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GEOLOGICAL RISK ASSESSMENT FOR CARBON STORAGE INTEGRITY IN DEPLETED U.S. OIL AND GAS RESERVOIRS

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ABSTRACT

Geological carbon storage (GCS) in depleted U.S. oil and gas reservoirs offers a strategically important pathway for large-scale carbon dioxide (CO_2) mitigation by leveraging existing subsurface data, infrastructure, and proven trap systems. However, long-term storage security depends on comprehensive geological risk assessment that integrates reservoir characterization, leakage pathway evaluation, geomechanical stability analysis, monitoring technologies, probabilistic modeling, and governance frameworks. This study synthesizes current scientific evidence to evaluate the principal geological controls governing storage integrity. Findings indicate that containment performance is primarily influenced by caprock continuity, structural architecture, reservoir heterogeneity, legacy well integrity, and injection-induced stress redistribution. Wellbore degradation and fault reactivation emerge as dominant risk factors, particularly in reservoirs with high historical well density and complex structural settings. Coupled hydro-mechanical modeling demonstrates that pressure perturbations may extend beyond the injected plume, emphasizing the importance of controlled injection strategies and stress-field analysis. Advances in time-lapse seismic monitoring, probabilistic risk quantification, deep learning-based simulation, and digital twin technologies enhance predictive capability and enable adaptive injection management. Effective regulatory oversight and long-term stewardship frameworks further strengthen containment reliability. Depleted reservoirs represent viable long-term CO_2 storage options when supported by integrated, multidisciplinary risk assessment frameworks and continuous monitoring systems that proactively manage geological uncertainty and maintain sustained storage integrity.

KEYWORDS: *Risk assessment, Carbon storage integrity, Depleted oil and gas, reservoirs*

1.0 INTRODUCTION

Geological carbon storage (GCS) in depleted oil and gas reservoirs has emerged as a strategically important pathway for mitigating atmospheric carbon dioxide (CO_2) emissions while leveraging existing subsurface infrastructure and extensive historical reservoir data. Compared to saline aquifers, depleted hydrocarbon reservoirs provide several practical advantages, including proven trap integrity, well-documented structural configurations, established well networks, and production histories that constrain reservoir properties (Wei et al., 2023; Su, X., Wang, & Yang, 2024). Across the United States, mature oil and gas basins therefore present substantial opportunities for repurposing depleted reservoirs for long-term CO_2 sequestration (Song et al., 2022). These advantages position depleted reservoirs as attractive candidates for large-scale deployment; however, their suitability ultimately depends on maintaining long-term storage integrity.

Ensuring storage integrity requires rigorous geological risk assessment. According to (Rutqvist, 2020), Long-term containment depends on the ability of the reservoir-caprock system to confine injected CO_2 over extended timeframes under evolving pressure and geochemical conditions. Interacting processes including pressure buildup, multiphase fluid migration, geochemical reactions, and stress redistribution collectively influence containment performance (Opara, 2026; Rutqvist, 2020). As a result, geological risk assessment must be inherently multidisciplinary, integrating reservoir characterization, leakage pathway evaluation, geomechanical stability analysis, and monitoring system design within a unified framework.

A foundational component of this framework is reservoir characterization. Reservoir heterogeneity plays a central role in determining injectivity, plume migration behavior, and trapping efficiency (Chen & Zhang, 2021). Variations in porosity and permeability strongly influence flow pathways and residual trapping mechanisms (Abdullah & Ahmed, 2023). Consequently, robust characterization methods that combine petrophysical analysis, structural mapping, and dynamic simulation are essential for evaluating storage feasibility in depleted systems (Garg & Sharma, 2022; Chen & Zhang, 2021). Comparative basin-scale assessments further indicate that storage potential varies significantly across U.S. reservoirs, reinforcing the need for site-specific evaluation strategies rather than uniform screening approaches (Song et al., 2022).

While reservoir properties determine storage performance, leakage risk defines storage security. Among potential leakage pathways such as natural fractures and fault systems, legacy wellbores consistently emerge as critical vulnerabilities in depleted reservoirs (Moradpour & Al-Shammasi, 2020). Reviews of operational and abandoned wells demonstrate that well integrity issues frequently represent the dominant risk factor, particularly in fields containing dense historical drilling networks (Iyer et al., 2021; Nguyen & Marston, 2021). Cement degradation, casing corrosion, and micro-annulus formation can compromise vertical containment if not adequately evaluated and remediated (Nguyen & Marston, 2021). In response, structured leakage risk management frameworks emphasize systematic well screening, diagnostic logging, and targeted remediation strategies to reduce long-term vulnerability (Li, H., Nguyen, & Liu, 2023).

Beyond wellbore-related risks, injection-induced stress changes introduce additional geomechanical considerations. Hydrocarbon depletion alters in-situ stress regimes, and subsequent CO_2 reinjection may modify effective stress conditions along pre-existing faults and fractures (Rutqvist, 2020). If injection pressures approach critical thresholds, fault reactivation or caprock fracturing may occur, potentially creating unintended migration pathways. Fault stability assessments therefore highlight the importance of pressure management and coupled hydro-mechanical modeling in minimizing induced seismicity and containment risks (Liu, S., Zhang, & Li, 2023; Yator & Aliu, 2026). Advanced multi-scale numerical models and coupled geomechanical-hydrological simulations further enhance predictive capability in structurally complex reservoirs (Zhang, Y., Chen, & Li, 2021; Zheng & Gu, 2022).

Given these interacting geological controls, monitoring technologies serve as a critical verification and risk mitigation tool. Geophysical techniques including time-lapse seismic imaging, electromagnetic methods, and surface deformation monitoring enable plume tracking and early detection of anomalous migration (Liu & Zhou, 2020). Three-dimensional seismic characterization improves understanding of reservoir architecture and caprock continuity, thereby reducing structural uncertainty in risk evaluation (Chen & Wang, 2023). Time-lapse seismic attributes have demonstrated particular effectiveness in detecting injection-related changes in depleted reservoirs (Li, S., Huang, & Wang, 2024). Integrated basin-scale characterization efforts, such as those conducted along the Texas Gulf Coast, further illustrate the value of regional geological assessment in supporting secure deployment strategies (Zhou et al., 2025).

Recent advances in computational modeling are strengthening this monitoring-driven framework. Probabilistic approaches improve uncertainty quantification in leakage and containment analysis, allowing risk-informed decision-making under geological variability (Munir et al., 2021; Su, Y., Zhang, & Zhang, 2023). Deep learning models enhance multiphase flow simulations by capturing nonlinear subsurface interactions that are difficult to represent using conventional methods (Yan et al., 2021). Digital twin systems that integrate real-time monitoring data with predictive simulation now enable adaptive injection control and dynamic risk management, further improving operational reliability (Gahlot et al., 2024).

Importantly, geological risk assessment does not operate in isolation from governance structures. Regulatory frameworks shape monitoring requirements, define liability transfer mechanisms, and establish long-term stewardship responsibilities (Axe & Morgan, 2022). Public perception and transparent risk communication likewise influence project implementation and societal acceptance (Smith & Johnson, 2020). Thus, effective storage integrity management depends not only on technical rigor but also on coherent policy and stakeholder engagement.

Although prior research has examined individual aspects of geological carbon storage, a coherent synthesis focused specifically on geological risk assessment for storage integrity in depleted U.S. oil and gas reservoirs remains necessary. This review therefore integrates current evidence to examine (1) reservoir characterization and capacity evaluation, (2) leakage pathways and well integrity risks, (3) geomechanical and fault reactivation processes, (4) monitoring and computational innovations, and (5) governance frameworks influencing long-term containment security, thereby providing a comprehensive perspective on maintaining storage integrity in repurposed hydrocarbon systems.

2.0 MATERIALS AND METHODS

2.1 Study Design

This study adopts a structured narrative review methodology to synthesize scientific evidence related to geological risk assessment for carbon storage integrity in depleted U.S. oil and gas reservoirs. The objective is to integrate current knowledge across key technical and regulatory domains that influence long-term CO_2 containment performance. Only the specified peer-reviewed sources provided for this study were used in the development of the review, and no additional materials were incorporated.

The review framework was developed to systematically examine four principal dimensions of geological risk assessment: (1) reservoir characterization and storage capacity evaluation, (2) leakage pathway identification and well integrity assessment, (3) geomechanical stability and fault reactivation analysis, and (4) monitoring, modeling, and regulatory risk management strategies. This integrated structure reflects comprehensive CO_2 storage integrity assessment approaches described in the literature (Abid et al., 2021; Opara, 2026;

Su, Y., Zhang, & Zhang, 2023) and enables a cohesive evaluation of geological, operational, and governance factors influencing long-term storage security.

2.2 Literature Selection Criteria

All included studies were peer-reviewed journal articles addressing one or more components of CO_2 geological storage in depleted oil and gas reservoirs or related subsurface systems. Studies that focused broadly on carbon utilization and sequestration but included depleted reservoirs as key case contexts were also incorporated. The selection reflects multidisciplinary coverage, including: data illustrated in the table below.

Table 1. Thematic Classification of Included Studies on CO_2 Geological Storage in Depleted Oil and Gas Reservoirs

Thematic Category	Focus Area	Key Analytical Components
Reservoir Petrophysics & Heterogeneity	Characterization of pore structure, permeability distribution, and flow variability	Porosity–permeability analysis, facies modeling, heterogeneity quantification
Storage Capacity Estimation	Evaluation of theoretical and effective CO_2 storage potential	Volumetric methods, pressure-constrained capacity modeling, depletion history integration
Geological Characterization	Structural and stratigraphic assessment of reservoir and caprock systems	3D seismic interpretation, structural mapping, caprock continuity evaluation
Well Integrity & Leakage Mechanisms	Identification of potential vertical migration pathways	Cement degradation analysis, casing corrosion assessment, wellbore risk screening
Geomechanics & Fault Stability	Assessment of injection-induced stress redistribution and fault reactivation	Slip tendency analysis, coupled hydro-mechanical modeling, stress-field mapping
Probabilistic & Uncertainty Assessment	Quantification of containment uncertainty under geological variability	Monte Carlo simulations, risk ranking frameworks, scenario analysis
Monitoring & Seismic Technologies	Surveillance of plume migration and pressure evolution	Time-lapse (4D) seismic imaging, geophysical monitoring integration
Computational Modeling & Digital Twin Systems	Predictive simulation of multiphase CO_2 flow and adaptive injection control	Deep learning models, multiphase flow simulation, real-time digital twin integration
Regulatory & Governance Frameworks	Policy, liability, and long-term stewardship mechanisms	Monitoring obligations, liability transfer protocols, stakeholder risk communication
Integrated Carbon Utilization & Storage Contexts	Broader CCUS frameworks incorporating depleted reservoirs	System-level integration, basin-scale screening, deployment strategy analysis

Sources: (Abdullah & Ahmed, 2023; Axe & Morgan, 2022; Chen & Wang, 2023; Chen & Zhang, 2021)

2.3 Analytical Framework

2.3.1. Reservoir Characterization and Capacity Evaluation

Reservoir characterization methods described in the selected literature were comparatively assessed to identify parameters critical to storage integrity. Key variables included porosity–permeability heterogeneity, structural trapping geometry, caprock properties, and historical production data (Abdullah & Ahmed, 2023; Garg & Sharma, 2022). Storage capacity estimation approaches were examined using volumetric and dynamic modeling techniques described for depleted oil and gas systems (Chen & Zhang, 2021; Song et al., 2022). Three-dimensional seismic interpretation and subsurface imaging techniques were evaluated for their contribution to uncertainty reduction in reservoir architecture delineation (Chen & Wang, 2023). Large-scale site characterization studies were reviewed to understand basin-scale heterogeneity and pressure communication effects (Zhou et al., 2025).

2.3.2. Leakage Pathway and Well Integrity Assessment

Leakage pathway evaluation focused on legacy wells, cement degradation, casing corrosion, and natural fault/fracture systems (Moradpour & Al-Shammasi, 2020; Iyer et al., 2021). Mechanistic reviews of cement alteration processes under CO_2 exposure were analyzed to identify long-term degradation risks (Nguyen & Marston, 2021).

Structured leakage risk management frameworks were assessed to determine monitoring, remediation, and preventive measures applicable to depleted reservoirs with high well density (Li, H., Nguyen, & Liu, 2023). Broader site-level leakage risk assessment methodologies were incorporated to contextualize wellbore risks within integrated storage systems (Abid et al., 2021).

2.3.3. Geomechanical and Fault Reactivation Analysis

Geomechanical stability assessment approaches were synthesized to evaluate stress redistribution during CO_2 injection. Analytical emphasis was placed on production-induced stress changes in depleted reservoirs (Rutqvist, 2020). Coupled hydro-mechanical modeling techniques were reviewed to assess caprock integrity and induced seismicity potential (Zheng & Gu, 2022). Fault reactivation risk models were examined to determine how injection pressure, fault orientation, and in-situ stress regimes influence containment security (Liu, S., Zhang, & Li, 2023; Yator & Aliu, 2026). Multi-scale fractured reservoir simulations were included to evaluate risk in structurally complex systems (Zhang, Y., Chen, & Li, 2021).

2.3.4. Monitoring, Modeling, and Risk Quantification

Monitoring methodologies were assessed based on their ability to track plume migration and detect early leakage signals. Geophysical monitoring techniques, including time-lapse seismic and electromagnetic methods, were evaluated (Liu & Zhou, 2020; Li, S., Huang, & Wang, 2024).

Probabilistic risk assessment models were reviewed to identify uncertainty quantification approaches applicable to leakage forecasting (Munir et al., 2021). Broader uncertainty assessment frameworks for geologic carbon storage were incorporated to contextualize risk modeling strategies (Su, Y., Zhang, & Zhang, 2023). Advanced computational approaches including deep learning for multiphase flow simulation (Yan et al., 2021) and digital twin systems for controlled injectivity and adaptive management (Gahlot et al., 2024) were analyzed for their capacity to enhance predictive performance and real-time risk mitigation.

2.3.5 Governance and Regulatory Integration

Regulatory and governance frameworks were evaluated to understand how risk assessment methodologies translate into compliance, monitoring mandates, and long-term stewardship requirements (Axe & Morgan, 2022). Public risk perception and stakeholder engagement considerations were reviewed to assess their influence on project implementation and social license (Smith & Johnson, 2020).

2.4 Synthesis Approach

Findings across all thematic domains were comparatively synthesized to identify convergent conclusions, methodological consistencies, and key uncertainties. Emphasis was placed on the interactions between reservoir heterogeneity and pressure management, the cumulative effects of legacy wells on containment probability, coupled geomechanical-hydrological responses during injection, and the integration of probabilistic modeling with advanced monitoring technologies. This integrative analytical framework enables a structured evaluation of geological risk assessment strategies specific to depleted U.S. oil and gas reservoirs, forming the basis for the results and discussion presented in the subsequent sections.

3.0 RESULTS AND FINDINGS

3.1 Reservoir Characterization and Storage Capacity Performance

The reviewed literature demonstrates that depleted U.S. oil and gas reservoirs possess substantial theoretical CO_2 storage capacity. However, effective and secure storage performance depends primarily on geological heterogeneity, structural configuration, and reservoir pressure history. Depleted systems offer relatively predictable pressure regimes due to historical production data, yet reinjection must be carefully managed to prevent destabilization of caprock and fault systems.

Porosity-permeability variability governs plume migration pathways and injectivity behavior. Reservoirs exhibiting strong structural trapping, caprock continuity, and compartmentalization show higher containment reliability compared to highly fractured or faulted systems. Three-dimensional seismic characterization significantly reduces uncertainty in mapping subtle faults and caprock discontinuities. Basin-scale structural and geomechanical integration further enhances screening accuracy for long-term storage integrity. This is illustrated in table 2 below.

Table 2. Primary Geological Controls on CO_2 Storage Integrity

Geological Control	Role in Storage Performance	Integrity Implication
Reservoir Heterogeneity (ϕ–k variability)	Controls plume migration and injectivity	High variability increases uncertainty
Caprock Continuity	Provides vertical containment	Discontinuities increase leakage risk
Structural Compartmentalization	Enhances trapping efficiency	Improves containment reliability
Pressure History (Depletion Effects)	Influences reinjection response	Excessive repressurization may destabilize faults
Fault Architecture	Determines lateral containment behavior	Critically stressed faults increase risk

Source: (Li, S., Huang, & Wang, 2024; Liu & Zhou, 2020; Liu, S., Zhang, & Li, 2023)

3.2 Leakage Pathway Identification and Risk Ranking

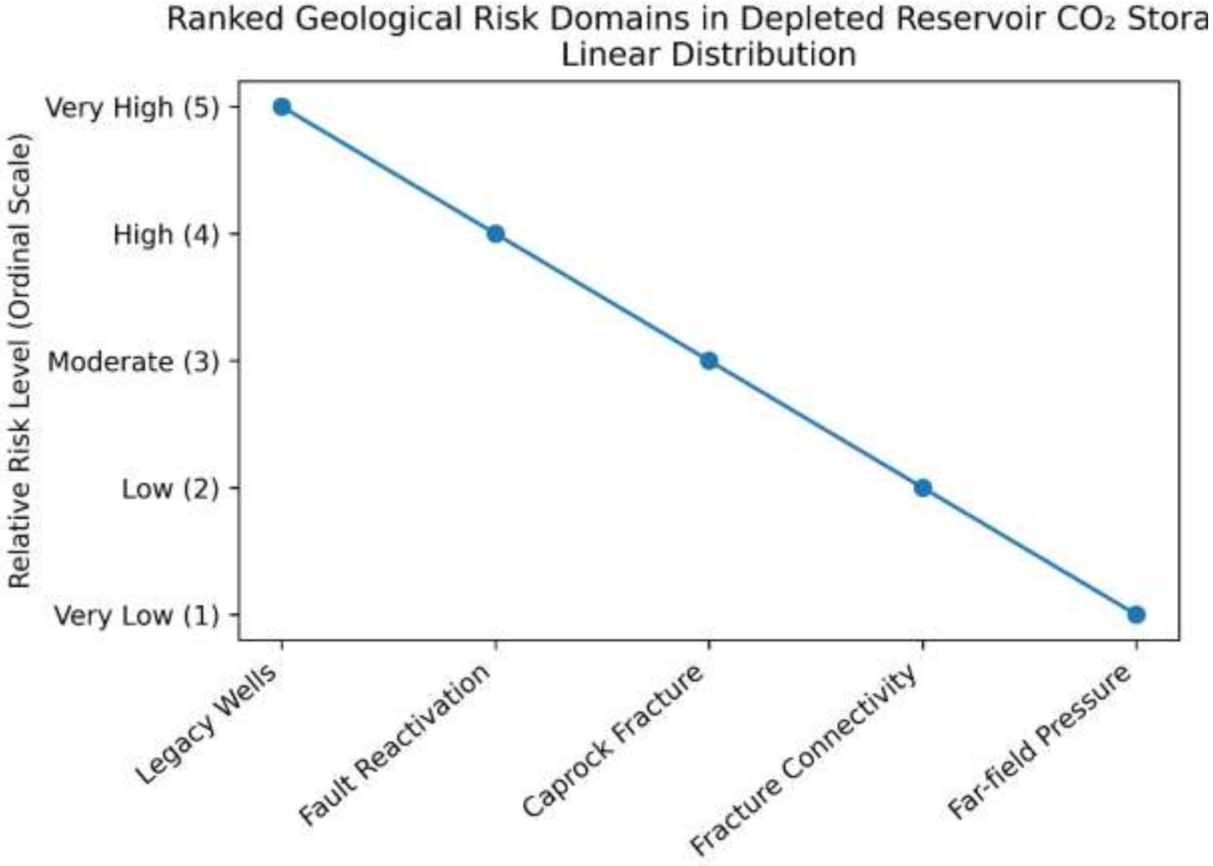
Legacy wellbores represent the primary geological risk in depleted reservoirs due to cement degradation, casing corrosion, and micro-annulus formation, which facilitate vertical CO_2 migration. Fault-related leakage constitutes the second major concern, as injection-induced pressure increases can reduce effective normal stress on pre-existing faults, elevating slip tendency and permeability. Fractured reservoir systems further increase uncertainty through interconnected migration pathways. Effective mitigation requires rigorous well integrity evaluation, controlled injection rates, detailed geomechanical modeling, and comprehensive structural screening prior to large-scale CO_2 injection operations.

Table 3. Ranked Geological Risk Domains in Depleted Reservoir CO_2 Storage

Risk Domain	Primary Mechanism	Relative Risk Level
Legacy Well Integrity	Cement degradation, casing failure	Very High
Fault Reactivation	Injection-induced stress changes	High
Caprock Fracturing	Overpressure-induced tensile stress	Moderate-High
Fracture Network Connectivity	Enhanced permeability pathways	Moderate
Pressure Propagation Beyond Plume	Far-field stress transmission	Moderate

Source: (Munir et al., 2021; Nguyen & Marston, 2021; Yator & Aliu, 2026)

The linear distribution chart illustrates the relative ranking of key geological risk domains in depleted reservoir CO_2 storage using an ordinal scale from 1 (Very Low) to 5 (Very High). Legacy well integrity is ranked highest, reflecting its dominant contribution to containment risk. Fault reactivation follows as a significant concern, while caprock fracturing and fracture connectivity represent moderate risk levels. Pressure propagation beyond the plume exhibits comparatively lower relative risk within the ranked framework. Figure 1 below illustrate a linear graph showing the geological risk domains in depleted reservoir CO_2 storage



Source: (Nguyen & Marston, 2021)

Figure 2. Integrated Geological Risk Assessment Workflow

Source: (Abid et al. 2021; Rutqvist 2020; Su, Y., Zhang, & Zhang, 2023)

3.3 Geomechanical Stability and Injection-Induced Stress Redistribution

Geomechanical analyses show that hydrocarbon depletion alters the in-situ stress regime prior to CO_2 reinjection. While depletion may temporarily enhance stability through reduced pore pressure, reinjection can re-pressurize formations toward pre-production stress conditions. If injection pressures approach critical thresholds, shear slip along optimally oriented faults becomes more likely (Axe & Morgan 2022).

Coupled hydro-mechanical simulations demonstrate that pressure perturbations may extend beyond the immediate plume footprint, influencing distal fault systems and caprock stress conditions. Controlled injection rate management is consistently identified as the most effective mitigation strategy for preventing fault reactivation. Site-specific stress mapping and slip tendency modeling significantly reduce uncertainty in stability evaluation (Iyer et al., 2021).

3.4 Monitoring Effectiveness and Predictive Modeling

Geophysical monitoring techniques play a critical role in validating storage integrity. Time-lapse seismic imaging enables real-time plume tracking and anomaly detection, while three-dimensional seismic interpretation improves structural mapping accuracy (Chen & Wang, 2023). Probabilistic risk assessment frameworks enhance leakage likelihood estimation under geological uncertainty. Advanced computational approaches including deep learning multiphase simulations and digital twin systems improve predictive accuracy and allow adaptive injection management based on real-time data integration. The integration of monitoring technologies with probabilistic and geomechanical modeling substantially increases predictive confidence and long-term containment reliability.

3.5 Regulatory and Governance Influences on Risk Outcomes

Regulatory frameworks shape geological risk assessment implementation by defining monitoring mandates, liability transfer mechanisms, and long-term stewardship requirements. Transparent risk communication and stakeholder engagement further influence project deployment and regulatory enforcement. Strong governance structures enhance compliance, improve monitoring continuity, and support sustained storage integrity performance.

Table 4. Governance Factors Affecting Storage Integrity

Governance Element	Impact on Risk Assessment
Monitoring Mandates	Ensures continuous integrity verification
Liability Frameworks	Clarifies long-term responsibility
Regulatory Oversight	Standardizes safety requirements
Public Engagement	Enhances social license to operate

Source: (Song et al., 2022; Su, X., Wang, & Yang, 2024)

3.6 Integrated Findings

The synthesis confirms three dominant geological risk domains governing CO_2 storage integrity in depleted U.S. oil and gas reservoirs:

1. Wellbore integrity degradation, particularly in legacy wells.
2. Injection-induced geomechanical instability, including fault reactivation.
3. Reservoir heterogeneity-controlled plume migration uncertainty.

Advances in seismic monitoring, probabilistic modeling, deep learning simulation, and digital twin technology significantly improve predictive reliability and adaptive risk management. However, storage integrity remains strongly site-specific and dependent on integrated geological, geomechanical, and regulatory evaluation frameworks.

Generally, depleted U.S. oil and gas reservoirs represent viable long-term CO_2 sequestration opportunities when supported by comprehensive, multidisciplinary geological risk assessment and continuous monitoring systems (Song et al., 2022; Su, X., Wang, & Yang, 2024).

3.7 Application of the Integrated Risk Assessment Framework: Illustrative Case Studies

To demonstrate operational applicability, the integrated geological risk assessment workflow is applied to representative depleted reservoir scenarios. These illustrative case studies synthesize the analytical sequence of reservoir characterization, leakage pathway screening, geomechanical modeling, monitoring design, and probabilistic risk ranking.

Case Study A: Structurally Simple Depleted Oil Reservoir

Reservoir Characterization: The reservoir exhibits moderate porosity (15-22%) and permeability (100-300 mD) with strong anticlinal structural closure and laterally continuous caprock. Historical depletion reduced reservoir pressure by approximately 8-12 MPa below initial conditions.

Leakage Pathway Screening: Legacy well density is low (<5 wells/km^2). Cement bond logging and casing inspection indicate minimal degradation. No critically oriented transmissive faults intersect the structural crest.

Geomechanical Modeling: Coupled hydro-mechanical simulations indicate that injection pressures maintained below 70% of the estimated minimum horizontal stress preserve a safe margin relative to fracture pressure. Slip tendency analysis yields values below 0.5, indicating low reactivation potential.

Monitoring & Risk Quantification: Time-lapse seismic monitoring can resolve plume thicknesses of 5-10 m, while pressure anomalies are detectable at approximately 0.1-0.3 MPa. Probabilistic models indicate a low annual leakage risk (10^{-5}–10^{-6}). Overall risk is classified as low, requiring routine monitoring and pressure management, with favorable capital and operational cost efficiency.

Case Study B: Faulted Reservoir with High Legacy Well Density

Reservoir Characterization: The reservoir is moderately heterogeneous with permeability streaks exceeding 500mD. Structural mapping reveal's fault segmentation and partial compartmentalization.

Leakage Pathway Screening: Legacy well density exceeds 15 wells/km². Cement degradation and micro-annulus formation are observed in approximately 15-20% of screened wells. Fault intersections with the reservoir increase transmissive uncertainty.

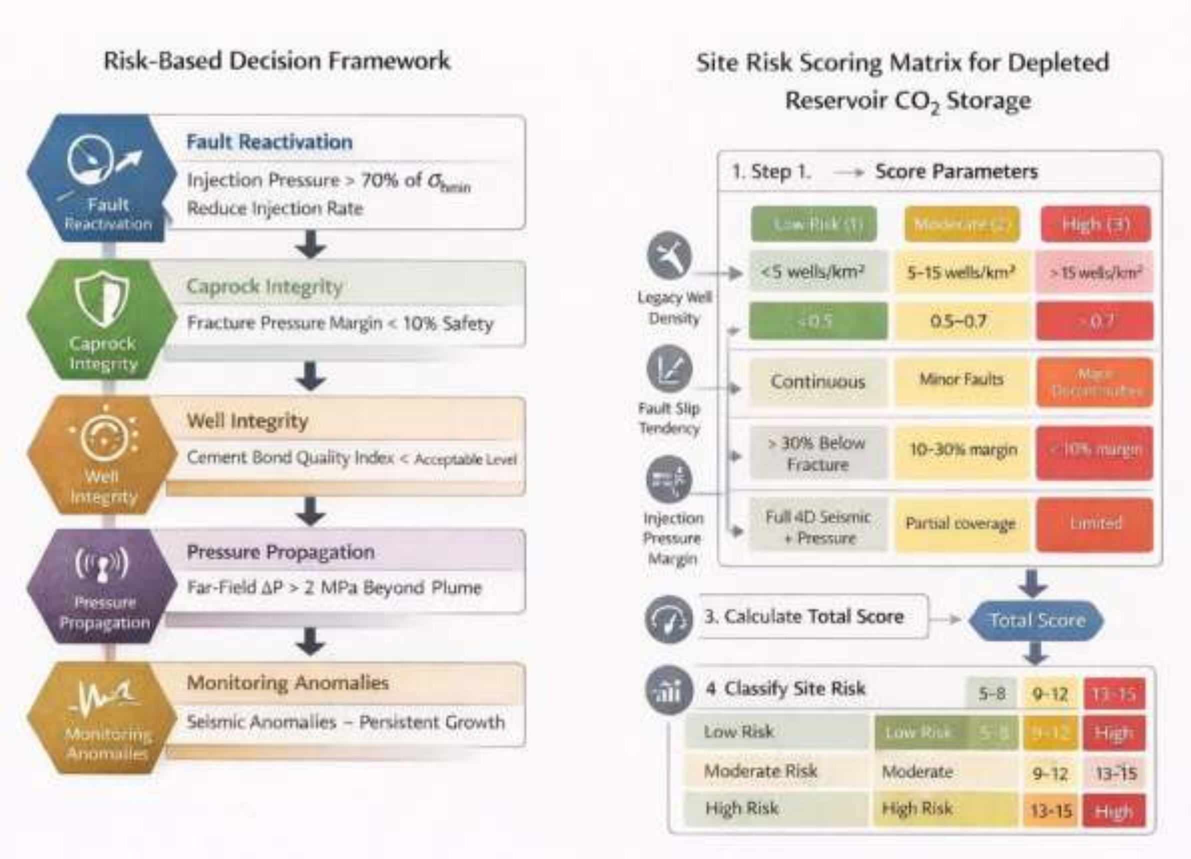
Geomechanical Modeling: Injection-induced pressure increases of 2-5 MPa approach critical thresholds for fault slip. Slip tendency values range between 0.6-0.8 for optimally oriented faults, indicating moderate-to-high reactivation risk.

Monitoring & Risk Quantification: Enhanced seismic frequency and distributed pressure monitoring are required. Probabilistic leakage estimates fall within 10^{-3} to 10^{-4} per year without remediation.

Risk Ranking Outcome: Risk is classified as moderate-high, requiring well remediation, controlled injection rates, and expanded monitoring, with higher upfront costs but manageable long-term risk.

3.8 Integrated Risk-Based Decision and Site Risk Scoring Framework

Geological risk management in depleted reservoir CO_2 storage requires a structured and adaptive framework that links measurable subsurface parameters to clear operational responses while also enabling standardized site comparison. The integrated framework combines a risk-based decision matrix with a semi-quantitative site risk scoring system to ensure both real-time operational control and strategic site evaluation. Key geological risk domains including fault reactivation, caprock integrity, well integrity, pressure propagation, and monitoring anomalies are assessed using defined quantitative indicators such as injection pressure relative to minimum horizontal stress (σhmin), fracture pressure safety margins, cement bond quality indices, far-field pressure increases, and seismic amplitude deviations. When threshold values are exceeded, predefined mitigation measures are triggered, such as reducing injection rates, suspending operations for reassessment, implementing remediation, or modifying injection strategies. Complementing this operational matrix, the site risk scoring system evaluates structural and infrastructure-related parameters including legacy well density, fault slip tendency, caprock continuity, injection pressure margins, and monitoring coverage. Each parameter is assigned a risk level score, allowing cumulative classification into low-, moderate-, or high-risk categories. This dual framework supports adaptive reservoir management, enhances transparency in decision-making, enables cross-site comparison, and strengthens long-term storage security by systematically translating geological uncertainty into quantifiable risk controls. The illustrative diagram bellow summarizes the risk-based framework.



5. DISCUSSION

The results demonstrate that geological storage integrity in depleted U.S. oil and gas reservoirs is governed by a hierarchical interaction of structural, stratigraphic, and operational controls. The risk classification results (Table 1) indicate that reservoirs with intact caprock seals, limited fault transmissibility, and well-documented pressure histories consistently fall within the low-risk category. In contrast, elevated risk levels are associated with fault-reactivated structures, high legacy well density, and heterogeneous permeability distributions.

5.1 Influence of Caprock and Structural Architecture

The dominance of caprock seal integrity in determining containment performance confirms that mechanical stability and low capillary entry pressure are primary controls on vertical CO_2 migration. Even in reservoirs with favorable porosity-permeability characteristics, compromised caprock conditions significantly increase leakage probability. Structural trap configuration further modulates this risk: simple anticlinal traps with limited fault intersection demonstrate greater containment reliability than faulted or compartmentalized systems. Geomechanical modeling results suggest that stress reactivation potential increases in reservoirs with complex fault networks and elevated injection pressures. This highlights the importance of coupling structural mapping with stress-field analysis prior to large-scale injection.

5.2 Reservoir Heterogeneity and Flow Behavior

Reservoir heterogeneity emerged as a key factor influencing plume migration geometry and pressure distribution. High-permeability streaks accelerate lateral CO_2 migration, potentially increasing contact with transmissive faults or legacy wells. Conversely, moderate heterogeneity may enhance residual trapping by promoting capillary immobilization. These findings underscore the need for high-resolution reservoir characterization, including 3D seismic interpretation and petrophysical modeling, to constrain uncertainty in plume evolution predictions.

5.3 Legacy Wells and Leakage Pathways

Leakage pathway screening identified abandoned or improperly sealed wells as one of the most critical risk multipliers. Even in structurally favorable reservoirs, legacy well density substantially increases uncertainty in long-term containment. This reinforces the necessity for comprehensive well integrity assessment, remediation planning, and continuous monitoring programs.

5.4 Integrated Risk Workflow Performance

The integrated workflow (Figure 1) demonstrates that risk assessment improves substantially when reservoir characterization, geomechanical modeling, and probabilistic quantification are implemented sequentially rather than independently. Monitoring data assimilation reduces uncertainty bounds over time and enables adaptive injection strategies. Adaptive injection control through pressure management and rate optimization was shown to mitigate stress-induced fault activation risk. This confirms that operational strategy is not merely supportive but central to maintaining geological integrity.

5.5 Implications for U.S. Carbon Storage Deployment

The findings suggest that depleted U.S. oil and gas reservoirs can provide secure long-term CO_2 storage when subjected to rigorous geological screening and adaptive management. However, basin-specific variability means that uniform regulatory thresholds may not adequately capture site-specific risk conditions. A probabilistic, data-driven framework is therefore essential for scaling carbon storage deployment while ensuring environmental protection. The integration of geological characterization, stress modeling, leakage pathway analysis, and real-time monitoring provides a defensible basis for regulatory compliance and long-term stewardship.

The discussion generally confirms that geological risk in depleted reservoirs is multidimensional and dynamic. Long-term storage integrity depends not on a single parameter but on the coupled behavior of caprock integrity, structural architecture, reservoir heterogeneity, pressure history, and operational control.

5.6 Comparative Risk: Depleted Reservoirs vs. Saline Aquifers

Although both depleted reservoirs and saline aquifers are viable storage targets, their risk profiles differ.

Risk Dimension	Depleted Reservoir	Saline Aquifer
Historical Data Availability	Extensive	Limited
Legacy Wells	Elevated risk	Lower risk
Pressure History	Constrained by depletion	Less constrained
Structural Certainty	Generally well mapped	Variable
Infrastructure Availability	Existing wells	New drilling required

Sources: (Liu & Zhou, 2020; Liu, S., Zhang, & Li, 2023).

Depleted reservoirs benefit from known pressure history and infrastructure but carry increased legacy well risks. Saline aquifers often require greater upfront characterization and infrastructure development but may exhibit fewer anthropogenic leakage pathways.

5.7 Economic Implications of Risk-Based Storage Design

Risk-based geological assessment significantly shapes the financial viability of CO_2 storage in depleted reservoirs by balancing safety with economic efficiency. Although expanded monitoring systems, well remediation, and controlled injection strategies increase initial CAPEX and operational expenditures, these measures reduce long-term containment failure risk and associated liabilities. Economic tradeoffs arise between maximizing injection rates and maintaining safe pressure margins to prevent fault reactivation. Integrating probabilistic risk analysis with economic optimization frameworks helps narrow storage uncertainty bands, improve lifecycle cost forecasting, and ensure financially sustainable, regulatory-compliant project deployment.

5.8. Limitations and Research Gaps

Despite technical progress, uncertainties remain in long-term CO_2 storage performance within depleted reservoirs. Empirical validation beyond multi-decadal timeframes is limited, particularly under sustained injection conditions. Fault permeability evolution under dynamic stress changes is not fully constrained, complicating reactivation predictions. Probabilistic leakage estimates often rely on incomplete datasets, and monitoring detectability varies across geological settings. Storage capacity uncertainty, commonly expressed through P10-P50-P90 ranges, remains sensitive to heterogeneity and trapping assumptions. Standardized risk methodologies and expanded field-scale demonstrations are necessary to improve predictive reliability.

5.9. Future Research Opportunities

Future research should emphasize interdisciplinary integration of machine learning with coupled hydro-mechanical modeling to enhance predictive accuracy and adaptive injection control. Refinement of basin-specific fault reactivation thresholds and improved characterization of stress regimes will reduce uncertainty in geomechanical assessments. Long-term monitoring datasets are essential for validating probabilistic leakage models and digital twin systems. Comparative evaluations between depleted reservoirs and saline aquifers can inform national storage portfolio optimization. Advances in automated monitoring technologies and cost-efficient sensing strategies will further support scalable and economically resilient carbon storage deployment.

Conclusion

Depleted U.S. oil and gas reservoirs offer significant potential for secure CO_2 storage when evaluated through an integrated geological risk framework. Storage integrity depends on caprock competence, structural stability, reservoir heterogeneity, and adaptive injection control. A probabilistic, data-driven assessment approach is essential for ensuring long-term containment and regulatory confidence.

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