Title: Advancing Carbon Storage Monitoring Through Digital Workflows

Introduction

Carbon storage monitoring spans baseline characterization before injection, real-time assurance during injection, and long-term post-injection surveillance to demonstrate secure containment and support closure and stewardship activities. Baseline datasets establish environmental and geophysical reference conditions for future comparison, while injection-phase monitoring focuses on tracking reservoir pressure, plume migration, and well integrity, with continued monitoring after injection to demonstrate long-term stability and address residual risks through periodic reassessment and stakeholder communication.

Measurement, Monitoring and Verification (MMV) planning and execution integrates subsurface characterization, CO_2 flow and geomechanical modeling, environmental baselining, risk assessment, monitoring design, and regulatory reporting; technical complexity is amplified by site specificity and evolving requirements, making traceability and consistency essential.

This paper describes a digital, workflow-driven MMV methodology that maintains explicit traceability between risks, monitoring objectives, measurement selection, and lifecycle decisions while enabling adaptive updates using modeling feedback and operational data integration.

Methodology: Workflow-driven digital MMV

The proposed digital MMV workflow links qualitative and quantitative risk assessment directly to monitoring objectives and measurement selection (C. Sorgi et al. 2024). Predictive reservoir, pressure, and geomechanical models are used to identify credible containment/leakage risks, quantify uncertainty, and define sensitivity requirements for monitoring technologies; each monitoring activity is mapped to one or more risks to provide a defensible technical basis for measurement selection and monitoring density.

Cost-effective monitoring design is supported through iterative modeling and scenario analysis to evaluate alternative monitoring portfolios. Technologies are selected based on their ability to detect changes in key risk indicators while minimizing redundant acquisition, enabling structured cost vs. benefit reasoning and adaptive monitoring strategies that can evolve as confidence increases.

During operations, real-time data integration streams field measurements, sensor outputs, and operational parameters into the digital environment and connects them with subsurface and surface models. Observations are compared against expected performance envelopes to support automated anomaly detection and identification of emerging deviations; as data are assimilated, risks can be re-ranked based on updated likelihoods and consequences, and monitoring plans can be adjusted by refining frequency, spatial focus, and technology selection.

The end-to-end workflow concept from planning through operations with modeling feedback is summarized in Figure 1.

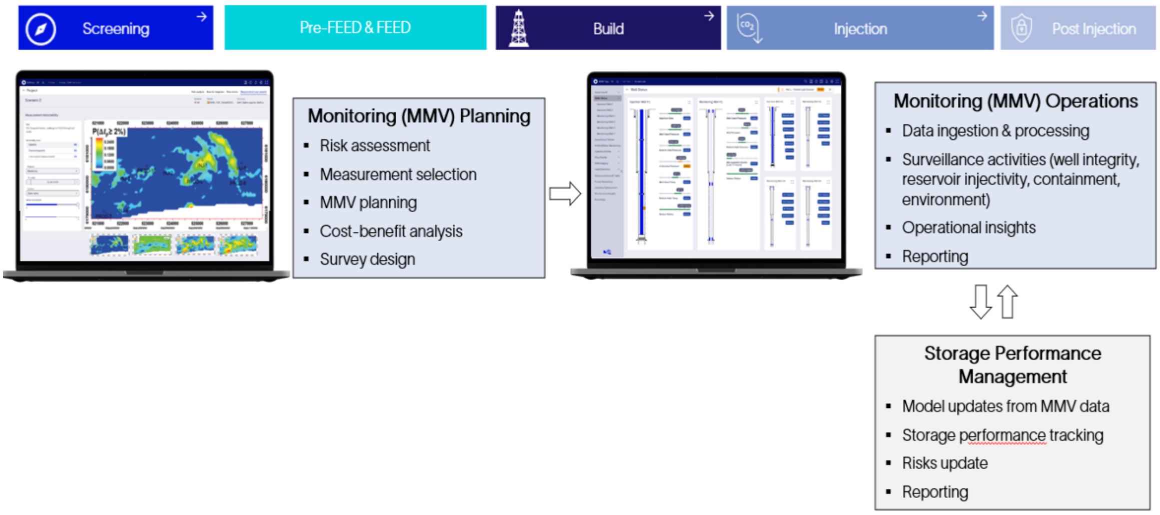

Figure 1. The digital monitoring workflow from planning to operations with the intermittent feedback from modelling enabling proactive storage monitoring.

Lifecycle application of the methodology

Before injection, baseline studies establish environmental and geophysical reference conditions. Typical activities include sampling groundwater and soil gases, performing seismic surveys to characterize subsurface structures, and defining benchmarks that support later detection and comparison. Once injection commences, monitoring efforts shift toward real-time assurance of containment and injectivity. Operators track reservoir pressure and CO_2 plume migration to confirm containment within the storage complex; continuous well-integrity monitoring remains critical, with preparedness for rapid response if containment risks are detected.

Monitoring workflows integrate wells, subsurface, and near-surface data to verify conformance with models. Real-time tracking of injection performance indicators (rates, pressure, temperature), plume migration, and well integrity is compared against model predictions to detect deviations; plume and pressure-front tracking continuous or intermittent data are used to refine forecasts and support decision-making.

Environmental monitoring provides an independent line of evidence for both onshore and offshore contexts, including CO_2 concentrations, soil and water chemistry, fluxes, and atmospheric conditions. Integrated datasets, automated alerts, and reporting streamline compliance and support a shift from reactive surveillance to proactive monitoring management.

After injection ceases, monitoring continues for an extended period (often decades) with the objective of demonstrating long-term stability and secure containment. Wells are plugged and abandoned to eliminate leakage pathways and closure plans define monitoring requirements and conditions for liability transfer. Even after formal site closure, long-term stewardship includes periodic reassessment informed by monitoring data and transparent communication with regulators and stakeholders as new information or risks emerge.

Digital workflows preserve a transparent and auditable record of assumptions, risk evaluations, monitoring rationales, and decisions, maintaining traceability between risks, monitoring strategy selection, and regulatory requirements. This continuity supports consistent communication, periodic reassessment, and defensible updates to monitoring strategies throughout the life of the project.

Technical implications for MMV design and execution

MMV programs are most effective when risk-based and adaptive, evolving with changes in project risk throughout the lifecycle. Measurements may be added or discontinued as risk profiles shift, informed by feedback from physics-based modelling prior to operation and by data acquisition and interpretation during operations. Programs must remain site-specific (IOGP, 2022), reflecting geological, regulatory, environmental, and socio-economic conditions, and can leverage lessons from existing CCS projects (K. Nii et al. 2024) to inform risk assessment and monitoring templates. The iterative relationship between modelling, risk evaluation, and MMV plan design is summarized in Figure 2.

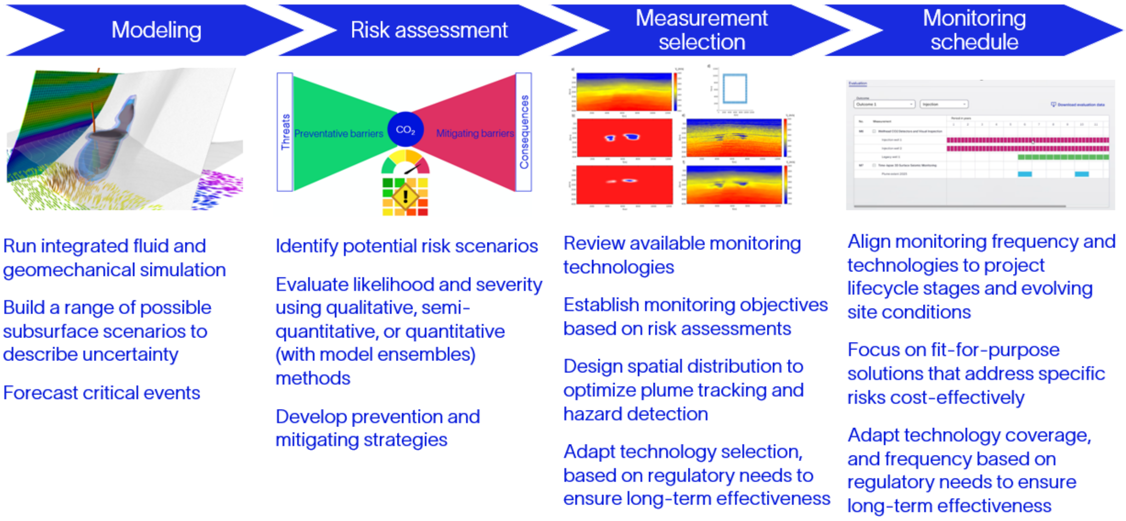

Figure 2. Modeling and risk-based design of MMV plan.

Monitoring teams are typically small and operate across multiple technical domains; integrated digital platforms enable collaboration by bringing diverse datasets into a consistent shared environment with common data models, visualization, analytics, and traceable decisions. A shared workspace supports real-time collaboration, rapid exchange of interpretations, and alignment as strategies evolve, while also supporting transparency and regulatory reporting needs over long timescales.

The International Organization for Standardization (ISO, 2017) and other industry guidelines (e.g., CSA, DOE Best Practice Manuals, Alberta Directive 065, EU CCS Directive) describe MMV as a structured and iterative risk management process spanning all project phases (screening through post-closure) and requiring continuous updates to document and communicate risks and opportunities. Regulatory frameworks also require monitoring across temporal and spatial domains, including wells, the geosphere, hydrosphere, and biosphere, supporting baseline characterization, continuous observation during injection, and post-injection surveillance.

Conclusions

A workflow-driven digital approach to carbon storage MMV can strengthen monitoring defensibility and continuity by explicitly mapping measurements to risks and by integrating modeling outputs into monitoring design and updates. Iterative scenario analysis supports optimized monitoring portfolios, while real-time integration of operational measurements enables model–data comparison, anomaly detection, and dynamic risk re-ranking to keep monitoring proportional to evolving risk profiles. Preserving an auditable record of assumptions and decisions supports lifecycle transitions from injection through post-injection and long-term stewardship and facilitates transparent communication and reporting.

References

IOGP (2022) Recommended practices for measurement, monitoring and verification plans associated with geologic storage of carbon dioxide. Report 652.

ISO (2017) ISO 27914: Carbon dioxide capture, transportation and geological storage.

Nii, K. et al. (2024) A conceptual subsurface risk management and MMV design for an offshore CCS site in Japan. 58th U.S. Rock Mechanics/Geomechanics Symposium.
Sorgi, C., De Gennaro, V., & Mandiuc, A. (2024) Quantitative risk assessment of CO_2 leakage in CCS projects. SPE Journal, 29(12), 7214–7233.
U.S. EPA (n.d.) 40 CFR 146.91 – Reporting Requirements. Code of Federal Regulations.