaxial compressibility. The uniaxial compressibility is expressed as: $C_m = \frac{\alpha(1+\nu)(1-2\nu)}{E(1-\nu)}$ where E is the Young's modulus and α is the Biot coefficient. Horizontal displacements and surface tilt are derived from the same analytical framework using simplified scaling expressions consistent with the Geertsma solution. An amplification factor is introduced to represent the mechanical contrast between the reservoir and the overburden.

4.2.3.6.4 Results

The surface ground movement analysis for the pilot injection scenario indicates a negligible deformation risk. The probabilistic assessment shows that the probability is extremely low, with an overall exceedance probability of 0.01%. The distribution of maximum vertical surface uplift, exhibited in Figure 36, confirms these findings. Most values remain well below 1 mm, with characteristic values of P50 ≈ 0.4 mm and P90 ≈ 2.4 mm. These results indicate that significant surface deformation is highly unlikely under pilot injection conditions. The pilot scenario is characterized by very small, localized, and transient surface displacements, consistent with the limited injected volume and short injection duration (Alavoine et al., 2026).

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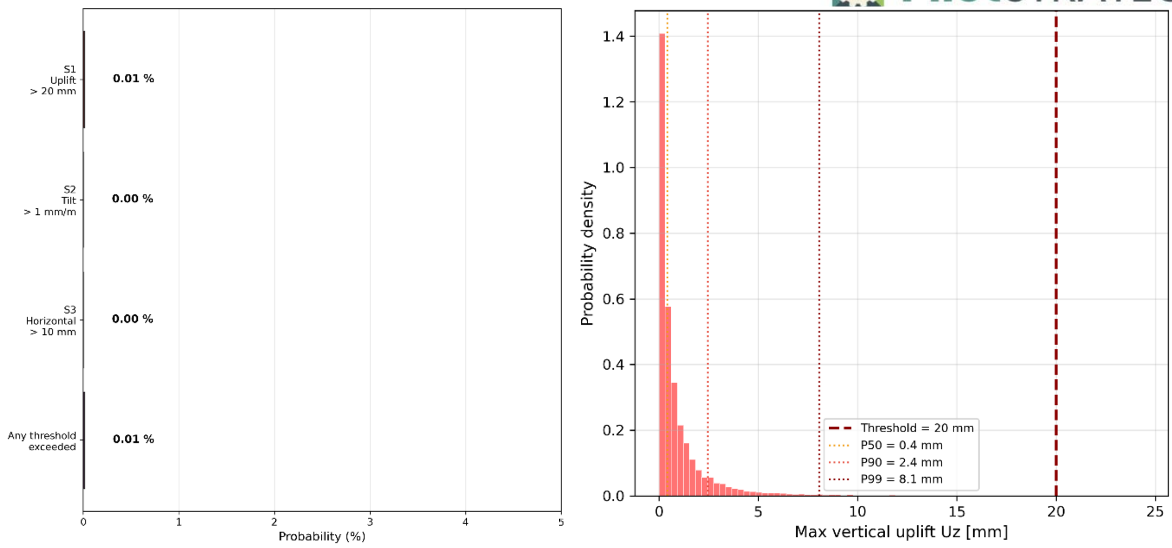

Figure 36: Left: Probability of surface ground movement exceedance. Right: Distribution of maximum surface uplift (pilot scenario)

4.2.3.6.5 Scale-up to commercial scenario and recommendations

The surface ground movement analysis for the commercial injection scenario indicates a very low deformation risk, despite the increased injection duration compared to the pilot case. The probabilistic assessment shows that the overall probability of exceeding any of the defined surface deformation thresholds remains extremely limited, at approximately 0.13%. This exceedance probability is entirely driven by the vertical uplift scenario 1, while the probabilities associated with scenarios 2 and 3 remain effectively negligible.

The results confirm that even under commercial operating conditions, the predicted surface deformation risks remain small. Although slightly higher than in the pilot case, the deformation levels that may occur are most likely to remain well below the thresholds considered critical for integrity.

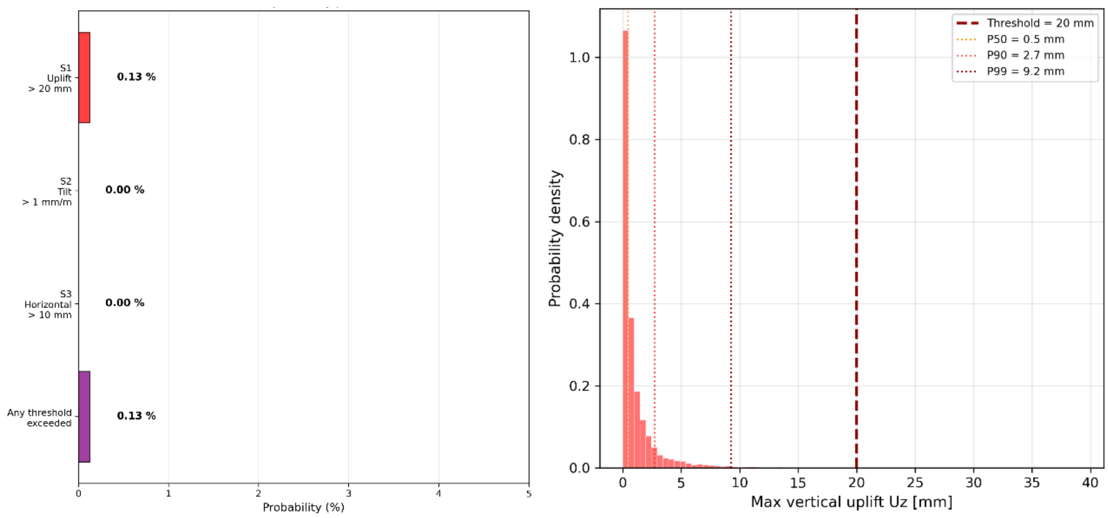

Figure 37:Left: Probability of surface ground movement exceedance. Right: Distribution of maximum surface uplift (commercial scenario)

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4.2.3.7 Brine at surface / leakage

4.2.3.7.1 Risk description

This risk category was called “brine at surface” in the risk register, but it is more accurate to speak about “brine leakage”. The main mechanism here is that brine from the reservoir is pushed upward by overpressure created in the reservoir from the CO_2 injection. If there is a pathway towards a freshwater aquifer, then the saline brine could contaminate it.

The pathways are similar than for CO_2. In this case, the main risk is thus a leakage through abandoned well lacking integrity. As for CO_2 leakage, the main scenario is a leak on the external annulus, between the cement and the formation.

The main strategic aquifer in the region is the Albian aquifer (Mathurin et al., 2023). However, the Lusitanian aquifer, which is not considered strategic as a water resource, is located between the Dogger and the Albian. Similarly to CO_2 leakage, the most probable scenario for brine leakage would be a leak in the Lusitanian. A leak into the Albian would require the combination of two independent failure in the cement barriers (i.e. one between Dogger and Lusitanian, and one between Lusitanian and Albian, with the assumption that there are no other aquifers).

The leakage of brine to the surface is a lower risk on both dimensions: lower probability (it requires at least three independent barriers to fail), and lower consequences as there is no identified water resource.

4.2.3.7.2 Key data and assumptions

The main properties of the reservoir brine, as well as the potential vulnerable aquifers are summarized in Mathurin et al. (2023).

The knowledge about existing wells is summarized in paragraph 4.2.3.3.

4.2.3.7.3 Modelling approach

A semi-quantitative assessment is used for this category. We use hydrostatic balance problem equations to reason about this risk, i.e. for a well open from reservoir (depth Zr) to aquifer (depth Za), brine will flow upward into the aquifer when (Nicot et al., 2009):

$$\Delta P_{res} > (\rho_{brine} - \rho_{fresh}) \cdot g \cdot (Zr - Za)$$

Semi-analytical approaches rely on an equivalent permeability parameter to model the lack of integrity of the well (Réveillère, 2013). We choose not to use this type of parameter because our current knowledge about the well does not allow for a meaningful estimation.

4.2.3.7.4 Results

In our case, considering well BIS1, which is the closest abandoned well to the injection well (SEIF is not abandoned and thus, more manageable from a risk perspective), we have the following data:

- Depth of Dogger reservoir at BIS 1: 1850 – 2000m
- Depth of Albian aquifer: around 850m
- Salinity of Dogger: 30-35g/l
- Salinity of Albian: < 1g/L

We thus have a difference of salinity Δsalinity ≈ 30 g/L

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Using a rule of thumb of ~0.7 kg/m³ per g/L TDS (Total Dissolved Solids) for NaCl-dominated brines (Batzle & Wang, 1992), we have a density contrast of ~21 kg/m³ between Dogger brine and Albian water.

Considering $Z_r - Z_a \approx 1000$m, and $g \approx 10$ m/s², then $\Delta P_{threshold} \approx 210000\ Pa$

Thus, at least 2 bars of sustained overpressure at the abandoned well location is required to initiate upward brine flow into the Albian (under the assumption that the well behaves like an open hole, which is an extreme worst-case scenario).

In the pilot case, the 2 bar overpressure front radius should be less than 2 km (Canteli et al., 2025), which is less than the distance between the injection well and the other abandoned wells (2,5 km in the case of BIS1 which is the closest). This suggests that the risk is not realized under pilot-scale conditions.

4.2.3.7.5 Scale-up to commercial scenario and recommendations

Using modelling results at the commercial scale, here are the overpressure distribution on the other wells in the area of interest (Figure 38). The figure shows that the 2 bar threshold is overpassed at those wells with non-negligible probabilities.

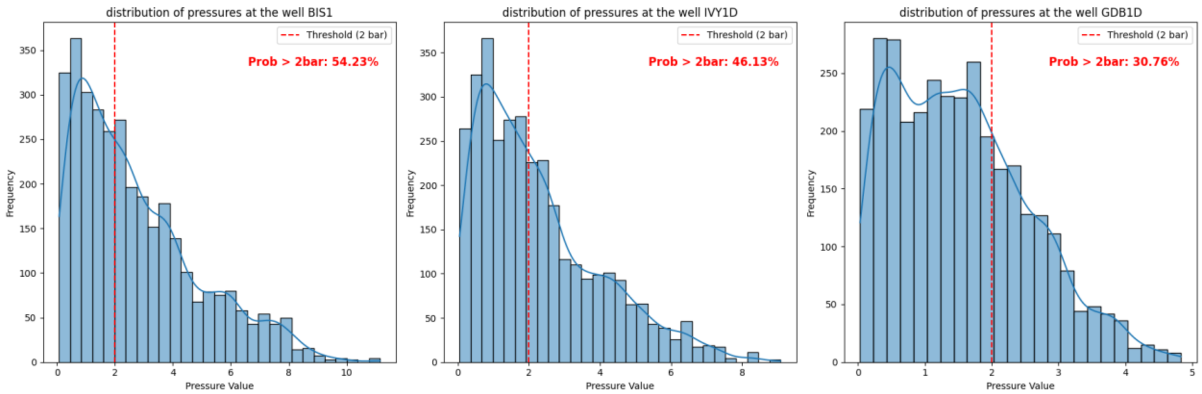

Figure 38: distribution of overpressure at the existing wells in the area of interest

However, this is an overly simplistic approach that is sufficient in the pilot case to dismiss the possibility. A dedicated approach should be used in the commercial case, using semi-analytical solutions (e.g. Réveillère, 2013) or numerical modelling. In that case, it will be necessary to make assumptions about the integrity of those wells (of which SEIF1 is still active, with recent cement evaluation logs).

Our recommendations:

- Monitor how the pressure evolves in the reservoir during injection. Ideally, this needs another pressure gauge at a distance from injection: consider using SEIF1 for this?
- Make a refined analysis of well integrity at the wells within the “area of review” (Nicot et al., 2009)
- Refine the modelling of brine leakage using semi-analytical or numeral models
- Consider the possibility of monitoring the Lusitanian aquifer for a large-scale application.

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4.2.3.8 Other uses

4.2.3.8.1 Risk description

This risk event addresses the probability that the CO_2 plume or the associated pressure perturbation migrates laterally beyond the storage permit area and reaches the neighbouring petroleum concessions, here of Chaunoy and Charmotte. Such an event would constitute both a performance and a legal risk: the presence of CO_2 mass within a third-party concession may interfere with ongoing petroleum operations and trigger regulatory consequences under the terms of the concession agreements. Two distinct risk metrics are therefore considered, the mass of CO_2 crossing into each concession and the maximum overpressure induced within each concession boundary each capturing a different dimension of the potential impact.

4.2.3.8.2 Key data and assumptions

The spatial extents of the Chaunoy and Charmotte concessions are defined by their respective polygon boundaries and are treated as fixed inputs in this assessment. These boundaries are intersected with the simulation grid (domain of approximately 20 km × 20 km) to generate binary masks identifying all grid cells falling within each concession. The Chaunoy concession and the Charmotte concession represent no spatial overlap between the two.

4.2.3.8.3 Modelling approach

The assessment draws directly from the full ensemble of realisations described in Section 4.2.1. For each realisation, CO_2 mass within a given concession cell is computed at each timestep. Overpressure is calculated as the difference between the simulated pressure at each timestep and the initial pressure field. Both metrics are tracked over all simulation timesteps, and the maximum value recorded over the full simulation period is retained for each realisation.

By aggregating these maximum values across the full ensemble, statistical distributions are derived for each metric, from which the P10, P50, and P90 values are extracted.

4.2.3.8.4 Results

At pilot scale, the simulation ensemble consistently shows that the CO_2 plume remains entirely contained within the seismic acquisition area (Figure 39). The plume is categorised spatially into five zones: CO_2 confined within the seismic area, CO_2 outside the seismic area, CO_2 outside the seismic area but within the concession, CO_2 within both the seismic area and the concession, and cells where no CO_2 is detected. In this case, no CO_2 mass is detected within either the Chaunoy or the Charmotte concession across any of the realisations. This result confirms that under the modelled injection scenario of 100 kt over 4 months, lateral plume migration does not constitute a risk to neighbouring concession.

However, the pressure perturbation associated with injection does extend beyond the seismic boundaries and into both concessions (Figure 40). In the Chaunoy concession, the maximum overpressure reaches a P10 of 0.460 bars, P50 of 1.88 bars and a P90 of 3.69 bars, with a maximum of 6.79 bars recorded across the ensemble. In the Charmotte concession, which is located further from the injection well, the pressure perturbation is more moderate, with a P10 of 0.258 bars, P50 of 1.23 bars and a P90 of 2.46 bars, and a maximum of 3.95 bars. These values represent the radial decay of the pressure field with distance from the injection well.

While these overpressure levels are not expected to affect the mechanical integrity of the neighbouring concessions, they represent a non-negligible pressure that should be considered in the

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context of ongoing operations within the Chaunoy and Charmotte concessions. Continuous pressure monitoring is therefore recommended as part of the pilot surveillance programme.

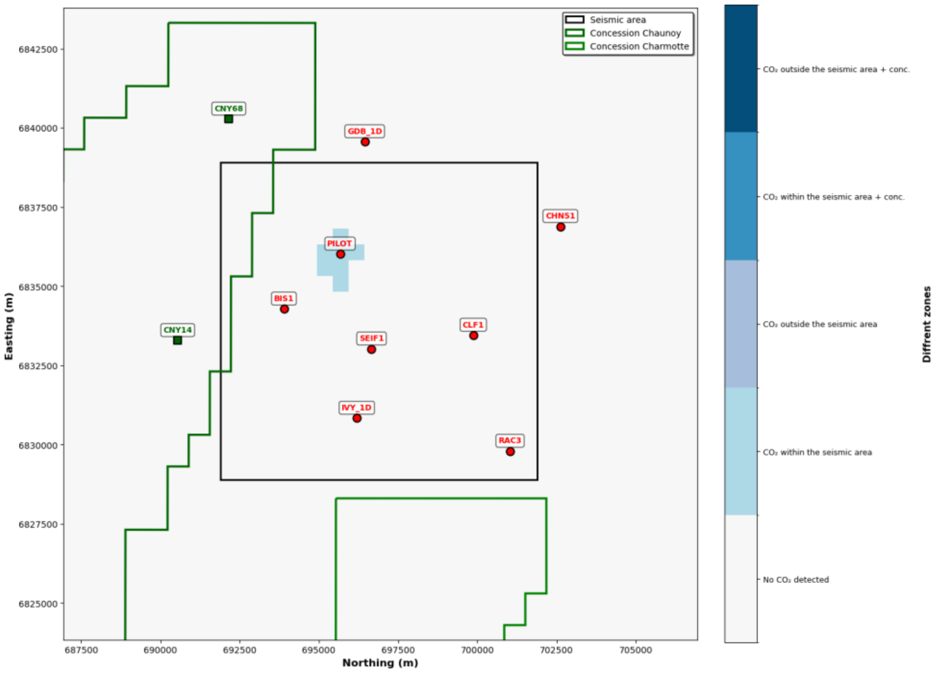

Figure 39: Spatial distribution of CO_2 at pilot scale relative to the seismic permit area and neighbouring concessions (Chaunoy and Charmotte)

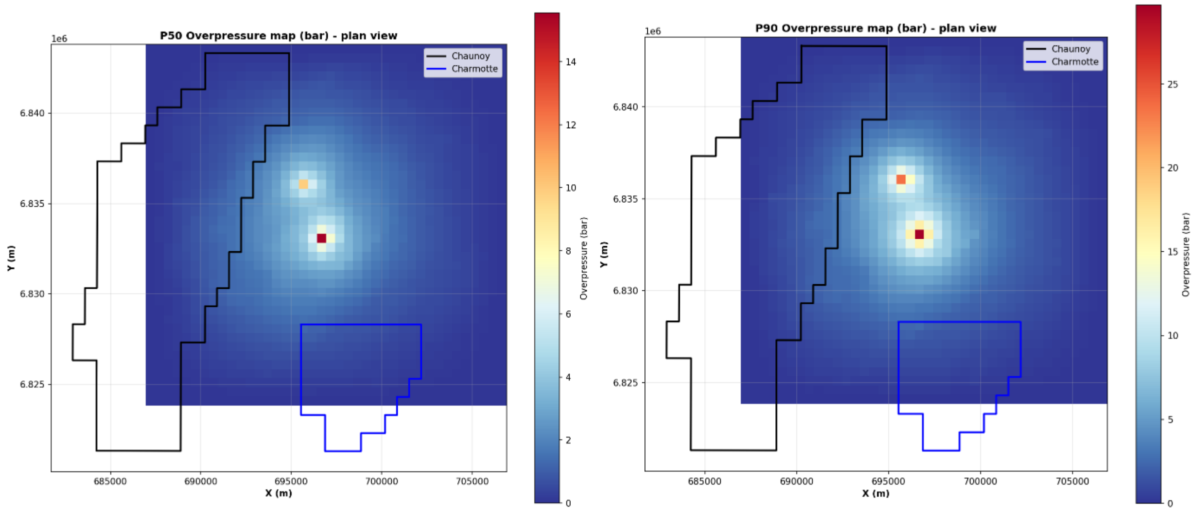

Figure 40: P50 (left) and P90 (right) overpressure map (bar) at pilot scale: plan view showing pressure distribution relative to the Chaunoy (black) and Charmotte (blue) concession boundaries.

4.2.3.8.5 Scale-up to commercial scenario and recommendations:

The commercial scale assessment, conducted over a longer injection period and higher cumulative volumes, reveals different results, as illustrated in Figure 41 and Figure 42.

The CO_2 plume footprint (Figure 41) extends beyond the seismic area boundary in the most unfavourable realisations, with CO_2 detected within the Chaunoy concession in a subset of simulations (maximum quantity of 193.808 kt). The Charmotte concession, located to the south, lies outside the

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primary migration pathway and does not show detectable CO_2 presence. Nevertheless, the probabilistic analysis demonstrates that the risk of CO_2 migrating beyond the seismic boundary, towards Chaunoy concession, remains very low across the ensemble. The maximum probability of CO_2 reaching that zone ranges from 0.23% to 1.79 %. The probability of CO_2 impacting at least one well outside the permit boundary is estimated at 0.12%, which remains negligible even under the most pessimistic realisations.

The pressure perturbation at commercial scale is more pronounced than at pilot scale, due to the larger cumulative injected volume. The overpressure maps (Figure 42) highlight the spatial extent of the calculated P50 and P90 scenarios of pressure perturbation. Under the P50, the pressure field is concentrated around the two injection sources, the CO_2 injection well and the nearby water disposal well, with maximum overpressures of approximately 16 bars near the wellbores and a rapid radial decay. The Chaunoy concession boundary intersects the outer pressure front, where overpressures remain limited. Under the P90 scenario, the pressure field is significantly more extensive, reaching maximum values in excess of 35 bars near the injection well. In the Chaunoy concession, the maximum overpressure reaches a P50 of 2.39 bars and a P90 of 5.79 bars, with a maximum of 9.95 bars across the ensemble. In the Charmotte concession, the perturbation is again more moderate, with a P50 of 1.50 bars and a P90 of 3.73 bars, and a maximum of 6.92 bars.

These results indicate that the risk of meaningful CO_2 or pressure impact on the Chaunoy and Charmotte concessions at commercial scale is low but non-negligible in the extreme cases of the distribution. Therefore, it is recommended to integrate a monitoring plan near the concession boundaries to detect early pressure and CO_2 migration. Certainly, a better reservoir description is advised to constrain extreme case behaviours to mitigate the potential impacts under worst-case scenarios.

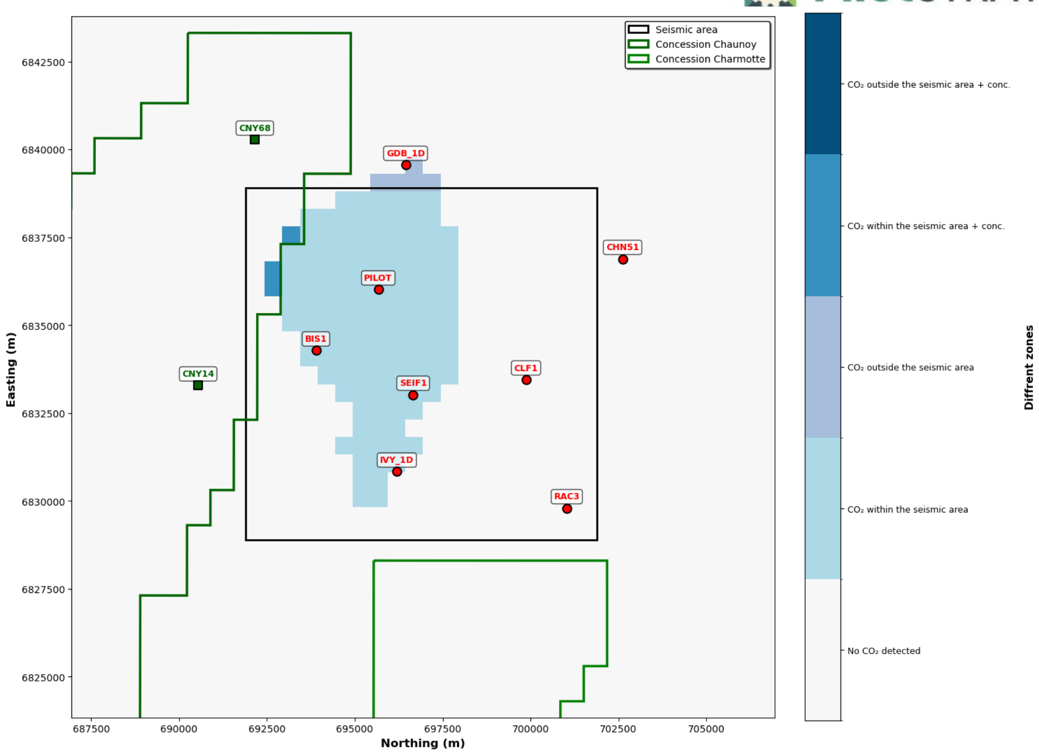

Figure 41: Spatial distribution of CO_2 at commercial scale relative to the seismic permit area and neighbouring concessions (Chaunoy and Charmotte)

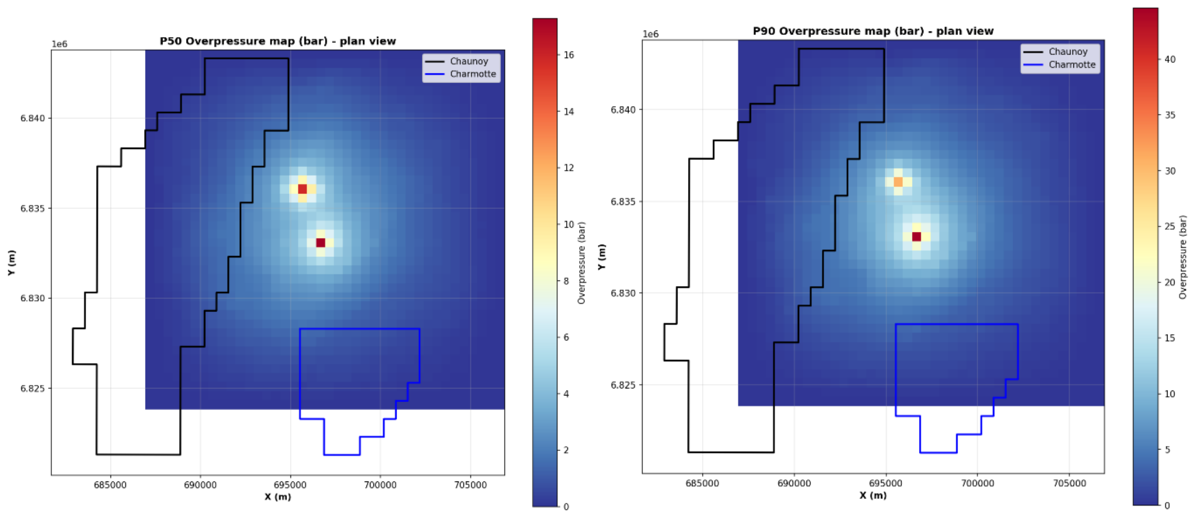

Figure 42 P50 (left) and P90 (right) overpressure map (bar) at commercial scale: plan view showing pressure distribution relative to the Chaunoy (black) and Charmotte (blue) concession boundaries.

4.2.4 Project risk analysis

This category assesses risks from the project point of view, i.e. the main negative consequence here is that the project of running a CO_2 injection pilot cannot proceed as intended.

We did not perform a detailed analysis for this section. Rather, we provide here qualitative elements and recommendations for managing those risks.

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4.2.4.1 Delays and costs

As for any kind of projects, some of the main risks are related to important delays in implementing the project and costs overrun. The D4.11 report (Canteli et al., 2026) contains an economic analysis of the pilot, with uncertainty. It also provides a potential timeline for the development of the pilot project.

The uncertainty includes the following contingencies:

- Errors of the estimation model,
- Uncertainties on unit costs,
- Uncertainties on quantities,
- Possible variations of the workforce,
- Variations of productivity,
- Risks associated to the selected process,
- Minor changes of design.

Regarding delays, the main risk is linked to the availability of resources and tools for construction of the infrastructure, such as the rig for drilling the well. The D4.11 report highlights CO_2 availability as a key uncertainty. Another key aspect is the uncertainty in the delay of permit approval by the administration.

Here, a risk assessment of this category is made difficult because currently mostly costs are assessed and not benefits of running a pilot. We can distinguish two types of pilot projects:

- Pre-commercial pilot projects: in this case, the operator first run a pilot project, before a commercial scale-up. The pilot is used to acquire key data before being able to operate at full scale. It is also a demonstrator for stakeholders, as a mean to build trust before getting the "social licence to operate". Some infrastructure can be re-used, notably the injection well. The goal is to unlock a full-scale project in particular
- One-shot pilot projects: they are purely done to demonstrate the technology and key innovations but are not designed for later commercial use. Examples in Europe include the Rousse project in South-West France or the Ketzin project in Germany. The goal is to unlock a technological field, and would usually require public funding, because it is not meant to generate a profit in the short term.

The concept of PilotStrategy is to design a pilot for the first category. Hence, the cost of the pilot should in fact consider the whole life of a commercial project. However, considering the current uncertainty regarding the CO_2 source for the commercial project, it is too early to run such an analysis.

Consequently, our key recommendation for this risk category is to make progress on the "post-pilot" phase. If the pilot is a pre-commercial project, there should be a credible case for such a commercial project.

It is a bit of a "chicken and egg" issue: the pilot project cannot make further progress until a commercial project is materializing. But one benefit of a pilot project is to convince stakeholders to support the further development into a commercial project.

4.2.4.2 Politics / Legal

This risk can refer to:

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- A piece of legislation/regulation which prevents from doing the project
- Lack of political support which impedes the project from moving forward

In France, the regulation of CO_2 storage projects is operational since the European directive was adapted in national law (Bouet et al., 2022), and storage is allowed on the French territory. Thus, the regulatory risk is limited.

We mentioned the delay in the permitting process, but what is the likelihood that the exploration permit is not delivered? In addition to the content of the application, there are also criteria regarding the technical and financial capacity of the applicant.

Regarding political support, we need to distinguish the national from the local scale. In theory, CO_2 storage is supported at a national level, as there is a CCS roadmap from the French government, and it is included in the official decarbonization strategy. However, support at the local level will be dependent on the perceived benefits. This was clearly expressed by local stakeholders during meetings (Preuß et al., 2026). The discussions identified an opportunity to discuss potential fiscal compensation mechanisms at the national level for future CO_2 storage projects.

Recommendations are thus:

- The applicant should demonstrate technical and financial capacity, or be backed by a company with sufficient expertise and financial capacity
- Local benefits should be clearly stated in addition to the national decarbonization benefits

4.2.4.3 Social

This category refers to the possibility of opposition from local communities, preventing the project from moving forward.

This aspect was mainly treated in WP6. The summary of citizen engagement activities is presented in Dütschke et al. (2025). Recommendations for better public engagement are in Dütschke et al. (2026).

In conclusion, this is clearly a key aspect of project risk management. It is key that the future operator follows the best practices in terms of public engagement and transparency. However, there were already signs of opposition from local movements despite the project still being at the research phase. This opposition appeared to convince some local elected officials, at least in their public stance. This is not necessarily a “showstopper”, but it requires to enhance local engagement and build the strongest case possible (in terms of safety and financial performance as well as local benefits) in order to obtain the “social license to operate”. Any minor shortcomings will appear as big hurdles in the context of local oppositions.

4.3 Risk assessment synthesis

The result of risk assessment is displayed in the following tables, including the analysis of likelihood and impact of each risk category, and recommendations for future work.

Likelihood and impact refer to the results at the **pilot scale.** They represent average values of the results and do not represent the full distribution that was computed in the case of quantitative risk assessment.

The column "Priority for commercial scale evaluation" synthesizes the outcome of additional modelling that was done on several risk categories at a commercial scale. High / low priority reflects the current level of uncertainty regarding risk assessment at this scale, but it does not mean the risk is high / low. High priority risks of commercial scale should be studied in more detail.

Table 10: Synthesis table for performance risk categories

Name	**Likelihood**	**Impact**	**Comment**	**Key decisions**	**Key recommendations**	***Priority for commercial scale evaluation***
Lateral extent	Very low	Very low	Based on modelling, the risk does not materialize	Contour of licence; Area of review for geophysical data	Reduce uncertainty with data acquisition during pilot; consider larger permit zone than initial seismic	*High priority*
Capacity	Low	Low	Based on modelling	Design capacity	Reduce uncertainty with data acquisition during pilot	*High priority*
Injectivity	High	High	Based on modelling.	Allowable Bottomhole pressure	Reduce uncertainty with data acquisition during pilot	*High priority*

Table 11: Synthesis table for safety risk categories

Name	**Likelihood**	**Impact**	**Comment**	**Key decision**	**Key recommendations**	***Priority for commercial scale evaluation***
Drilling / Construction / handling CO2 at surface	Low	Low	Qualitative analysis; several sub-scenarios included	Front End Engineering Desing	Further analysis and safety design of surface operations	*Not assessed*
Injection well	Low	Low	Based on literature review and specific design options	Final design of the well; choice of materials	Be conservative in the design to cover for future commercial scenarios	*High priority*
Pre-existing wells	Very low	Low	Quantitative modelling of	Injection design (location, rate,	Reduce uncertainty in	*High priority*

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			the plume and expert opinion on the well integrity	etc.), legacy well characterization design	plume movement with data acquisition during pilot. Monitor around legacy wells	
Leakage through caprock	Very low	Low	Based on numerical modelling of overpressure	Allowable bottomhole pressure	Reduce uncertainty in geomechanical parameters with data acquisition during pilot	*Low priority*
Induced seismicity	Low	Very Low	Based on numerical modelling of overpressure and analytical geomechanical expressions	MMV design	Reduce uncertainty in geomechanical parameters with data acquisition during pilot	*Low priority*
Surface ground movements	Very Low	Low	Based on analytical geomechanical modelling			*Low priority*
Brine at surface / leakage	Very low	Low	Based on analytical analysis	legacy well characterization design, pressure "budget"	Monitor pressure, assess legacy well integrity, improve modelling of brine leakage, potential monitoring of Lusitanian	*High priority*
Other uses	Low	Low	Based on numerical modelling	Pressure "budget", design capacity	Improve understanding of potential consequences of CO2 storage on other uses	*High priority*

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Table 12: Synthesis table for project risk categories

Name	**Likelihood**	**Impact**	**Comment**	**Key decision**	**Key recommendations**	***Priority for commercial scale evaluation***
Delays and costs	High	High	Expert opinion and WP4 studies	Final Investment Decision	Anticipate design of commercial scale project	*High priority*
Politics / legal	Low	High	Expert opinion	Final investment Decision	Demonstrate financial and technical capacity of applicant; Provide elements into concrete benefits for local communities	*Low priority*
Social	High	High	Expert opinion and WP6 studies	Final Investment Decision	Follow best practices in terms of public engagement and transparency; Provide elements into concrete benefits for local communities	*High priority*

5. Conclusion

This report presents the safety and performance risk assessment carried out for the proposed CO_2 storage pilot in the Paris Basin. The assessment builds on the geological and hydrogeological characterisation developed within the PilotSTRATEGY project, on preliminary risk screening, and on an updated probabilistic analysis based on ensembles of numerical simulations and risk-specific analytical models.

At pilot scale, the results indicate that the proposed injection scenario is associated with a generally low level of safety risk. The CO_2 plume remains limited in spatial extent and does not reach any identified pre-existing well in the simulation ensemble. The probability of leakage through the caprock is negligible under the modelled pressure conditions, and the risk of induced seismicity remains low, with very low probabilities of events reaching magnitudes of concern. Surface ground movements are predicted to remain very small, and brine leakage risks are not expected to materialise under the pilot-scale pressure footprint. Risks related to drilling, construction, surface handling of CO_2 and injection well integrity are considered manageable through standard engineering design, regulatory requirements and established HSE practices.

From a performance perspective, the pilot-scale assessment is also broadly favourable, but it highlights the importance of injectivity as a key uncertainty. While the target injected volume is reached or nearly reached in most simulations, some realisations show limitations related to pressure constraints and reservoir properties. Injectivity therefore appears as one of the main technical aspects to be confirmed during the pilot. The pilot phase should be designed to provide high-quality data on pressure build-up, near-well behaviour, effective injectivity, and plume evolution, as these observations will be essential to reduce uncertainty and update the models.

The assessment also shows that several risks that are negligible or very low at pilot scale may become more relevant in a possible commercial-scale development. This is particularly the case for lateral plume extent, interactions with pre-existing wells, brine leakage, pressure impacts on neighbouring subsurface uses, storage capacity and long-term injectivity. The commercial-scale simulations do not indicate immediate showstoppers, but they highlight the need for a larger and more detailed area of review, improved characterisation of legacy wells, better constraints on pressure propagation, and a more robust understanding of reservoir heterogeneity and geomechanical parameters.

The pilot should therefore be regarded not only as a limited injection test, but also as a key uncertainty-reduction step before any potential scale-up. Its value lies in its ability to provide site-specific dynamic data, validate or revise the current models, improve confidence in storage performance, and support future decisions regarding monitoring, operating constraints, permit boundaries and commercial development options.

The main recommendations arising from this assessment are to:

- acquire and interpret pressure and plume-monitoring data during the pilot to constrain reservoir behaviour and reduce uncertainty on injectivity and lateral migration;
- maintain conservative pressure management and define clear operational limits, especially regarding allowable bottom-hole pressure;
- further assess the integrity and accessibility of legacy wells within the area of review, particularly for any future commercial-scale development;

- refine geomechanical characterisation, including stress state and caprock properties, to support future assessments of caprock integrity and induced seismicity;
- consider pressure monitoring and potential interactions with neighbouring subsurface uses, including petroleum concessions and existing injection activities;
- ensure that surface facilities, CO_2 handling operations and emergency response plans are developed in line with best available HSE practices;
- integrate public engagement, transparency and local-benefit considerations as central elements of project risk management.

Overall, the risk assessment supports the technical feasibility of a well-designed and properly monitored CO_2 storage pilot in the Paris Basin. No major safety concern has been identified for the pilot-scale scenario under the assumptions considered. However, the analysis also confirms that uncertainty remains significant for several parameters that will be critical for commercial-scale deployment. The pilot phase would therefore be an important and valuable step to improve confidence, refine the risk assessment, and support evidence-based decision-making for any future development of CO_2 geological storage in the Paris Basin.

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6. References

Alavoine, A., Bouquet, S., Estublier, A., Fornel, A., Meiller, C., Urych, T., CHEĆKO, J., Stańczyk, K., Al Mala Khudhur, K. S. A., Pereira, P., Carneiro, J., Hardwick, J., Santos, M., Casacão, J., Ron Martín, M., Mañas Fernandez, M., Blanco Pericana, A., Ibañez, E., Fernández-Canelas, P., & Francisco, P. (2024). *D3.3 Report on optimization – Injection strategy and storage capacity*. https://doi.org/10.5281/zenodo.18865032

Alavoine, A., Bouquet, S., Estublier, A., FREY, J., Meiller, C., Pereira, P., Behnous, D., MAZEZO, A., Carneiro, J., Al Mala Khudhur, K. S. A., Guillon, T., Arnold, B., Mário, S., Caeiro, M. H., Marta, M., Manuel, R., & Antonio, M.-M. (2026). *D3.5 Report on near wellbore, caprock and faults/fractures integrity*. https://doi.org/10.5281/zenodo.19677376

André, L., Audigane, P., Azaroual, M., & Menjoz, A. (2007). Numerical modeling of fluid–rock chemical interactions at the supercritical CO2–liquid interface during CO2 injection into a carbonate reservoir, the Dogger aquifer (Paris Basin, France). *Energy Conversion and Management*, *48*(6), 1782-1797. https://doi.org/10.1016/j.enconman.2007.01.006

Batzle, M. L., & Wang, Z. (1992). Seismic properties of pore fluids. *Geophysics*, *57*(11), 1396-1408. https://doi.org/10.1190/1.1443207

Bordenave, A., & Issautier, B. (2024). *D2.7_PilotSTRATEGY_Paris_Basin_France*. https://doi.org/10.5281/zenodo.12626574

Bouet, Y., Prat, L., & Versluys, V. (2022). *Analysis of the French Permitting Process for CO2 Geological Storage and Operational Implications* (SSRN Scholarly Paper N° 4286126). https://doi.org/10.2139/ssrn.4286126

Canteli, P. (2026). *Environment Impact Assessment D4.8* (D4.8). EU H2020 PilotSTRATEGY project, Grant Agreement: 101022664.

Canteli, P., Moreno, I., Ron, M., Le Gallo, Y., Jannel, H., Casacao, J., Sliwinska, A., Tartaras, E., Tyrologou, P., & Koukouzas, N. (2024). *D4.2_PilotSTRATEGY_Conceptual scenarios*. https://doi.org/10.5281/zenodo.12633855

Canteli, P., Ron, M., Lachen, L., Cron, J., Le Gallo, Y., Rivière, A., Marty, L., Casacão, J., Caeiro, M. H., Varelas, F., Carneiro, J., Carro, A., Mesquita, P., Soni, G., da Silva Veloso, R. C., Afonso, P., Ferreira Cardoso Madureira, P. M., Krawczyk, P., Śliwińska, A., … Karatrantou, C. (2026). *D4.11 Description and results of the probabilistic assessment and sensitivity analysis of the development concept*. https://doi.org/10.5281/zenodo.20068438

Canteli, P., Ron, M., Moreno, I., Le Gallo, yann, Casacão, J., Śliwińska, A., Krawczyk, P., Tartars, E., Ktenas, D., Tyrologou, P., Karatrantou, C., & Koukouzas, N. (2025). *D4.9 Economic evaluation of alternatives and prioritisation results*. https://doi.org/10.5281/zenodo.14856834

Carles, P., Bachaud, P., Lasseur, E., Berne, P., & Bretonnier, P. (2010a). Confining Properties of Carbonated Dogger Caprocks (Parisian Basin) for CO2 Storage Purpose. *Oil & Gas Science and Technology – Revue de l'Institut Français Du Pétrole*, *65*(3), Article 3. https://doi.org/10.2516/ogst/2009082

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Carles, P., Bachaud, P., Lasseur, E., Berne, P., & Bretonnier, P. (2010b). Confining Properties of Carbonated Dogger Caprocks (Parisian Basin) for CO2 Storage Purpose. *Oil & Gas Science and Technology – Revue de l'Institut Français Du Pétrole*, *65*(3), Article 3. https://doi.org/10.2516/ogst/2009082

Christ, A., Mattioni, L., Urych, T., Chećko, J., Stańczyk, K., Pereira, P., Caeiro, M. H., Carneiro, J., Khudhur, K., Ribeiro, C., Lopes, A. M., Santos, M., da Silva, D. M., Garcia, J., Moreno, I., Mediato, J. F., & Canteli, P. (2024). *D3.2_PilotSTRATEGY_Static_Modelling_and_Uncertainties*. https://doi.org/10.5281/zenodo.12626870

Daniels, S., Hardiman, L., Hartgill, D., Hunn, V., Jones, R., & Robertson, N. (2023). *Deep Geological Storage of CO2 on the UK Continental Shelf : Containment Certainty* (p. 87). https://www.gov.uk/government/publications/deep-geological-storage-of-carbon-dioxide-co2-offshore-uk-containment-certainty

Delmas, J., Brosse, E., & Houel, P. (2010). Petrophysical Properties of the Middle Jurassic Carbonates in the PICOREF Sector (South Champagne, Paris Basin, France). *Oil & Gas Science and Technology – Revue de l'Institut Français du Pétrole*, *65*(3), 405-434. https://doi.org/10.2516/ogst/2010002

Doherty, B., Vasylkivska, V., Huerta, N. J., & Dilmore, R. (2017). Estimating the Leakage along Wells during Geologic CO2 Storage : Application of the Well Leakage Assessment Tool to a Hypothetical Storage Scenario in Natrona County, Wyoming. *Energy Procedia, 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland*, *114*, 5151-5172. https://doi.org/10.1016/j.egypro.2017.03.1669

Dütschke, E., Alsheimer, S., Carneiro, J., Delicado, A., Gonçalves Oliveira, L., Kappler, L., Mays, C., Oltra, C., Poumadère, M., & Preuß, S. (2026). *D6.7 Policy Brief with Guidelines for Public Engagement and Recommendations*. https://doi.org/10.5281/zenodo.19232041

Dütschke, E., Alsheimer, S., Oltra, C., Delicado, A., Gonçalves Oliveira, L., Mays, C., Poumadère, M., & Rowland, J. (2025). *D6.5 Summary report on public acceptance—Findings from second survey and citizen engagement*. https://doi.org/10.5281/zenodo.18163364

Geertsma, J. (1973). Land Subsidence Above Compacting Oil and Gas Reservoirs. *Journal of Petroleum Technology*, *25*(06), 734-744. https://doi.org/10.2118/3730-PA

Gholami, R., Raza, A., & Iglauer, S. (2021). Leakage risk assessment of a CO2 storage site : A review. *Earth-Science Reviews*, *223*, 103849. https://doi.org/10.1016/j.earscirev.2021.103849

Gonçalvès, J., Violette, S., Robin, C., Pagel, M., Guillocheau, F., de Marsily, G., Bruel, D., & Ledoux, E. (2003). 3-D modelling of salt and heat transport during the 248 my evolution of the Paris basin : Diagenetic implications. *Bulletin de la Société géologique de France*, *174*(5), 429-439.

Hannon, M. J., & Esposito, R. A. (2015a). Screening considerations for caprock properties in regards to commercial-scale carbon-sequestration operations. *International Journal of Greenhouse Gas Control*, *32*, 213-223. https://doi.org/10.1016/j.ijggc.2014.11.016

Hannon, M. J., & Esposito, R. A. (2015b). Screening considerations for caprock properties in regards to commercial-scale carbon-sequestration operations. *International Journal of Greenhouse Gas Control*, *32*, 213-223. https://doi.org/10.1016/j.ijggc.2014.11.016

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

IEAGHG Risk Management Network Meeting Report (N^{os} 2023-TR03). (2023). IEA Greenhouse Gas R&D Programme. https://ieaghg.org/publications/risk-management-network-meeting-report/

IOGP Safety performance indicators—2024 data (N° 2024s; Data Series, p. 153). (2025). IOGP. https://www.iogp.org/bookstore/product/iogp-safety-performance-indicators-2024-data/

Jougnot, D., Revil, A., & Leroy, P. (2009). Diffusion of ionic tracers in the Callovo-Oxfordian clay-rock using the Donnan equilibrium model and the formation factor. *Geochimica et Cosmochimica Acta*, *73*(10), 2712-2726. https://doi.org/10.1016/j.gca.2009.01.035

Lachen, L., Pagazani, C., Ron, M., Canteli, P., Moreno, I., Bocquet, R., Carlier, B., Coutand, F., Le Gallo, Y., Moreau, S., Riviere, A., Casacão, J., Sliwinska, A., Krawczyk, P., Tyrologou, P., Koukouzas, N., Karatrantou, C., Tartaras, E., & Ktenas, K. (2025). *D4.5 From capture to the injection facilities definition : Capture, transport and CO_2 stream quality*. https://doi.org/10.5281/zenodo.16537784

Lackey, G., Wolterbeek, T. K. T., Cahill, A., Cavanagh, A., Moghadam, A., Iyer, J., Jordan, P., & Pawar, R. (2026). A decade of progress in understanding and managing legacy well integrity for geologic carbon storage. *International Journal of Greenhouse Gas Control*, *151*, 104604. https://doi.org/10.1016/j.ijggc.2026.104604

Le Guenan, T., Gravaud, I., & Eguilor, S. (2024). *D5.1_PilotSTRATEGY_Methodological guidelines for risk assessment*. https://doi.org/10.5281/zenodo.12634006

Loizzo, M. (2024, juillet). *Can we use permeability with microannuli?* https://www.linkedin.com/pulse/can-we-use-permeability-microannuli-matteo-loizzo-3camf/?trackingId=KKj5x6UGQ9ib05tVMYOvaw%3D%3D

Masson, C., Mazzotti, S., Vernant, P., & Doerflinger, E. (2019). Extracting small deformation beyond individual station precision from dense Global Navigation Satellite System (GNSS) networks in France and western Europe. *Solid Earth*, *10*(6), 1905-1920. https://doi.org/10.5194/se-10-1905-2019

Mathurin, F., Carneiro, J., López-Gutiérrez, J., Matos, C., & Moreno, I. (2023). *D2.11_PilotSTRATEGY_Regional_Hydrogeological_Systems_Final*. https://doi.org/10.5281/zenodo.12625553

Metcalfe, R., Maul, P. R., Benbow, S. J., Watson, C. E., Hodgkinson, D. P., Paulley, A., Limer, L., Walke, R. C., & Savage, D. (2009). A unified approach to Performance Assessment (PA) of geological CO2 storage. *Energy Procedia*, *1*(1), 2503-2510.

Moghadam, A., & Amiri, S. (2025). Quantitative assessment of well leakage, part II : Case studies for CCS. *Geomechanics for Energy and the Environment*, *42*, 100675. https://doi.org/10.1016/j.gete.2025.100675

Moghadam, A., & Loizzo, M. (2024). Quantitative assessment of well leakage, part I : Cement stress evolution. *Geomechanics for Energy and the Environment*, *40*, 100586. https://doi.org/10.1016/j.gete.2024.100586

Nicot, J.-P., Oldenburg, C. M., Bryant, S. L., & Hovorka, S. D. (2009). Pressure perturbations from geologic carbon sequestration : Area-of-review boundaries and borehole leakage driving forces. *Energy Procedia, Greenhouse Gas Control Technologies 9*, *1*(1), 47-54. https://doi.org/10.1016/j.egypro.2009.01.009

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Preuß, S., Kappler, L., Delicado, A., Dütschke, E., Gonçalves Oliveira, L., López Asensio, S., Mays, C., Oltra, C., Poumadère, M., Rowland, J., BORDENAVE, A., Fernández-Canteli Álvarez, P., Carneiro, J., Gravaud, I., Koukouzas, N., Manoukian, E., Maraslidis, G. S., Stergiou, C. L., Stańczyk, K., & Strugała-Wilczek, A. (2026). *D6.4 Stakeholder engagement—Regional committees*. https://doi.org/10.5281/zenodo.18772600

Rasmussen, A. F., Sandve, T. H., Bao, K., Lauser, A., Hove, J., Skaflestad, B., Klöfkorn, R., Blatt, M., Rustad, A. B., Sævareid, O., Lie, K.-A., & Thune, A. (2021). The Open Porous Media Flow reservoir simulator. *Computers & Mathematics with Applications, Development and Application of Open-source Software for Problems with Numerical PDEs*, *81*, 159-185. https://doi.org/10.1016/j.camwa.2020.05.014

Réveillère, A. (2013). Semi-analytical Solution for Brine Leakage Through Passive Abandoned Wells Taking Account of Brine Density Differences. *Transport in Porous Media*, *100*(2), 337-361. https://doi.org/10.1007/s11242-013-0221-3

Rohmer, J., & Bouc, O. (2010). A response surface methodology to address uncertainties in cap rock failure assessment for CO2 geological storage in deep aquifers. *International Journal of Greenhouse Gas Control, The Ninth International Conference on Greenhouse Gas Control Technologies*, *4*(2), 198-208. https://doi.org/10.1016/j.ijggc.2009.12.001

Ron Martín, M., Chávez Nuñez, S., De Faria, B., Canteli, P., Le Gallo, Y., Casacão, J., Caeiro, M. H., Varelas, F., Carneiro, J., Carro, A., Mesquita, P., Soni, G., Veloso, R., Afonso, P., Madureira, P., Śliwińska, A., Krawczyk, P., Tartaras, E., Ktenas, D., … Koukouzas, N. (2026). *Permit Dossier : Operations, logistics and well maintenance plans description, Well permits road map, MMV plan and HSE, emergency response and well containment plans.* (Deliverable 4.6; p. 169). H2020 project PilotSTRATEGY.

Shapiro, S. A., Dinske, C., Langenbruch, C., & Wenzel, F. (2010). Seismogenic index and magnitude probability of earthquakes induced during reservoir fluid stimulations. *The Leading Edge*, *29*(3), 304-309. https://doi.org/10.1190/1.3353727

Song, J., & Zhang, D. (2013). Comprehensive Review of Caprock-Sealing Mechanisms for Geologic Carbon Sequestration. *Environmental Science & Technology*, *47*(1), 9-22. https://doi.org/10.1021/es301610p

Sonke, J., Bos, W. M., & Paterson, S. J. (2022). Materials challenges with CO2 transport and injection for carbon capture and storage. *International Journal of Greenhouse Gas Control*, *114*, 103601. https://doi.org/10.1016/j.ijggc.2022.103601

Timur, A. (1968, juin 23). *An Investigation Of Permeability, Porosity, And Residual Water Saturation Relationships*. SPWLA 9th Annual Logging Symposium. https://dx.doi.org/

Veloso, F., Estublier, A., Bonte, D., Mathurin, F., Frey, J., Maury, J., Poumadère, M., & Stephan, S. (2021). *D2.1 - Target area of Paris Basin Region (FR) : Data inventory, seismic target and GAP analysis*. https://doi.org/10.5281/zenodo.12625233

Vilarrasa, V., Carrera, J., Bolster, D., & Dentz, M. (2013). Semianalytical Solution for CO2 Plume Shape and Pressure Evolution During CO2 Injection in Deep Saline Formations. *Transport in Porous Media*, *97*(1), 43-65. https://doi.org/10.1007/s11242-012-0109-7

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Wu, H., Vilarrasa, V., De Simone, S., Saaltink, M., & Parisio, F. (2021). Analytical Solution to Assess the Induced Seismicity Potential of Faults in Pressurized and Depleted Reservoirs. *Journal of Geophysical Research: Solid Earth*, *126*(1), e2020JB020436. https://doi.org/10.1029/2020JB020436

Zhai, G., Shirzaei, M., Manga, M., & Chen, X. (2019). Pore-pressure diffusion, enhanced by poroelastic stresses, controls induced seismicity in Oklahoma. *Proceedings of the National Academy of Sciences*, *116*(33), 16228-16233. https://doi.org/10.1073/pnas.1819225116

7. APPENDIX

7.1 Preliminary risk assessment appendix

7.1.1 Review of models for abandoned wells risk analysis

As part of round 1, we also reviewed the literature regarding risk analysis of wells, particularly for models of leaking wells. Here we mean both potential existing codes that we could use to simulate a leak, or conceptual models that can help in better identify the exact risk scenarios (i.e. the list of cause-events-consequences).

Regarding, the latter, Figure 43 shows a systematic identification of various pathways. This can be considered for a more detailed assessment in the second round.

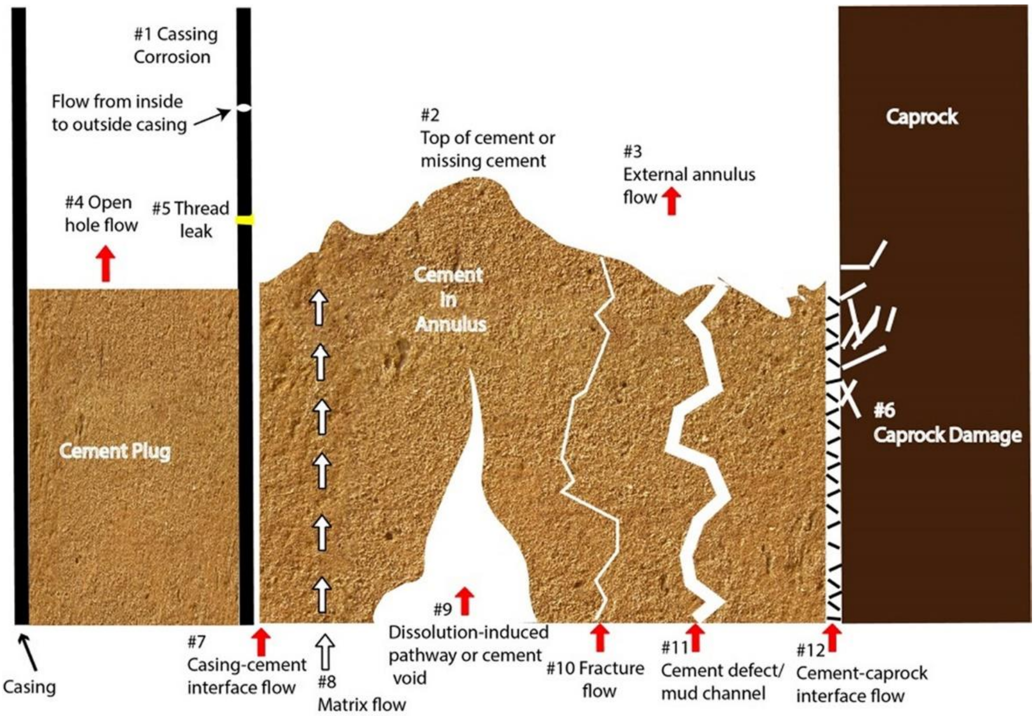

Figure 43: identification of potential pathways for leak through wellbores (Gholami et al., 2021)

Regarding potential codes or models that can be used for modelling leakage through wells, Doherty *et al.* (2017) describe a tool for well leakage : well leakage analysis tool (WLAT). It proposes four types of models ("cemented wellbore model", "multisegmented wellbore model", "open wellbore model" and "brine leakage model") based on previous references (not repeated here). The tool is available online on the NRAP (National Risk Assessment Partnership) webpage. While it is certainly a great help for our study, all the models rely on an equivalent permeability to represent the leak path. It facilitates computing, but some experts believe it can underestimate the amount of CO_2 leaking in an annulus (Loizzo, 2024). A search did not bring any results regarding useable code to model annulus. The previous reference however provides the equations that can be used to improve simulation with respect to equivalent permeability.

7.1.2 Analytical model of caprock risk analysis

We considered the following values for a preliminary assessment:

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Table 13: values used for determining critical pressures

Variable	Value	Reference / justification
Depth	1800 m	WP2
Vertical stress gradient	0.0245 MPa / m	(Rohmer & Bouc, 2010)
Horizontal stress to vertical stress ratio	0.5 to 1.0	(Rohmer & Bouc, 2010)
Hydrostatic pressure gradient	0.01 MPa / m	Typical value
Poro-elastic coefficient b0	0.55	(Hannon & Esposito, 2015b)
Coefficient of static friction	0.6	(Hannon & Esposito, 2015b)
Fault orientation angle	0° to 180°	All possible values

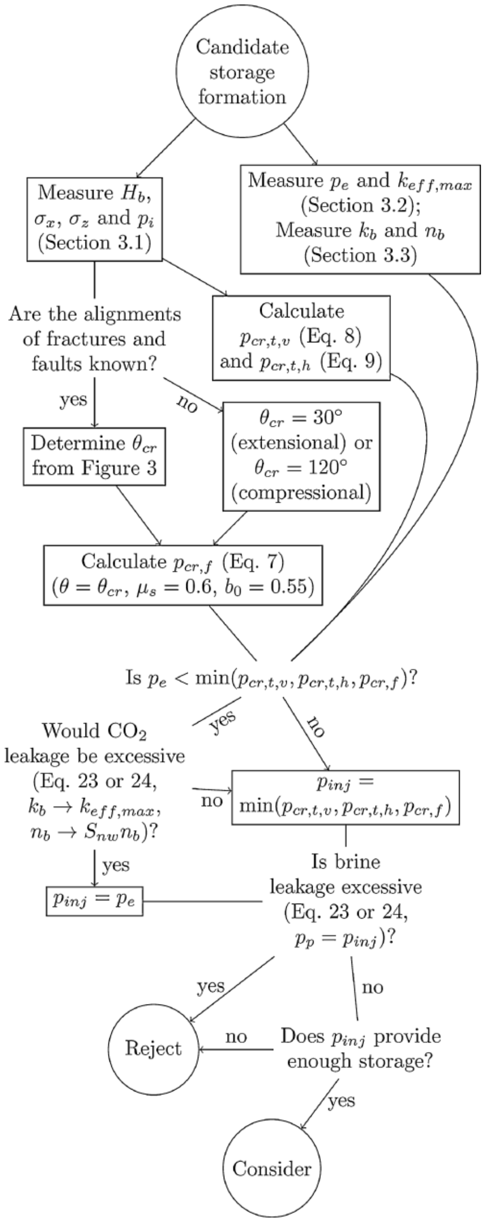

Figure 44: workflow for determining design criteria for caprock (Hannon & Esposito, 2015b)

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Regarding the case of fault re-activation, we computed equation (7) of Hannon *et al.* (2015) as a function of the ratio of horizontal stress to vertical stress (between 0.5 and 1.0), as well as potential orientation of an existing fault (all possible values). The results are displayed in Figure 45. It shows the critical pressure as a multiple of initial pressure. Therefore, the limit according to this model is above twice the initial pressure except for the lowest value of horizontal stress and for a critical orientation of the fault around 30°. As a reminder, there is currently no known fault in the zone so a full risk assessment should also consider the chance of such a fault existing and not being detected.

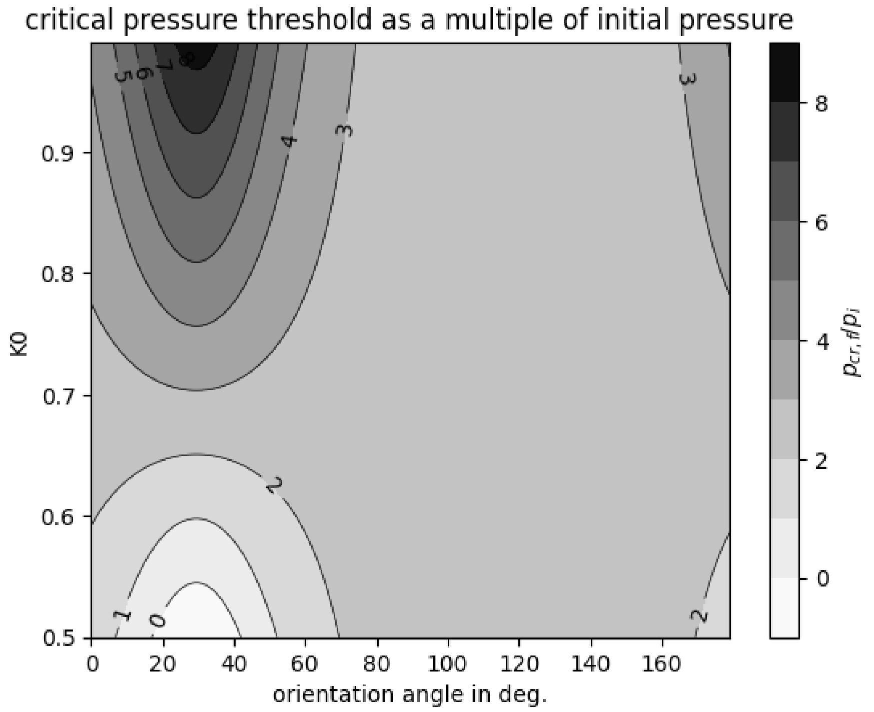

Figure 45: critical pressure threshold for re-activation of existing faults

Regarding the risk of tensile fracture, we computed equation (8) of Hannon *et al.* (2015) as a function of the value of horizontal stress (Figure 46). The minimum value again corresponds to the lowest value of horizontal stress. The result is just above 1,5 times the initial pressure.

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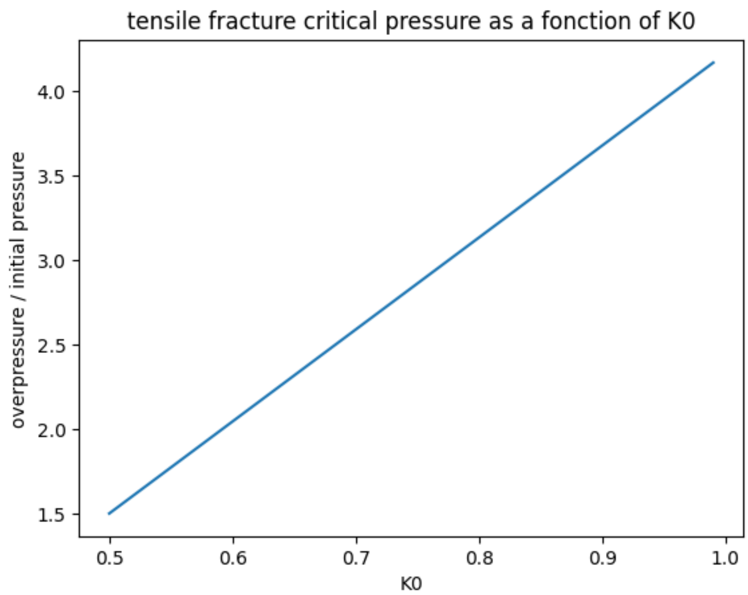

Figure 46: tensile fracture critical pressure as a function of the ratio of horizontal stress to vertical stress

7.2 Risk assessment appendix: Modelling approach and uncertainties

7.2.1 Uncertain parameters of the reference model used for most of the risk events

The set of uncertain parameters used in this probabilistic workflow reflects the variable subsurface properties and furthermore the luck of site-specific data. These parameters control the behaviour of the reservoir in terms of injectivity, pressure evolution, fluid flow… The uncertainty ranges were defined using the combination of:

- Experimental data obtained on representative samples of Dogger formations,
- Correlations from the literature
- Analogues from similar geological formations
- Expert judgement where measurements were not available

Relative permeability parameters:

Relative permeability and saturation functions are described using a modified Van Genuchten formulation and empirical correlations.

- The irreducible water saturation (Swi) is derived from the correlation proposed by (Timur, 1968), calibrated using experimental data and adapted for each reservoir formation.
- The modified Van Genuchten parameter (m) is based on laboratory measurements performed on Lavoux limestone samples (André et al., 2007). For formations lacking data, representative values were assigned based on analogues.
- The residual gas saturation (Sgr) is defined within a broad range to reflect variability in multiphase flow behaviour.

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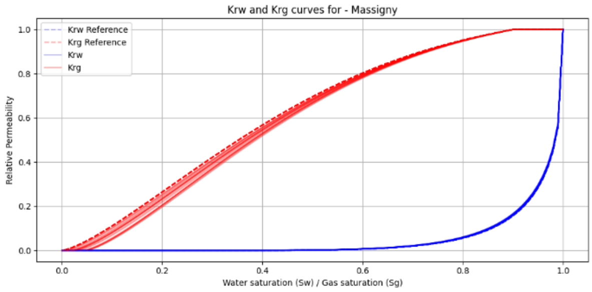

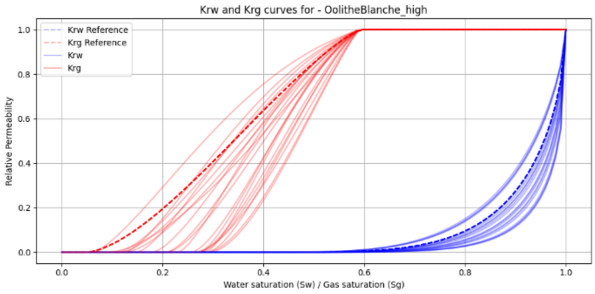

Capillary pressure parameters:

Capillary pressure is modelled using a standard Van Genuchten–Mualem formulation. The entry pressure (Pe) is estimated using the Leverett (1941) scaling function, based on petrophysical properties of the formations. Experimental data from the Oolithe Blanche formation are used as a reference, while values for other layers are derived from the literature.

A wide uncertainty range is applied to account for heterogeneity across formations and limited direct measurements.

Permeability and anisotropy:

Permeability is one of the most uncertain parameters in the model. The permeability-porosity is a key driver of reservoir behaviour, as it directly controls fluid mobility, injectivity, pressure propagation, and CO_2 plume migration. In this study, permeability is a relationship defined using empirical laws specific to each geological facies (Massingy, Dallenacree, Comblanchien, Oolithe formations). These relationships take the exponential form: $K = a\, e^{b\phi}$, where: a and b are empirical coefficients, ϕ is porosity, K is permeability. The relationships for the different formations are derived from the core experimental measurements. However, these relationships are poorly constrained due to limited core data and are therefore sampled using truncated normal distributions. The scatter observed in experimental data (Figure X) highlights the intrinsic variability of permeability for a given porosity. To account for this variability, uncertainty is introduced on the k–ϕ relationships through variation of the coefficients a and b using truncated normal distributions application of a global permeability multiplier.

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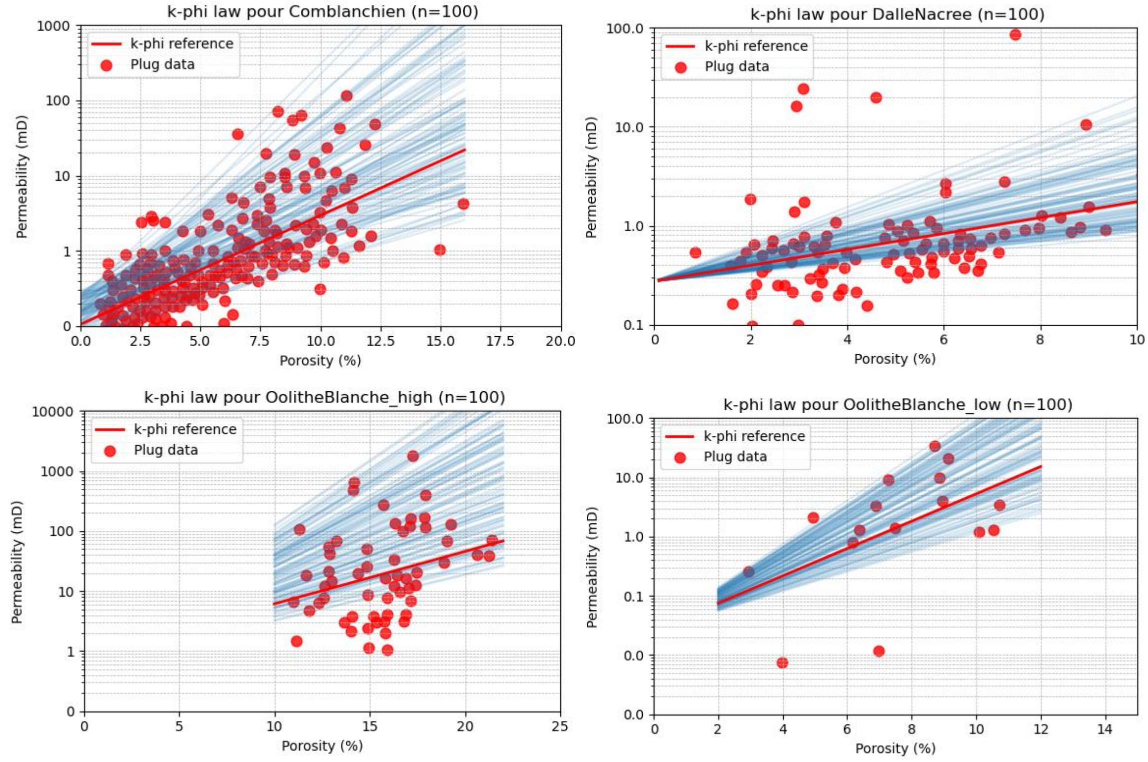

Permeability anisotropy is introduced to account for stratification effects in the Comblanchien formation, with values ranging typically between 0.3 and 3, based on literature (Delmas et al., 2010).

The uncertainty in permeability is also considered for caprock formations (Callovo-Oxfordian, COX) and marls (Massingy): COX permeability values (~10^{-17} m², (Gonçalvès et al., 2003)) are relatively high for a sealing formation and may allow pressure propagation into the lower caprock. However, the literature values show a wide range (10^{-21} to 10^{-18} m²) from (Fleury et al., 2023), or from ANDRA site measurements with a range between 10^{-21} and 10^{-19} m² (Jougnot et al., 2009), highlighting significant uncertainty for the caprock. Similarly, Massingy marls exhibit permeability values spanning several orders of magnitude depending on the source, which is incorporated into the uncertainty analysis. A global permeability multiplier is also used to represent large-scale variability not captured by local correlations.

Fluid and thermodynamic properties

Key fluid properties for the **wastewater injection** include well activity is represented as a binary variable (active/shut-in), allowing the modelling of operational uncertainties. Injection rate is varied within operational bounds to represent potential variability in injection performance

CO_2 injection conditions are also treated probabilistically mainly through: Injection duration is defined according to the scenario (pilot vs. commercial). Salinity, which is assumed to range between approximately 17 and 23 g/L in the study area, based on regional data and confirmed by nearby wells. Temperature, which is treated as an uncertain parameter using a normal distribution, reflecting limited knowledge of operational constraints.

These parameters influence fluid density, viscosity, and phase behaviour, and therefore affect injectivity and pressure evolution.

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Derived parameters and compressibility:

Pore compressibility values are defined per facies, using representative average values. These parameters control the storage capacity of the reservoir and the response to pressure changes. Given the limited availability of direct measurements, these values are treated as uncertain and may contribute significantly to variability in pressure build-up.

The Table 14 presents the set of parameters defined for the different geological formations. Parameters treated as uncertain within the Monte Carlo framework are highlighted in bold and underlined, while underlined parameters denote values that were selected based on expert judgment in the absence of site-specific data but no included in this study. Table 15 provides the corresponding probability distributions used to describe these uncertainties. The parameter distributions are sampled independently within the Monte Carlo framework.

Table 14: List of parameters' value for different formations

Parameter		Formation's values						
		COX	Mas	DN	Camb	OBHP	OBLP	LB
Relative permeability	Swi	0,1	0,1	0,37	0,43	**0,41 ≠ data from Andre et al 2007**	0,38	0,42
	parameter m	0,39	0,39	0,60	0,60	**0,60**	0,60	0,60
	Sgr	0	0	0,05	0,05	**0,05**	0,05	0,05
	Krg,max	1	1	1	1	1	1	1
	Krw,max	1	1	1	1	1	1	1
Capillary pressure	Pe (Pa)	4.20E+06	**7.24E+04**	7.44E+03	8.59E+03	2.52 E+03	1.44E+04	1.23E+04
Permeability anisotropy		1	1	1	1	1	1	1
Permeability		**Perm Mult by 0.005-1**	a	**a, b**	**a, b**	**a, b**	**a, b**	**a, b**
Salinity		**The chosen salinity 0.019 kg/L (BRGM, 2001)**						
Pore compressibility values		Mean value per facies						
Temperature of CO_2		**60 °C**						
Injection period and rate CO_2		**4 months or 30 years**						

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is SEIF1 active?	Active (for 10 years) or shut
Water injection rate	Daily or monthly rate

Table 15: The uncertain variables used in the Monte Carlo framework and their distribution

Variable	Distribution
temperature	Normal (μ=50, σ=5)
well_active	Bernoulli (p=0.5)
rate_water	Uniform (--, --)
mult_COX	Uniform (0.005, 1)
a_Massingy	Uniform (0.00001, 0.05)
a_dallenacree	TruncatedNormal (μ=0.2747, σ=0.1, min=0.2477, max=0.3017)
b_dallenacree	TruncatedNormal (μ=0.1852, σ=0.1, min=0.1672, max=0.2032)
a_comblanchien	TruncatedNormal (μ=0.1047, σ=0.1, min=0.0947, max=0.1147)
b_comblanchien	TruncatedNormal (μ=0.334, σ=0.1, min=0.0301, max=0.367)
a_oolithe_high	TruncatedNormal (μ=0.8226, σ=0.1, min=0.7406, max=0.9026)
b_oolithe_high	TruncatedNormal (μ=0.2009, σ=0.1, min=0.1809, max=0.2209)
a_oolithe_low	TruncatedNormal (μ=0.0261, σ=0.1, min=0.0231, max=0.0291)
b_oolithe_low	TruncatedNormal (μ=0.5305, σ=0.1, min=0.4775, max=0.5835)
a_lower_bathonien	TruncatedNormal (μ=0.01, σ=0.1, min=0.009, max=0.011)
b_lower_bathonien	TruncatedNormal (μ=0.5, σ=0.1, min=0.45, max=0.55)
m_OolitheBlanche_high	Uniform (0.4, 0.7)
Sgr_OolitheBlanche_high	Uniform (0.05, 0.3)
Pe_ Massingy	Uniform (0.05, 4.2)
Anisotropy	Uniform (0.1, 3.0)
Salinity	Uniform (0.3080, 0.3422)

Figure 47 illustrates an example of random sampling of uncertain parameters for the pilot scenario. Each realization corresponds to a unique combination of input parameters drawn from their respective probability distributions.

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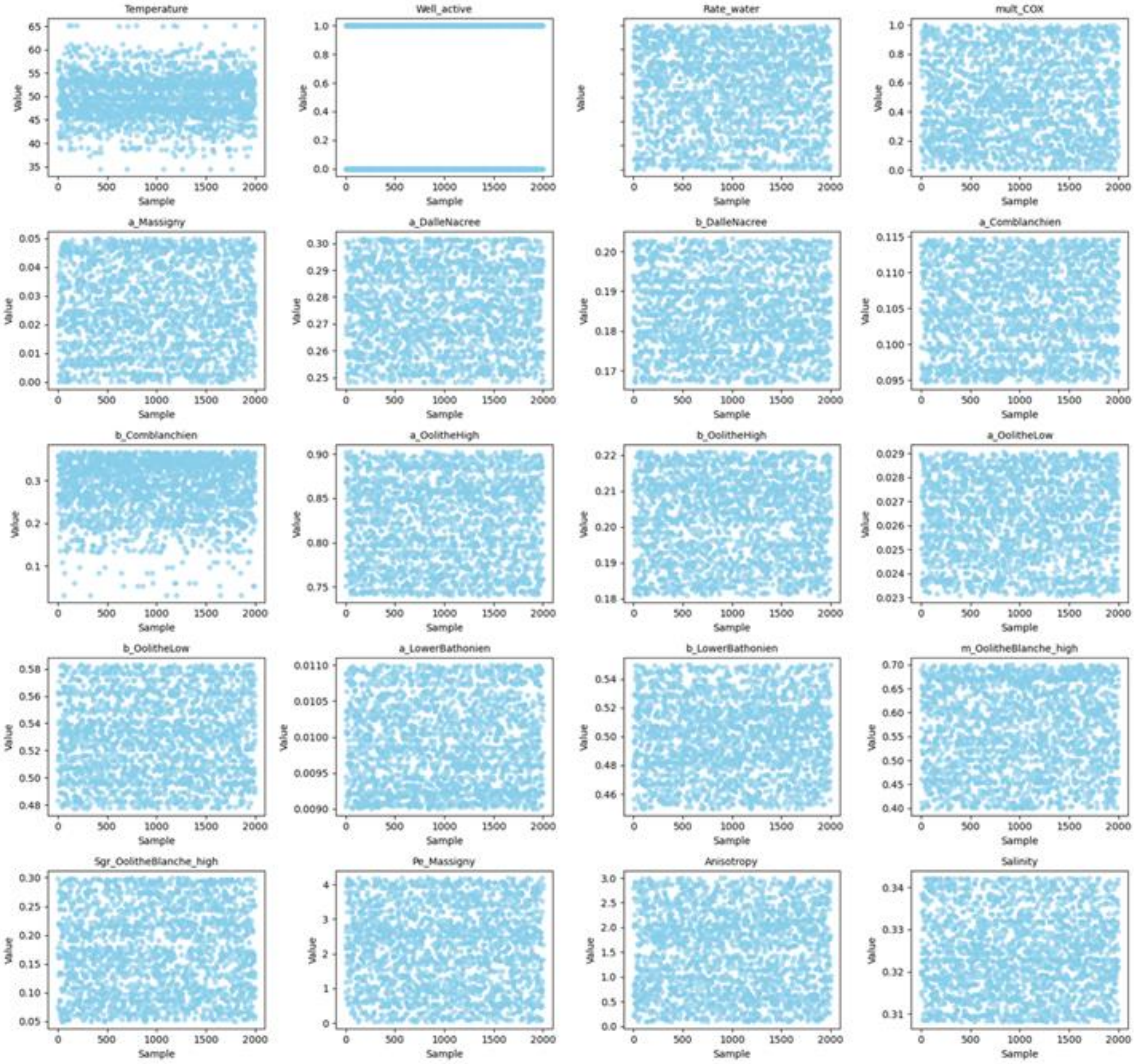

Figure 47: Monte Carlo sampling for the pilot scenario

7.2.2 Analytical models for induced seismicity and surface ground movement:

The risks related to induced seismicity and surface ground movement are evaluated using analytical models driven by the reservoir pressure response. These models rely on simplified physical formulations and a set of uncertain parameters introduced within the Monte Carlo framework.

The parameters presented in the following tables correspond to the uncertain variables used in the Monte Carlo framework for the assessment of induced seismicity.

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Table 16: Monte Carlo Parameters for Induced Seismicity

Category	Parameter	Symbol	Distribution	Range / Values	Comment
Reservoir	Overpressure	ΔP	Empirical (OPM flow) / Log-normal		Derived from simulations (max over time)
Stress state	Minimum horizontal stress ratio	Sh/Sv	Truncated normal	0.55 – 0.85	Expert judgement
Rock properties	Biot coefficient	α	Truncated normal	0.6 – 1.0	Expert judgement
Rock properties	Poisson’s ratio	ν	Truncated normal	0.15 – 0.35	Expert judgement
Fault mechanics	Friction coefficient	μ	Truncated normal	0.4 – 0.85	Expert judgement
Fault mechanics	Cohesion	C	Truncated normal	0 – 2	Weak faults assumed
Fault geometry (S1)	Fault dip	–	Uniform	50 – 85	
Fault geometry (S1)	Fault length	L	Derived	50 – 4000	
Fault geometry (S2)	Distance to reservoir	d	Uniform	200 – 5000	
Hydraulics	Diffusivity	D	Truncated normal	0.01 – 1.0	Expert judgement
Seismicity (S3)	Seismogenic index	Σ	Truncated normal	-10 – 0	Expert judgement
Seismicity (S3)	b-value	b	Truncated normal	0.6 – 1.5	Expert judgement
Injection	Injection rate	Q	Normal	scenario-dependent	Decision

The parameters presented in the following tables correspond to the uncertain variables used in the Monte Carlo framework for the assessment of surface ground movement.

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Table 17: Monte Carlo Parameters for Surface Ground Movement

Category	Parameter	Symbol	Distribution	Range / Values	Comment
Reservoir	Overpressure	ΔP	Empirical (OPM flow) / Log-normal	Same as seismicity	
Reservoir	Thickness	H	Truncated normal	80 – 180	
Geometry	Plume radius	R	Truncated normal	500 – 6000	
Geometry	Reservoir depth	D	Normal	1500 – 2000	
Rock properties	Biot coefficient	α	Truncated normal	0.6 – 1.0	
Rock properties	Poisson's ratio	ν	Truncated normal	0.15 – 0.35	
Rock properties	Young's modulus (reservoir)	E_res	Truncated normal	5000 – 35000	
Rock properties	Young's modulus (overburden)	E_ovb	Truncated normal	3000 – 20000	
Model	Amplification factor	A	Truncated normal	0.8 – 2.5	

7.2.3 Sensitivity analysis

The Figure 48 presents the relative importance of input parameters based on a Random Forest model applied to several wells. The results for the SEIF1 scenario indicate that several parameters contribute comparably to the model response, with no single dominant driver clearly emerging. This suggests a distributed sensitivity of the system, reflecting the combined influence of the identified uncertainties. Differences between model-based importance and permutation importance highlight potential interactions between parameters. For the IVY1D, GDB1D and BIS1 cases, the results highlight variability in parameter influence, with several parameters contributing significantly to the model response.

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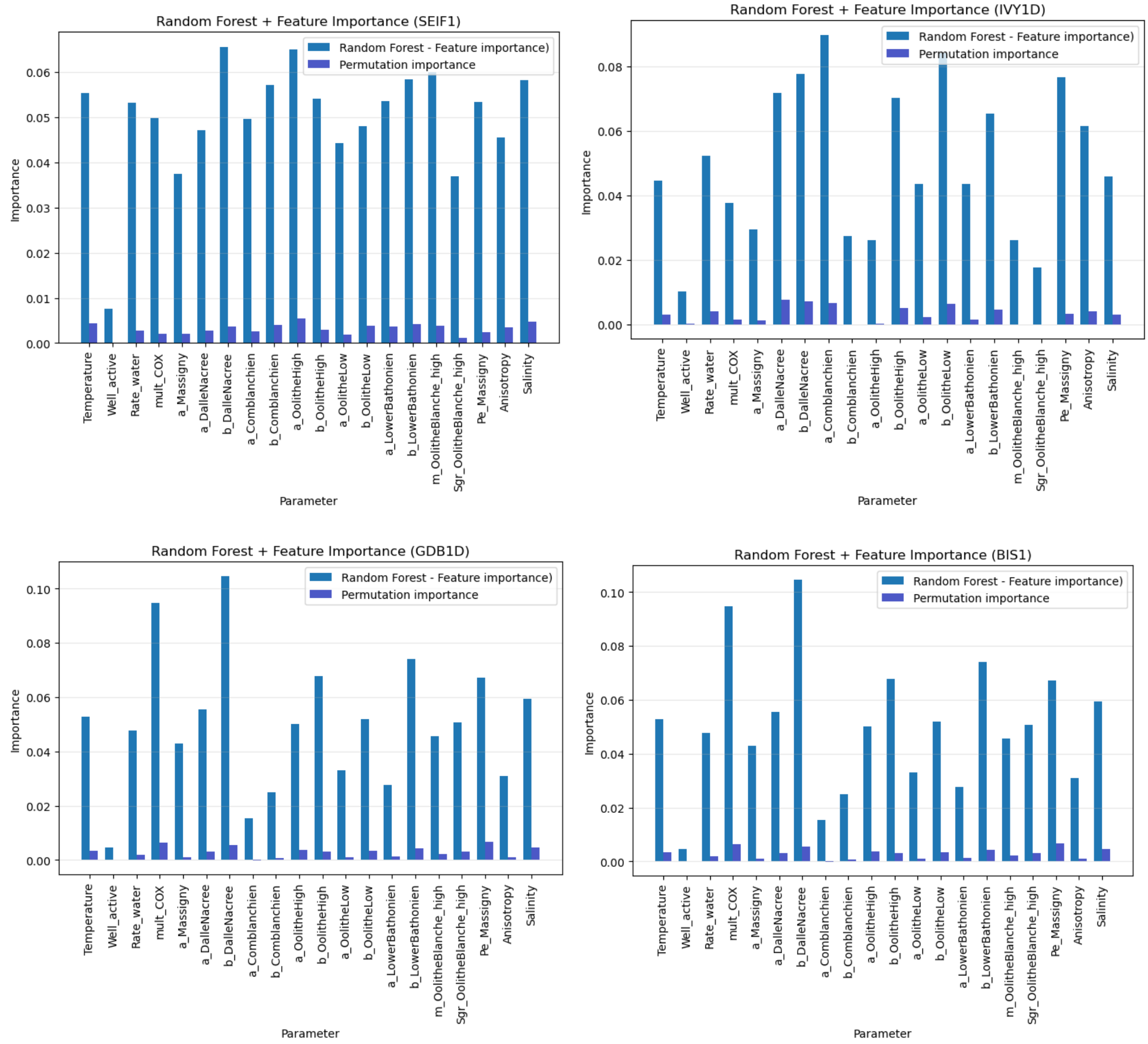

Figure 48: Feature importance from Random Forest analysis for the different wells present in the area: SEIF1, IVY1D, GDB1D, and BIS1 respectively.

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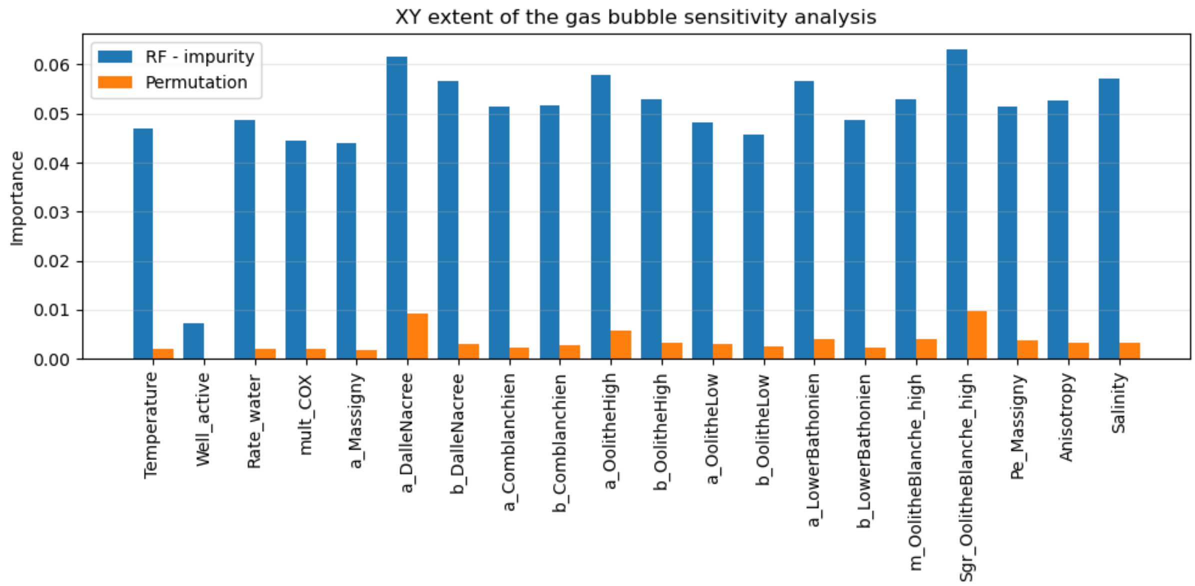

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