



## Risk assessment for a conceptual CO<sub>2</sub> storage project in a mature oil field in India

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### Summary

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The current study presents a comprehensive risk assessment framework for a conceptual CO<sub>2</sub> storage project in the Gandhar Field, located in the Cambay Basin, India. The project aims to repurpose a mature hydrocarbon-producing field for CO<sub>2</sub>-enhanced oil recovery and long-term storage, aligning with global CCUS strategies for climate change mitigation. The geological model of the site consists of a sequence of sand units interspersed with marine shale layers. The project concept involves injecting 15 Mt CO<sub>2</sub> over 25 years, targeting depleted reservoirs and saline aquifers within the Hazad Member. The risk assessment focuses on identifying and mitigating key risks, including CO<sub>2</sub> leakage through existing faults and fractures and lateral migration beyond the storage complex. A risk matrix is used to rank the risks based on probability and severity, guiding the development of mitigation strategies. Enhanced monitoring, acquisition of additional seismic data, and pressure barrier analysis to prevent fault reactivation are identified as essential mitigation strategies. The study highlights the importance of rigorous risk management to ensure the safety and effectiveness of CO<sub>2</sub> storage in the Gandhar Field, which can provide insights into advancing CCUS projects in mature oil and gas fields globally.



## **Risk assessment for a conceptual CO<sub>2</sub> storage project in a mature oil field in India**

### **Introduction**

With its vast CO<sub>2</sub> storage potential, India is actively exploring CCUS opportunities, particularly in mature oil and gas fields (Vishal et al., 2023, 2021). This study presents a comprehensive risk assessment for a conceptual CO<sub>2</sub> storage project in the Gandhar Field, located in the Cambay Basin, India. The Gandhar Field, operational since 1986, is a mature field with over 700 wells drilled and has been identified as a potential pilot site for CO<sub>2</sub>-enhanced oil recovery (CO<sub>2</sub>-EOR) and storage in India's CCUS roadmap (Mishra et al., 2023; NITI Aayog, 2022).

The Cambay Basin, a proven hydrocarbon province, offers significant potential for CO<sub>2</sub> storage due to its well-characterized geology and existing infrastructure (Jaiswal et al., 2018). The Gandhar Field, in particular, is an attractive candidate for CO<sub>2</sub> storage due to its depleted reservoirs, saline aquifers, and well-defined stratigraphic seals (Vishal et al., 2024). However, the successful implementation of CO<sub>2</sub> storage projects requires a thorough understanding of the associated risks, including containment, leakage, and environmental impacts. The current study aims to address these challenges by first defining a conceptual CO<sub>2</sub> storage project within the depleting Gandhar Field. Next, a detailed risk assessment is conducted to identify and quantify the associated risks. Finally, a portfolio of mitigation strategies has been developed to reduce these risks and ensure the safety and effectiveness of the storage site.

### **Conceptual CO<sub>2</sub> storage project**

The Gandhar Field is characterized by a complex geological architecture that includes a sequence of pay sand units interspersed with marine shale layers. In the developed conceptual model, the primary reservoir is the Hazad Member, while the Kanwa Shale acts as the seal. The sandstones of the Ardol Member, above Kanwa Shale, act as the secondary storage reservoir, and the Telwa Member on top of it acts as the seal. The theoretical storage capacity of the primary reservoir in Hazad Member is estimated to be approximately 1550 Mt CO<sub>2</sub>. However, an effective storage capacity of around 15 Mt CO<sub>2</sub> is assumed when considering a conservative 1% operational efficiency. Based on an initial fault slip potential analysis, this capacity would be able to support an injection rate of over 0.6 Mt/year. This allows planning a long-term plan to inject 15 Mt CO<sub>2</sub> over a period of 25 years through a minimum of two strategically located wells targeting the lower sand units within the Hazad Member.

### **Risk assessment**

The risk assessment framework employed in this study is rooted in geological evaluation and risk management principles as prescribed by the EC Storage Directive (European Commission, 2011). The approach integrates multidisciplinary analysis, including geological modelling, petrophysical analysis, and dynamic reservoir simulation, to understand the inherent threats to CO<sub>2</sub> containment and leakage in the storage complex.

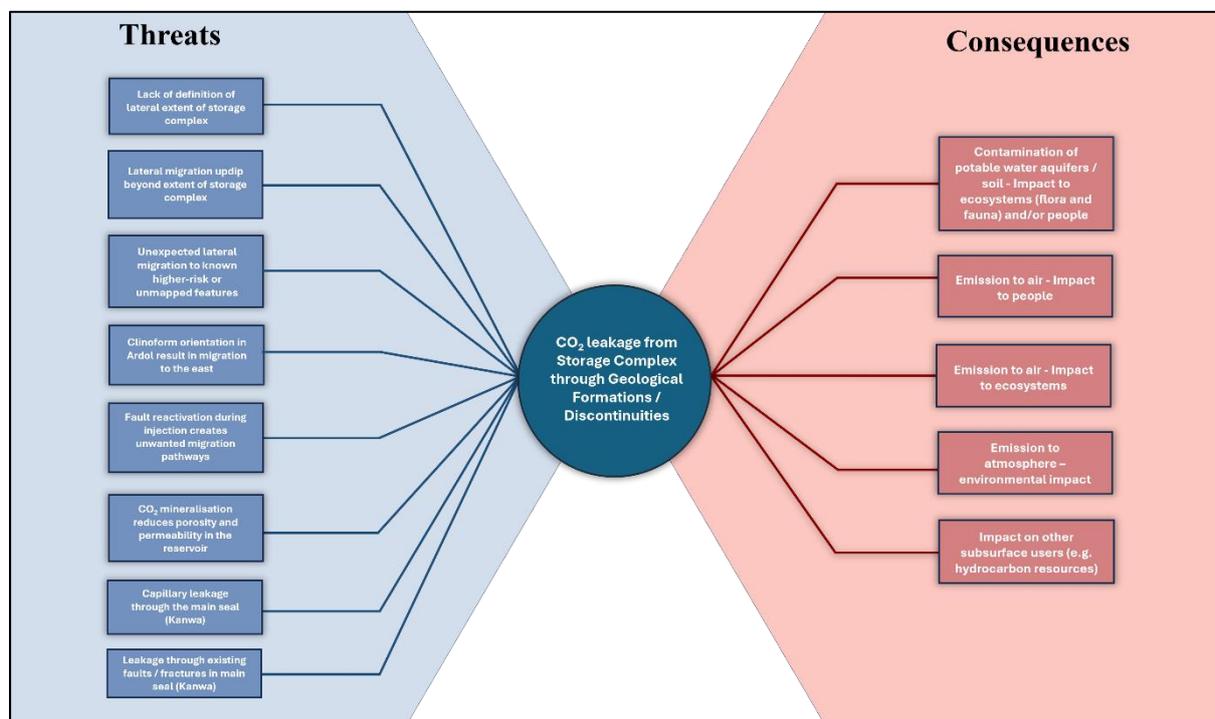
A key feature of the risk assessment process is the identification and quantification of potential leakage pathways. The framework addresses several fundamental questions: Does the geological model incorporate all existing and potential future leakage routes, such as faults, fractures, and legacy wellbores? What is the potential magnitude of leakage events for each identified pathway? Is the storage capacity estimated consistent with the maximum allowed reservoir pressure levels? A comprehensive risk register developed as part of this study serves as a dynamic tool that captures the full spectrum of identified risks. Each risk entry in the register includes detailed descriptions of the initiating causes, the resulting hazards, and the designated barriers for prevention and mitigation. Furthermore, the study employs a risk matrix in which each potential hazard is characterized by a probability and severity rating. This quantification enables a systematic ranking of risks and informs the allocation of resources towards the most critical mitigation strategies.



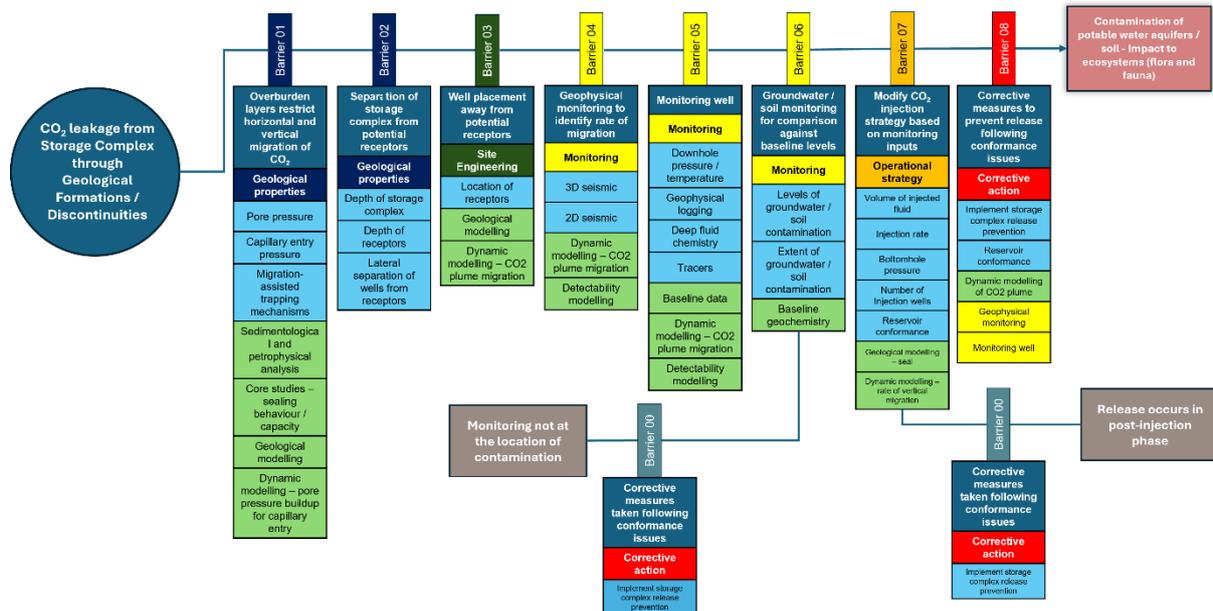
For instance, one of the primary concerns is the lateral migration of CO<sub>2</sub> beyond the confines of the storage complex, a scenario that could result from leakage through existing faults or capillary leakage across the main seal, among other causes. The risk assessment process identifies the critical parameters such as maximum reservoir pressure, injection rate, and the degradation factors that may compromise the sealing integrity of the overburden. This approach facilitates a comprehensive understanding of both the direct risks associated with CO<sub>2</sub> leakage and the environmental and health impacts that may ensue, such as the potential contamination of potable water aquifers and adverse ecological effects due to the mobilization of heavy metals or other contaminants.

## Bowtie risk analysis

The methodological framework is further supplemented through a bowtie risk analysis, which visually represents the causal pathways leading to potential failure events and delineates the corresponding preventive and mitigative barriers. In the bowtie analysis, the central event—such as leakage through geological formations/discontinuities—is surrounded by a series of threats that could trigger the event and the consequences that may arise from it (Figure 1). A series of identified prevention and mitigation barriers counter each threat, and the effectiveness of these barriers is evaluated in terms of their ability to prevent the occurrence of the adverse event or mitigate its consequences. Figure 2 shows the barriers (colour-coded according to their type) for the event to cause contamination of potable water aquifers or soil. It also highlights the degradation factors (in brown) that can negatively affect the barriers, and furthermore, barriers to the degradation factors. This approach identifies the vulnerabilities within the storage system and highlights areas where additional monitoring or further studies are necessary. The collaborative nature of the risk assessment process is underscored by the participation of experts from different disciplines, who contributed to the workshops and review sessions that refined the risk matrix and the associated mitigation measures.



**Figure 1** Example of a master bowtie for the event, CO<sub>2</sub> leakage from the storage complex through geological formations. The left side of the bowtie details the threats that might cause the event, and the right side details the consequences of the event occurring.



**Figure 2** The barriers between the event, CO<sub>2</sub> leakage through geological formations, and the consequence of contamination of potable water aquifers or soil. The barriers are colour-coded according to their type. The degradation factors are shown in brown, and the barriers to the degradation factors are listed as well.

## Research directions for mitigation of identified risks

In addition to the immediate risk mitigation strategies, the study outlines an extensive roadmap for future research aimed at reducing the uncertainties that currently limit the predictive capabilities of the geological and reservoir models. Future research directions are organized into several key areas, each addressing specific aspects of the storage system. One area of focus is the enhancement of seismic data acquisition and processing techniques, which are essential for extending the geological model in the updip direction and for identifying previously unmapped faults and fractures. Detailed core sample analysis from the Kanwa Shale is also recommended to provide direct insights into the petrophysical properties of the cap rock, including porosity, permeability, and capillary entry pressures. These investigations are expected to refine the estimation of the effective storage capacity and to enhance the understanding of the mechanical properties of the seal, thereby reducing the risk of unexpected leakage.

Another critical research direction involves dynamic modelling of CO<sub>2</sub> plume migration within the reservoir. Advanced numerical simulations are proposed to capture the risks involved in injection-induced pressure build-up combined with the heterogeneity of the reservoir. Such models are expected to quantify the effectiveness of various trapping mechanisms, including migration-assisted trapping and stratigraphic trapping, in limiting the lateral spread of the injected CO<sub>2</sub>. By incorporating real-time monitoring data, these models can be continually updated to reflect the evolving conditions within the reservoir, thus providing a robust framework for adaptive risk management over the lifespan of the project.

## Conclusions

In conclusion, this study presents a detailed risk assessment framework for a conceptual CO<sub>2</sub> storage project in the Gandhar Field, that identifies the major geological, reservoir, and operational factors that affect the safety and efficacy of CO<sub>2</sub> sequestration. The study identifies the critical risks associated with CO<sub>2</sub> storage and proposes a series of mitigation measures and future research studies aimed at reducing



these uncertainties. The integrated risk management process, which combines quantitative risk ranking with a bowtie analysis approach, has proven instrumental in highlighting the areas where further analysis and targeted research are most urgently needed. The implications of this work extend beyond the immediate context of the Gandhar Field, offering a scalable framework that can be adapted and applied to CO<sub>2</sub> storage projects in varied geological settings around the world. As the global community continues to pursue ambitious climate change mitigation strategies, the insights presented in this work are expected to play a crucial role in advancing the safety and reliability of CCUS technologies.

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