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PERSPECTIVE

THE MONITORING OF CO_2 GEOLOGICAL STORAGE

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CONTENTS

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All current CO_2 storage projects are operated under risk-based monitoring systems and regulatory frameworks.

KEY POINTS

Monitoring is:

- **Necessary:** Every commercial CO_2 storage project has a robust, comprehensive monitoring plan employing tested and proven technologies and techniques.
- **Proven:** Commercial CO_2 storage projects have proven the viability of monitoring, offering insights into best practices and the importance of dynamic, site-specific monitoring plans based on adaptive and iterative risk assessment plans.
- **Adaptive and scalable:** Monitoring plans driven by risk assessments are tailored to site-specific risks and evolve with project maturity to optimise safety and efficiency.
- **Comprehensive:** Monitoring frameworks integrate advanced technologies with operational needs and regulatory requirements to ensure containment, conformance, and environmental safety across diverse geological settings and jurisdictions.
- **Critical:** Effective monitoring is a cornerstone for scaling CCS projects, building regulatory and public trust, and supporting global climate goals by ensuring the safe and permanent storage of CO_2.

1.0 INTRODUCTION

Robust monitoring plans are essential to maintaining storage site integrity and safety, and effective monitoring enables CO_2 storage from an operational standpoint. Monitoring also instils public and regulatory confidence by verifying that CO_2 remains securely contained, encouraging further investment in carbon capture and storage (CCS) initiatives.

This perspective explores the objectives of monitoring, introduces key technologies, and provides examples of how robust monitoring within regulatory frameworks ensures CCS projects achieve their objective of safely and permanently injecting and storing CO_2 underground.

2.0 OBJECTIVES OF STORAGE MONITORING

While monitoring plans are site-specific and tailored to address the unique risks and requirements of each CO_2 storage project, the four overarching objectives outlined below have guided all 18 operating commercial-scale CCS projects since 1996 that focus on dedicated geological storage.. The objectives are:

QUANTIFYING CO_2 STORED

Essential for regulatory compliance and carbon accounting frameworks, and for verifying storage capacity aligns with licence and operational requirements.

ENSURING CONFORMANCE

Ensures CO_2 behaves as predicted, follows the expected plume movement/pressure front, and interacts with the storage environment as modelled.

ENSURING CONTAINMENT

Ensures CO_2 remains securely stored within the designated storage formation, preventing migration into unintended areas.

ENSURING ENVIRONMENTAL SAFETY (ASSURANCE)

Prioritises the protection of ecosystems, groundwater resources, and air quality, ensuring operations do not compromise environmental safety.

3.0 RISK MANAGEMENT PLAN

Effective risk management underpins the safety and success of every CO_2 storage project (Figure 1). By identifying and assessing potential risks, a risk management plan establishes a clear framework for mitigation. Monitoring programs are designed around this framework, focusing on high-priority areas and behaviours to detect early signs of deviation from the expected operating conditions and regulatory requirements. This targeted approach enables swift intervention, ensuring monitoring remains efficient and effective.

3.1. The Evolving Risk Profile

A CO_2 storage site's risk profile evolves from the pre-injection phase through to post-closure. Risks are highest during injection[1], but continuous risk assessment ensures that monitoring remains dynamic and responsive. As new data and operational insights emerge, monitoring adapts by incorporating real-time information, adjusting frequencies, refining areas of focus, and updating mitigation measures. This adaptive approach ensures safe, compliant, and reliable CO_2 storage, bolstering public confidence in the integrity of CCS projects.

3.2. A Risk-Based Approach to CO_2 Storage Monitoring

The complexity and scale of CO_2 storage requires a systematic approach to identifying, assessing, and mitigating potential risks of the project. A series of targeted actions and efforts, guided by risk management plans and aligned with CO_2 monitoring objectives, form the blueprint for effective monitoring plans.

Implementing a risk-based monitoring approach evolves across the different phases of a CO_2 storage project, as detailed in Table 1. Each phase carries distinct priorities, risks, and milestones, requiring tailored monitoring strategies aligned with regulatory requirements and site-specific characteristics. An example is the evolution of the Shell Quest monitoring plan *(See Case Study)*.

ACTIONS AND EFFORTS

QUANTIFYING CO_2 STORED

ENSURING CONFORMANCE

- Monitoring injection rates at the wellhead and validating against CO_2, in the subsurface.
- Monitoring CO_2, plume movement, ensuring movement and evolution of the plume and pressure front aligns with the predicted models.
- Frequently updating modelled predictions through real-time CO_2, monitoring and subsequent data.

ACTIONS AND EFFORTS

ENSURING CONTAINMENT

ENSURING ENVIRONMENTAL SAFETY (ASSURANCE)

- Monitoring the atmosphere/water column, soil /seabed, groundwater, geosphere, reservoir and caprock ensuring containment and environmental safety.
- Continuously measuring and verifying the reservoir, caprock, and well conditions for integrity, stability, and any changes under CO_2, rich conditions.
- Continuously detecting unintended migration of CO_2 or brine in wells, in the surrounding geology, and for seismicity.

Figure 1: Life-cycle risk profile for CO_2 storage[2]

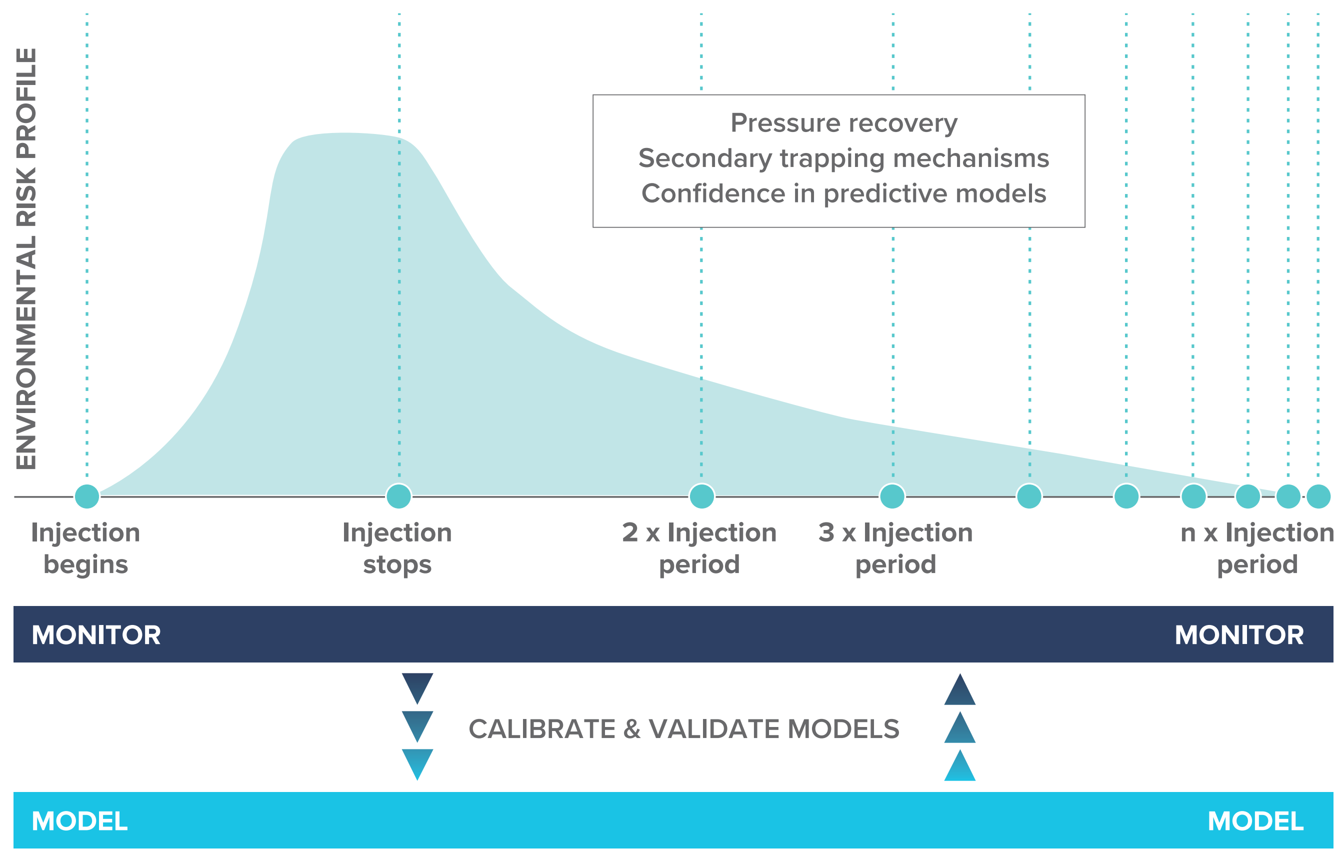


Table 1: The evolving lifecycle of a CO_2 storage monitoring plan.

PROJECT PHASE	PRIMARY FOCUS	KEY RISKS	MILESTONES
Pre-Injection	Identifying the best monitoring tools based on site characterisation and according to the risk assessment, operational parameters and regulatory requirements.	• Insufficient baseline data. • Monitoring plan does not meet operational or regulatory requirements. • Legacy wells and faults are not identified before injection	• Site thoroughly characterised. • Environmental/ operational baselines established. • Monitoring plan developed. • Risk assessment completed. • Regulatory approval/permitting achieved.
Injection	Conformance and assurance monitoring to confirm operational requirements and regulatory compliance.	• Injection rates and capacity targets not met. • Rapid over-pressurisation of the reservoir. • Loss of well integrity. • Unintended CO_2 migration outside of the targeted storage complex.	• Operation and Monitoring plans meet objectives and are updated as needed. • Risk assessment conformance is achieved and is updated as needed.
Post-Injection	Monitoring for ongoing regulatory compliance and confirming containment.	• Unintended well/ storage complex migration.	• Update the monitoring plan and risk assessment to reflect the injection cessation. • Ensure long-term stewardship.

[1] Benson, S. (2007). Addressing Long-term Liability of Carbon Dioxide Capture and Geological Sequestration. World Resources Institute Workshop Summary.

[2] Model reproduced from Benson, S., Carbon Capture and Storage: Research Pathways, Progress and Potential, GCEP Annual Symposium, Stanford University, 2007.

AFTER NEARLY A DECADE OF OPERATING AND INJECTING 8.8 MILLION TONNES OF CO_2, THE SHELL QUEST PROJECT GATHERED EXTENSIVE DATA DEMONSTRATING THAT THE INJECTED CO_2 BEHAVED AS PREDICTED WITHIN THE STORAGE COMPLEX.[3]

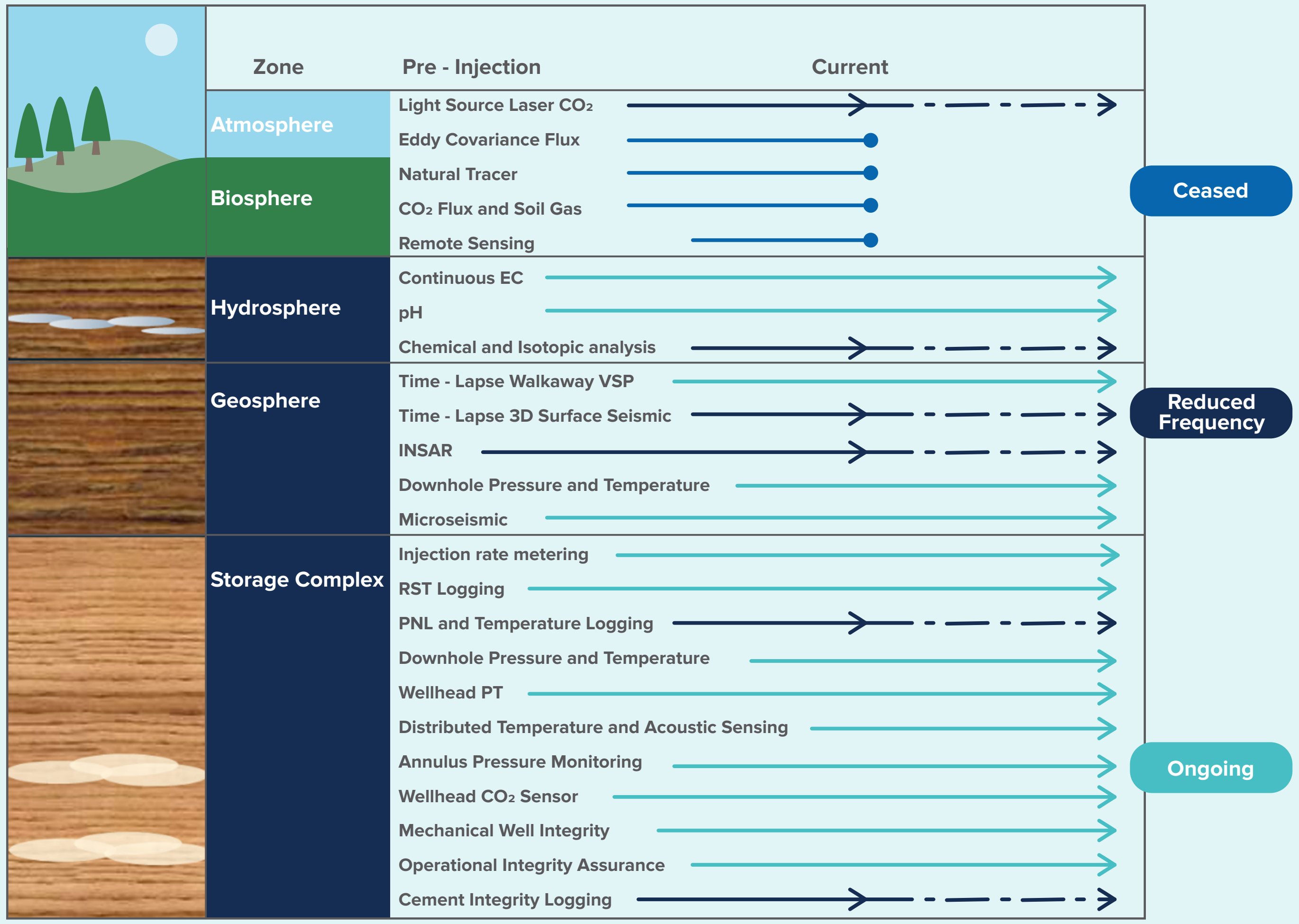
CASE STUDY

SHELL QUEST MONITORING PLAN EVOLUTION

In 2023, the Quest Project implemented a strategic optimisation in monitoring activities, reflecting an adaptive approach based on accumulated data and risk assessments.[3] After nearly a decade of operating and injecting 8.8 million tonnes of CO_2, the project gathered extensive data demonstrating that the injected CO_2 behaved as predicted within the storage complex.

With the likelihood of surface leakage now minimal, atmospheric and biosphere monitoring tools were no longer required. Additionally, time-intensive and costly activities, such as time-lapse 3D seismic surveys, were scaled back. Beyond demonstrating continued conformance and assurance, the updated monitoring plan reduces risk by detecting potential leakage through wells. These adjustments were made in close consultation with regulatory authorities to ensure ongoing compliance and transparency. This real-world data aligns with the lifecycle risk profile discussed above.

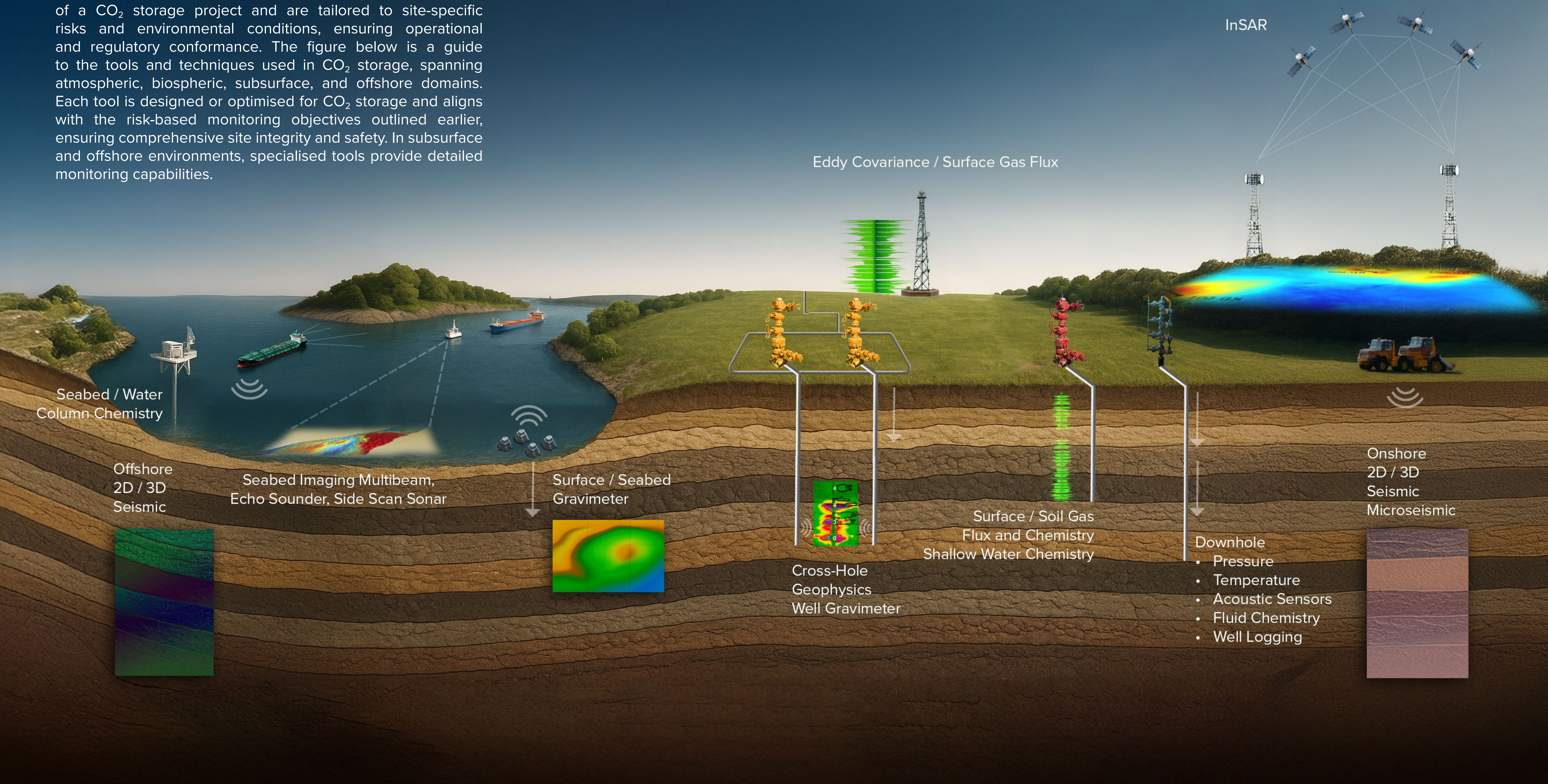
Figure 3: The evolution of Shell Quest's monitoring plan.



[3] Shell Canada Limited. (2023). Quest Carbon Capture and Storage Project: Measurement, Monitoring and Verification Plan.

4.0 MONITORING TECHNOLOGIES

Monitoring technologies are employed throughout the lifecycle of a CO_2 storage project and are tailored to site-specific risks and environmental conditions, ensuring operational and regulatory conformance. The figure below is a guide to the tools and techniques used in CO_2 storage, spanning atmospheric, biospheric, subsurface, and offshore domains. Each tool is designed or optimised for CO_2 storage and aligns with the risk-based monitoring objectives outlined earlier, ensuring comprehensive site integrity and safety. In subsurface and offshore environments, specialised tools provide detailed monitoring capabilities.



4.1 Monitoring Zone Objectives

In addition, the monitoring tools deployed have special objectives depending on the environment in which they operate. The five key environments and technology deployment are:

ATMOSPHERE

Airborne electromagnetic (EM) systems and airborne spectral imaging indirectly and directly monitor CO_2 concentrations and detect unexpected emissions. Satellite interferometry (InSAR) detects surface deformation related to CO_2 plume movement in the storage formation

BIOSPHERE

Technologies such as eddy covariance, soil gas concentration measurements, and groundwater chemistry analysis are used to monitor gas fluxes and detect changes in soil or groundwater chemistry that could indicate CO_2 leaks.

WATER COLUMN & SEABED

Technologies include bubble stream detection, multi-echo soundings, and seafloor gas sampling to monitor CO_2 leakage and ensure integrity above the storage site.

BIOSPHERE TO SUBSURFACE

Surface seismic imaging and gravity measurements contribute to monitoring by detecting subsurface changes such as CO_2 plume movement, density variations, and potential structural shifts in the storage formation.

SUBSURFACE

Downhole sensors measure fluid chemistry, pressure, and temperature in the injection zone, enabling precise tracking of CO_2 behaviour. Geophysical logging and seismic profiling detect changes in rock formations, while cross-hole and well gravimetry map the movement of the CO_2 plume within the storage formation.

This multi-layered approach, integrating diverse technologies, provides comprehensive safeguards for CO_2 storage sites, ensuring their safety and integrity over time.

4.2 Commercial Deployment

Extensive commercial experience supports the application of these technologies. For instance, Equinor's Sleipner CCS projects, operating offshore since 1996, has successfully employed a suite of monitoring techniques – including seismic surveys, gravimetric measurements, controlled-source electromagnetic (EM) surveys, and seabed monitoring. These are complemented by chemical sampling of water columns and seabed sediments, as well as wellhead gauges and metering systems. Together, some combination of these methods has effectively ensured the safety and long-term stability of the injected CO_2 at the Sleipner storage site.

Since their deployment in 1996, commercially available technologies used at Sleipner have been deployed at CCS projects worldwide. These technologies have been further refined for CO_2 detection and the operating environments of a CO_2 storage site. Collectively, these technologies have been deployed across a wide range of environments, geological settings, and operating conditions.

5.0 REGULATORY FRAMEWORKS AND STANDARDS ON STORAGE MONITORING

Regulatory frameworks are designed to ensure CO_2 storage monitoring practices achieve the objectives of quantification, containment, conformance, and assurance. By providing clear directives on the tools, methodologies, and monitoring frequencies, regulations ensure safety and some level of consistency across various CO_2 storage projects. This standardisation facilitates the comparison and analysis of data on a global scale, enabling stakeholders to assess performance metrics uniformly and share best practices effectively. However, limited availability of public monitoring data remains a challenge, highlighting the need for greater transparency and improved data access across the CCS community.

Mandated periodic reporting to regulatory bodies fosters transparency and accountability within CO_2 storage operations. These reports typically encompass monitoring results, risk assessments, and mitigation strategies, ensuring operators adhere to established protocols. When this information is published, that transparency can build public trust by demonstrating successful storage, environmental stewardship, and public safety.

Monitoring requirements can also incentivise the development and adoption of advanced technologies. To meet regulatory standards, operators can be driven to innovate, leading to the application of cutting-edge solutions such as satellite monitoring, machine learning algorithms for data analysis, and real-time sensing systems. While many of these technologies were not initially developed for CO_2 monitoring, they are increasingly being adapted and applied to the CCS context. These technological advancements enhance the precision and efficiency of monitoring activities, contributing to the overall effectiveness of CO_2 sequestration efforts.

Collaboration between regulators and industry stakeholders can foster the development of cost-effective monitoring solutions that balance financial feasibility with operational effectiveness. Encouraging the adoption of advanced technologies, such as real-time sensing systems and machine learning for data analysis, can improve the reliability and precision of monitoring practices. Additionally, establishing balanced regulatory frameworks tailored to individual project risk profiles can optimise monitoring requirements. For example, low-risk sites could adopt less intensive monitoring, while high-risk sites would necessitate more comprehensive measures.

Finally, reporting and regulatory oversight are important to identify and address project risks as early as possible. By addressing cost, technical, and regulatory challenges, these solutions can enhance the efficacy and economic viability of CO_2 storage projects, ensuring their long-term success.

Table 2: Regulatory requirements throughout the lifecycle of a CO_2 storage monitoring plan.

KEY STAGES	REGULATORY REQUIREMENT	EXAMPLES
Baseline Data Collection	Perform detailed site characterisation: geological assessments, seismic surveys, and fluid sampling to establish baseline conditions.	• European Union (EU) Directive 2009/31/EC, Article 8: Requires comprehensive site characterisation to assess potential risks. • ISO 27914: Section 7.4: Baseline monitoring requirements. • US Environmental Protection Agency (EPA) Underground Injection Control Class VI: Extensive site characterisation requirements.
Monitoring Plan Approval	Develop and submit a monitoring plan for regulatory approval, detailing methods for tracking CO_2 plume migration and detecting leaks.	• EU Directive 2009/31/EC, Article 13: The monitoring plan must be site-specific and approved by the competent authority. • EPA Class VI 40 CFR 146.90: A detailed monitoring plan is required to address all aspects of well integrity, CO_2 injection and storage, and groundwater quality.
Monitoring During Operations	Conduct regular monitoring during injection, including seismic surveys, pressure and temperature measurements, and detecting anomalies.	• EU Directive 2009/31/EC, Annex II: Specifies techniques for operational monitoring, including seismic imaging and pressure testing. • EPA Class VI 40 CFR 146.84: Comprehensive monitoring requirements that address all aspects of well integrity, CO_2 injection, and long-term storage.
Post-Closure Monitoring	Perform long-term monitoring to confirm secure storage of CO_2, ensuring pressure stabilisation and absence of leaks.	• EU Directive 2009/31/EC, Article 18: Requires at least 20 years of post-closure monitoring unless stability is confirmed earlier. • ISO 27914: Section 8.3.3: Outlines parameters for post-closure performance assessment. • EPA Class VI 40 CFR 146.93: Post-injection site care. • Australia OPGGSA: Operators are responsible for the site for a minimum of 15 years, known as the closure assurance period.

6.0 CONCLUSION

CO_2 storage monitoring ensures CCS projects' safety, efficacy, and scalability. By addressing key objectives of quantification, containment, conformance, and environmental safety, CO_2 storage monitoring provides the foundation for verifying the secure and permanent storage of CO_2. Comprehensive risk management plans, underpinned by advanced monitoring technologies and robust regulatory frameworks, enable operators to detect and mitigate risks effectively across a storage project's lifecycle.

The evolution of monitoring programs, as demonstrated by landmark projects such as Sleipner, Quest, and others, showcases the importance of adapting strategies based on real-time data and site-specific risks. These projects highlight how balancing operational efficiency, cost-effectiveness, and regulatory compliance can foster public trust and ensure long-term storage integrity. Tailoring monitoring requirements to risk profiles and integrating advanced tools into cost-effective frameworks will be essential for scaling CCS while maintaining environmental and operational safety.

As the CO_2 storage industry grows, the collaborative efforts of regulators, industry stakeholders, and technology developers will be pivotal in optimising monitoring practices and ensuring the safety of CO_2 storage.

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