17th International Conference on Greenhouse Gas Control Technologies, GHGT-17

20th -24th October 2024, Calgary Canada

Environmental MMV for offshore storage – are we there yet?

Jerry Blackford[a]*, Guttorm Alendal[b]

[a]*Plymouth Marine Laboratory, Prospect Place, Plymouth, PL1 3DH, UK*
[b]*Department of Mathematics, University of Bergen, N-5020 Bergen, Norway,*

Abstract

Over the last two decades the environmental aspects of offshore storage have attracted a significant amount of research. Initially questions were framed around assessing if unplanned events, namely leakage, posed a significant threat to marine ecosystems. Subsequently the research refocused onto the development of tools and strategies to enable offshore MMV. This short paper provides an assessment of the key conclusions to date, the state of play in transferring this research into operational practice and details the next steps.

Keywords: Carbon Capture and Storage, Monitoring Measurement and Verification, Offshore, Marine, Environment.

1. Background

Subsea CO_2 storage is an essential contributor to net zero goals, mitigating climate change [1], but requires monitoring for safety and reliability (MMV, Measurement, Monitoring and Verification). As the number of offshore storage projects increases to meet the global demand for carbon sequestration, the development of efficient MMV approaches becomes more pressing, primarily to provide assurance of geological containment. Subsurface monitoring techniques, such as seismic surveys, pressure monitoring and tracer tests, combined with numerical geological flow modelling, are the first line of technology to verify the integrity of CO_2 storage and detect any anomalies in the storage reservoir. However, in the unlikely event or threat of leakage, for regulatory reasons, or simply for additional assurance, monitoring in the marine environment, at or near the seabed, may be required to detect and quantify any CO_2 fluxes and resulting impact, if any, on the marine ecosystem. Release of hypersaline brines into the marine environment may also occur or be necessary as part of pressure management of saline aquifer CO_2 stores, also requiring monitoring.

Marine monitoring may also help to increase public acceptance and confidence in the safety and effectiveness of offshore storage technology. Environmental monitoring of offshore CO_2 storage is aligned with the objectives of the

* Corresponding author. Tel.: +44 7747862190, jcb@pml.ac.uk

UN Decade of Ocean Science for Sustainable Development (2021–2030) and the Sustainable Development Goal 14 (SDG 14) to conserve and sustainably use the oceans, seas, and marine resources. Whilst international CCS monitoring policies, regulations and guidelines are numerous, they in general contain similar principles which do not prescribe particular technologies or thresholds, but mandate that best-available technology and site-specific approaches be taken [2].

The bow tie method is a valuable tool for communicating and managing risks for CCUS by visualizing threats, consequences, and safeguards. It starts with identifying a top event, such as CO_2 migrating out of the intended formation, and analyzing events that can cause the top event, like geological faults or abandoned wells and potential consequences. Preventive measures, such as robust site selection and proper well design, and corrective actions, like leak response plans, are established. This method also guides the design of MMV plans with ongoing monitoring and inspections, enhancing the safety and effectiveness of CCUS projects. However, the method relies on expert judgment, potential oversimplification, and the need for high-quality data to ensure reliability [3,4].

Relating to environmental MMV, the top event would be stored CO_2 reaching the ocean floor. Preventative measures like proper site characterization, selection, and monitoring, combined with modeling efforts, are essential. If anomalies are detected, corrective measures like pressure reduction can be implemented. Even with these measures, a leak could impact the marine environment, though research suggests this impact would be local. Another significant consequence of a leak could be the loss of public acceptance, especially given the substantial resources invested in CO_2 storage.

Monitoring to provide environmental assurance of robust storage for subsea geological storage can in theory be an expensive undertaking, and with low likelihood of leakage, cost inefficient. Challenges are numerous. Apart from accessing a remote and sometimes hostile environment, natural gas seeps and the highly dynamic nature of marine chemistry and biology make anomaly detection with acceptably low false positive rates potentially hard to achieve. There can be uncertainty about the requirements for baseline monitoring, and the necessity of long-term monitoring programs. The level and frequency of monitoring needed to provide sufficient assurance is a key question.

Over the last two decades a significant research and development effort has been devoted to offshore environmental impact assessment and MMV approaches [e.g. 5,6,7]. So, where are we, and what is left to do?

2. Methods

Various methodologies enabled the conclusions presented here. Controlled release experiments have been instrumental in assessing flows, impacts and testing instruments [5,8], whilst many different modelling systems, both geological and marine have allowed the exploration of what-if scenarios [9, 10]. More recently digital techniques have been supplemented by machine learning to develop decision support tools [11,12]. These are explained in detail in the cited papers.

3. Key questions reviewed

We consider 5 key questions:

- Is there potential for significant environmental impact from releases due to storage faults or pressure management activities?
- How could a non-conformity (leak) be distinguished from natural variation and what measurements (prior or ongoing) are needed to support monitoring and is this site-specific?
- What is the technology readiness level of sensors and platforms?
- Can we define cost-efficient strategies for monitoring?
- What is the optimal translation of the R&D into practice, including consideration of social licence to operate?

3.1 Impact Assessment

Whilst predicting or quantifying any impact is subject to ecosystem heterogeneity, there is a robust relationship between release rates of CO_2 or hypersaline brines, the area impacted by the resulting perturbation and consequently the distance from the source within which the signal would be detectable [9,13], fig 1. From this work, which is mainly model driven, but corroborated by release experiments, we can conclude that (unlikely) releases of order 1TCO_2/d or less, whilst challenging to detect, would have a very minimal impact on the ecosystem, due to rapid dilution driven by hydrodynamic mixing. In the highly unlikely case of a larger release, detection, potentially prior to any CO_2 reaching the environment, would be relatively easy, such that the release could be mitigated by plugging or pressure management at an early stage. Other work [14] has shown that biological systems can recover over relatively short timescales, if impacted, although other stressors (climate, eutrophication, hypoxia etc.), would be a factor. Similarly for scenarios of hypersaline brine release, impact from salinity or temperature perturbations occupy a very small area. Contaminants, such as heavy metals, may be the most hazardous issue associated with hypersaline brine release [13].

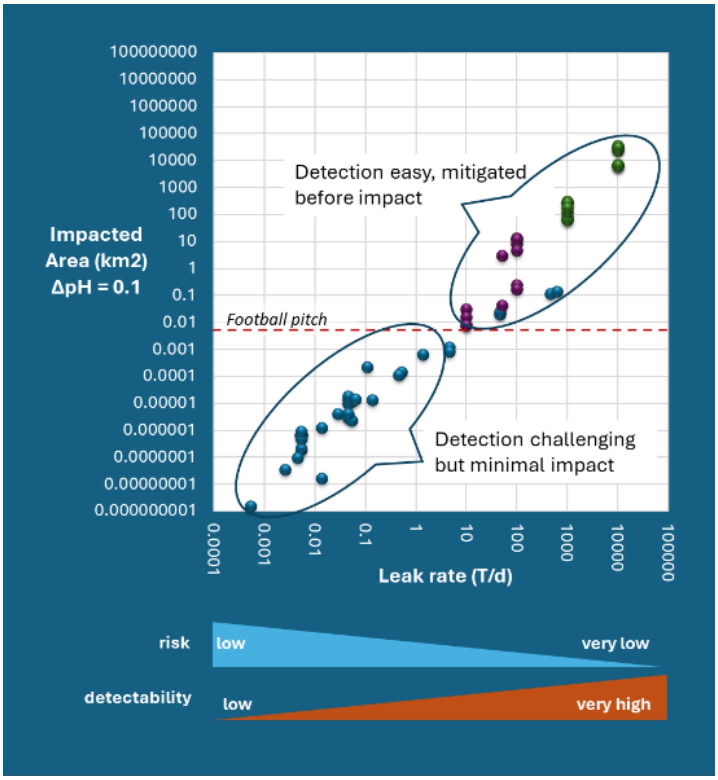

Fig 1. Relationship between leak rate and impacted area, based on an ensemble of different model simulations (marker colours denote different model systems). Redrawn from [7].

3.2 Anomaly recognition and data needs

A challenge, especially in detecting small releases, is how to distinguish anomalous signals from the potentially complex natural variability of the marine system, without creating too many expensive false positives (or damaging false negatives). Various detection methods have been tested, concluding that a dual approach of using acoustic techniques to detect bubbles, coupled with chemical sensors to detect dissolved plumes is optimal. Both have advantages and disadvantages, but together can cover the Detection/Attribution/Quantification/Impact Assessment flow of the monitoring process [15], see fig 2.

Gas flow in ocean sediments is a natural and frequent phenomenon, caused by respiration, decomposition, methane hydrate breakdown, thermogenic breakdown of organic matter and natural geological processes. The shape of the bubble plume, with respect to the individual bubble size may provide clues as to bubble composition. For example, CO_2 bubbles dissolve rapidly e.g. within meters of leaving the seafloor, whilst methane is less soluble, and a greater rise height would be expected. Data needs to support monitoring may require a baseline survey of extant, natural bubble plumes, however both natural and leakage bubble plumes can be intermittent, suggesting that attribution via direct gas sampling would be important.

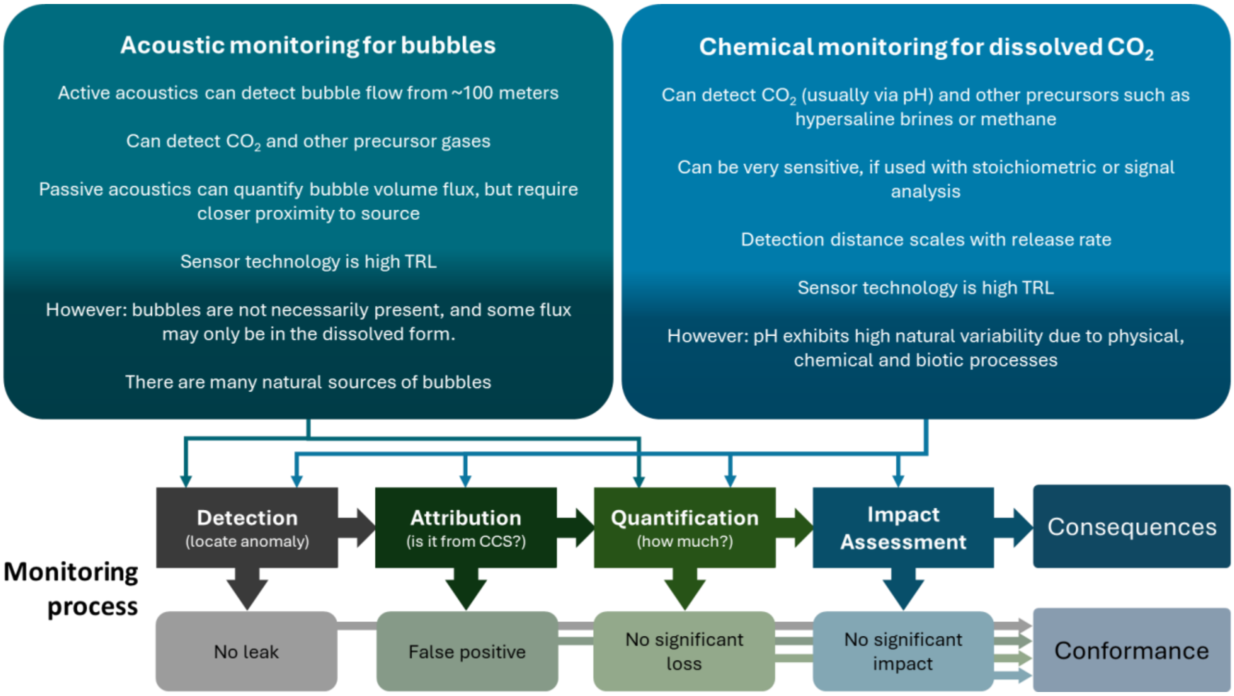

Fig 2. The relationship between monitoring techniques and monitoring process.

Dissolved CO_2 is a ubiquitous, substantive and variable quantity in the oceans, affected by processes such as photosynthesis, respiration, temperature changes and alkalinity – all of which vary spatially and seasonally. Thus, defining anomaly thresholds as a simple exceedance of a given value provides a relatively insensitive metric, prone to false results. Two methodologies have been developed which deliver highly sensitive anomaly criteria. The first emerges from the natural co-variance of marine CO_2 (as measured by pH or pCO_2) with other variables such as temperature, oxygen, and sometimes salinity or nutrients, as these are also affected by natural processes. Hence an exceedance from a defined stoichiometric relationship, as enshrined in the CSEEP method [16], provides a robust metric of an anomalous signal. The second depends on tidally driven mixing, and whilst only requiring pH to be measured, is best suited to regions where tidally driven oscillation of the water mass is strong (the NW European Shelf being one such location). This method depends on higher frequency measurements with an anomaly triggered by a more rapid change in pH than normal for natural processes, which occur as tidal currents sweep a plume of high CO_2 water over a sensor location [17]. Both methods require a characterization of natural variability, rather than a fixed baseline to establish the reference conditions.

Collating baseline or characterization data can be potentially expensive in offshore environments, however much information, in the form of observational databases, reanalysis model systems (models that have assimilated observations to reduce error) and reports exist and are in the public domain, depending on location [18]. Additional data can be sourced opportunistically from planned at sea operations to supplement. Hence data collation, whilst essential to reduce costs associated with false positives/negatives is not necessarily a costly process, and can be assembled via a staged approach, fig 3. Sharing data and contributing to ocean observatory initiatives from CCUS projects can also help strengthen public acceptance [19,20]. The growing collection of offshore environmental data is enhancing marine spatial planning and ocean governance. This is and will further enable, artificial intelligence (AI) and machine learning (ML) methods to improve analysis and predictions.

	HOW to use in a staged characterisation approach	**WHERE** to access	**WHAT** needs to be measured	**WHY** it needs to be measured
0.	**Geological characterisation** Definition of storage complex location and infrastructure siting	Operator site assessment Existing geological surveys	Presence and location of geological features that may affect risk.	**Detection:** Monitoring strategy – distribution of sensors **Attribution:** Connecting anomalies to geological features **Impact potential:** Distribution of risk relative to ecological sensitivities
1.	**Regional physical and biochemical characterisation** Use existing datasets to characterise the regional marine system and understand the principle drivers , variability and stressors of the system in terms of physics and biochemistry.	Models derived projections Earth Observation data Observational databases	Spatial and temporal discrimination of: Carbonate system (DIC, pH, pCO2) Co-variables (O2, T, S, nutrients) Risks of anoxia Dominant currents and tidal features	**Detection:** Provision of baseline charcterisation enabling definition of high fidelity anomaly criteria and planning of monitoring strategies relative to hydrodynamic features.
2.	**Geophysical and ecological key features, site utilisation.** Desk study to assess key features of the complex: relating to resource use, ecological importance and geophysical features	Observational databases, Scientific literature Marine traffic data Govt. agency databases and reports	Protected species, areas and functions (e.g. spawning ground, MPAs), attributes (e.g. supports fisheries), fishing pressures Occurrence of biogenic sediment gas production including CH4, CO2. Sediment type distributions and associated ecosystems	**Impact potential:** Are there ecologically or social important uses of the area that indicate a greater sensitivity to CCS operations? Identification of ecosystem types and distribution. **Attribution:** Enabling attribution of anomalies to CCS processes via knowledge of natural seepage **Detection:** Will other uses impede monitoring activities?
3.	**Leakage characterisation** High resolution simulation models to simulate hypothetical scenarios, identifying areas that have an enhanced risk of impact Could occur in response to geological or water column anomalies, rather than a-priori, especially if high resolution model systems describing the region already exist.	High resolution hydrodynamic modelling systems Existing models or requiring some model development, depending on location.	Spatial and temporal discrimination of: carbonate system (DIC, pH, pCO2) for a selection of leak scenarios.	**Detection:** Enables detail planning and assessment of marine monitoring strategies **Quantification:** Describes relationship between leak rates and observable footprints **Attribution:** Describes relationship between leak location and observable footprints **Impact potential:** Identifying areas that have an enhanced risk of impact
4.	**Focused Surveys** Sampling of hydrodynamics, physics and chemistry to validate models and EO data; observations of more vulnerable habitats and ecosystems; assessment of seeps May not be required if model and observational data is sufficiently evaluated and detailed.	New deployments, of existing oceanographic technology, potentially autonomous.	Carbonate system (DIC, pH, pCO2) Co-variables (O2, T, S, nutrients) Spatial and temporal discrimination Protected species, functions (e.g. spawning ground), attributes (e.g. supports fisheries) Occurrence of biogenic sediment gas production including CH4, CO2.	**Impact potential:** Are there any ecologically of social important uses of the area that indicate a greater sensitivity to CCS operations? Identification of ecosystem types and distribution. **Detection:** Ground truthing/evaluation of synthetic data from models, earth observation and updating of direct observations.

Fig 3. A staged approach to data acquisition to support offshore monitoring, reproduced from [16]

Further progress with data-driven analytical solutions for monitoring optimisation will rely on the integrated development of data collation, simulation modelling and AI/ML techniques. Data-driven modelling, such as ML, require simulations and predictions of how unlikely gas releases through the seafloor might impact environmental parameters [21]. That said, anomaly detection based on such model predictions, which are tuned and validated by environmental data, will inherit any uncertainties and biases present in the data [22,23]. When stakes are high, it is crucial that AI predictions can be explained and justified. This then mandates increasing research activities in the field of explainable AI [24]. Model error comes from two main sources: using a model that's too simple and errors spreading from uncertain input data. When a model is too simple, it doesn't capture all the important details, but making the model more complex can reduce this error. However, as the model gets more complex, the uncertainty in the input data can cause more errors in the output. In complex systems, missing important processes can lead to errors, so it's crucial to find the right balance in model complexity [25]. Aleatory uncertainties, i.e. natural variability, will require a probabilistic approach in the data analysis. Unforeseen events, or epistemic uncertainties, that are not resolved in measurements and modelling will also impose uncertainties in the analysis.

3.3 Technology readiness of Sensors and Platforms

Instruments and sensors suitable for marine environmental monitoring are generally well established. Oxygen, pH, temperature, salinity and nutrient probes are all available off the shelf, to a high specification and incorporation of these onto fixed landers or mobile vehicles is routine [26]. Similarly acoustic sensors, both passive and active are available [27, 28] and have been tested operationally. There are certainly improvements in sight, for example battery longevity, protection against sensor drift and biofouling, and optimal methods of communicating data to "shore" for analysis. Mobile vehicles have some constraints in operating near the sea floor due to collision danger, and all platforms are at risk from other marine activities, especially if deployed in busy near coast settings. Choice of sensor – platform options is facilitated by open online tools, e.g. [29,30].

3.4 Monitoring Strategies

Given that the precise location of an unplanned release is a-priori unknown, and that environmental monitoring needs in theory to cover a storage footprint that may be order 100 km^2, the optimal placement or deployment of sensors is imperative. Site characterization is crucial. In particular this should include [18]:

1. Knowledge of geophysical features that may increase risk of CO_2 movement – such as faults, outcrops and abandoned wells. Such information will be readily available from geological site characterization.
2. Knowledge of marine hydrodynamics as influenced by geostrophic, tidal, coastal and atmospheric processes. Such information is readily provided by reanalysis models covering much of the globe.
3. Knowledge of biochemical variability, in particular carbonate chemistry and co-variables such as oxygen and nutrients. Here a combination of predictive and reanalysis models and observational datasets can minimize the need for additional data acquisition.

Various digital techniques that enable optimal monitoring strategies have been developed recently, using techniques such as set cover set [9] or greedy set algorithms [10] for fixed installations and Bayesian methods [31] or travelling salesman algorithms for moving platforms [32,33]. The ACTOM MMV strategy tool [34], provides a desktop enabled toolkit that derives a site-specific deployment strategy, based on geological feature mapping, prevailing hydrodynamics and biochemical characterization. This enables the user to examine deployment options, such as number of sensors, discover the optimal anomaly approach, test the consequences of different monitoring sensitivities and understand impact potential, collectively underpinning a cost benefit analysis (fig 4).

3.5 Operational considerations and social license

Whilst science, research and development provide more than adequate tools and knowledge by which to deliver MMV, the unresolved question is how much monitoring is required, factoring in regulatory, operational and societal needs. Regulations are non-prescriptive, operational needs require a balance between cost and assurance, whilst social license derives from a complex mix of perceptions about safety, the environment, cost, technology, multiple use, and the industries involved [35]. Optimal MMV solutions could well have an element of locally mandated features, beyond that necessitated by the biogeochemical nature of the site. The development of best practice guides based on operational deployments would be the next logical step, enabling the testing of sensors and strategies in a cost-benefit, regulatory and social arena.

4. Summary and next steps

We propose that the various studies undertaken investigating impact potential, developing sensors and platforms, determining anomaly criteria, and developing deployment strategies put us in a position such that understanding, technology and techniques are fully adequate for the task at hand. What remains is firstly to ease the translation of generic understanding to specific sites and operations, secondly a multi-stakeholder led dialogue about how much monitoring and assurance is desirable or required – an answer which will likely be specific to circumstances, and thirdly the embedding of this knowledge in guidance in a way that is useful without creating inflexibilities.

Without doubt further sensor development, more controlled release experiments, the improvement of decision support tools and evolution of monitoring platforms, smart autonomy, sea to shore comms and especially the exploitation of emerging AI/ML capabilities will deliver more robust and cost-efficient MMV systems that support subsea CO_2 storage in the future. Our key argument is that existing capability and understanding are sufficient for the task at hand, do not in any way create a barrier for offshore storage deployment now. The climate time bomb is ticking loudly, action is imperative.

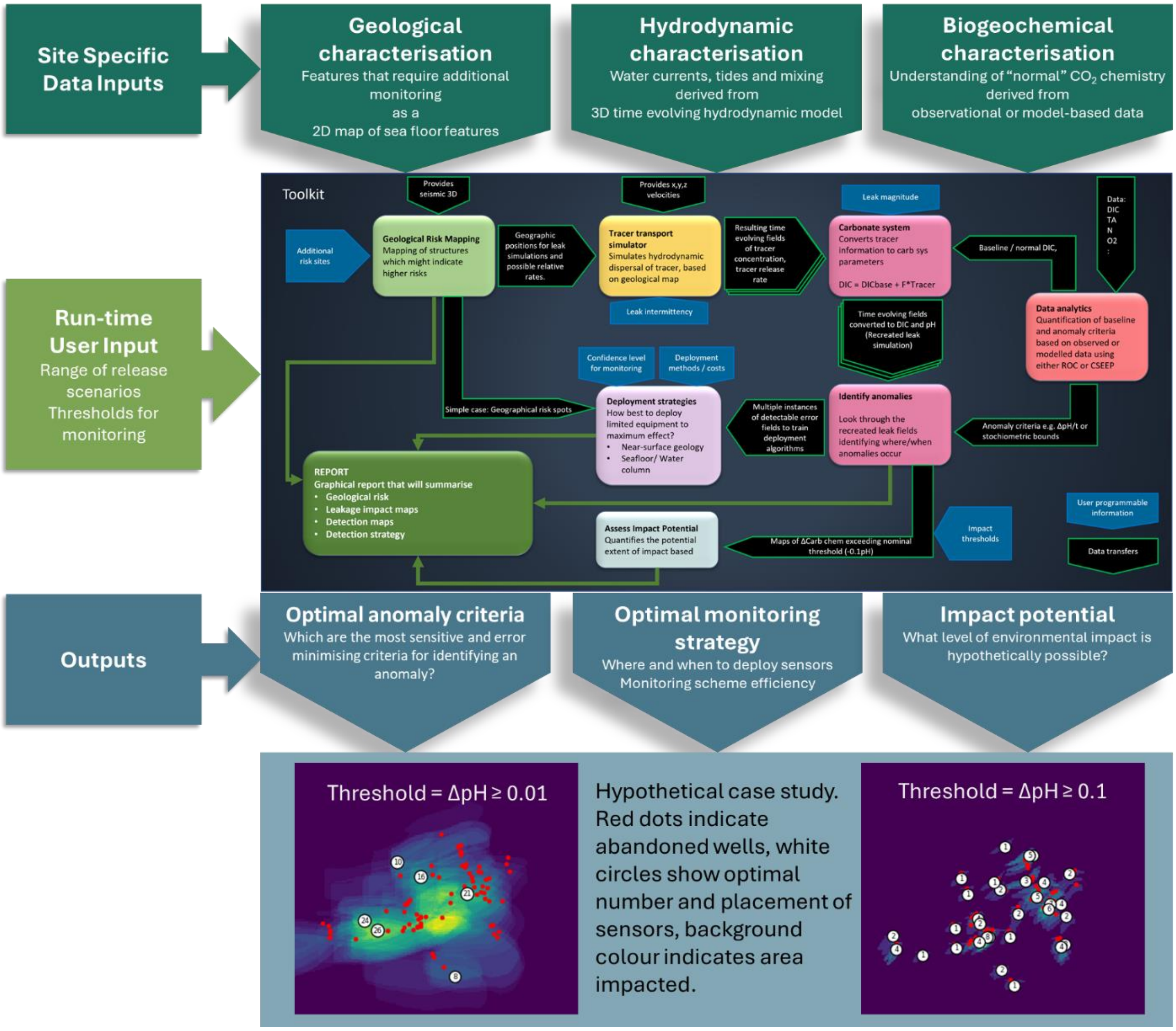

Fig 4. Schematic of the ACTOM decision support tool, enabling the planning of monitoring strategies.

References

[1] IPCC. Carbon Dioxide Capture and Storage. Metz B, Davidson O, Coninck H, Loos M and Meyer L (Eds.) Cambridge University Press, UK. pp 431. 2005.

[2] Schütz, S. E., & Omar, A. Report on regulations and technological capabilities for monitoring CO_2 storage sites. Universitetet i Bergen. https://hdl.handle.net/11250/3091342, 2023.

[3] Ruijter, A. de, and F. Guldenmund. 'The Bowtie Method: A Review'. Safety Science 88: 211–18. 2016.

[4] Dean, M & O'Brien, S. Best Practices for Risk-Based Measurement, Monitoring, and Verification in CCUS Projects. TWA. 2024. https://jpt.spe.org/twa/best-practices-for-risk-based-measurement-monitoring-and-verification-in-ccus-projects.

[5] Blackford, J., Stahl, H., Bull, et al. Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage. Nat Clim Change 4(11), 1011-1016, 2014.

[6] Dean, M., Blackford, J., Connelly, D., Hines, R. Insights and guidance for offshore CO_2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects. Int J Greenh Gas Con 100, 2020.
[7] Connelly, D.P., Bull, J.M., Flohr, A., et al. Assuring the integrity of offshore carbon dioxide storage. Renewable & Sustainable Energy Reviews 166, 2022.
[8] Flohr, A., Schaap, A., Achterberg, E.P., et al. Towards improved monitoring of offshore carbon storage: A real-world field experiment detecting a controlled sub-seafloor CO_2 release. Int J Greenh Gas Con 106, 103237, 2021.
[9] Blackford, J., Alendal, G., Avlesen, H., et al., Impact and detectability of hypothetical CCS offshore seep scenarios as an aid to storage assurance and risk assessment. Int J Greenh Gas Con 95, 2020.
[10] Xi Jiang. A review of physical modelling and numerical simulation of long-term geological storage of CO_2, Applied Energy, Vol. 88, Issue 11, pp. 3557-3566, 2011.
[11] Oleynik, A., Garcia-Ibanez, M.I., Blaser, N., Omar, A., Alendal, G. Optimal sensors placement for detecting CO_2 discharges from unknown locations on the seafloor. Int J Greenh Gas Con 95, 2020.
[12] Cazenave, P.W., Bedington, M., Bruggeman, J., et al. Optimising environmental monitoring for carbon dioxide sequestered offshore. Int J Greenh Gas Con, 110:103397, 2021.
[13] Dewar, M., et al. Impact potential of hypersaline brines released into the marine environment for CCS reservoir pressure management. Int J Greenh Gas Con 114: 103559, 2022.
[14] Widdicombe, S., et al. Impact of sub-seabed CO_2 leakage on macrobenthic community structure and diversity. Int J Greenh Gas Con 38: 182-192, 2015.
[15] Dixon, T. and Romanak, KD. Improving monitoring protocols for CO_2 geological storage with technical advances in CO_2 attribution monitoring. Int J Greenh Gas Con 41: 29-40, 2015.
[16] Omar, A.M., García-Ibáñez, M.I., Schaap, A., et al. Detection and quantification of CO_2 seepage in seawater using the stoichiometric Cseep method: Results from a recent subsea CO_2 release experiment in the North Sea. Int J Greenh Gas Con 108: 103310, 2021.
[17] Blackford, J., Artioli, Y., Clark, J., de Mora, L. Monitoring of offshore geological carbon storage integrity: Implications of natural variability in the marine system and the assessment of anomaly detection criteria. Int J Greenh Gas Con 64: 99-112, 2017.
[18] Blackford, J., Romanak, K., Huvenne, V.A., et al. Efficient marine environmental characterisation to support monitoring of geological CO2 storage. Int J Greenh Gas Con 109: 103388, 2021.
[19] Ågerstrand, M, Arinaitwe K, Backhaus T, et al. Key Principles for the Intergovernmental Science–Policy Panel on Chemicals and Waste. Environmental Science & Technology, 2023.
[20] Smith, LM., Barth JA, Kelley DS, et al. The Ocean Observatories Initiative. Oceanography 31 (1): 16–35, 2018.
[21] Gundersen, K, Alendal G, Oleynik A, and Blaser N. Binary Time Series Classification with Bayesian Convolutional Neural Networks When Monitoring for Marine Gas Discharges. Algorithms 13 (6): 145, 2020.
[22] Allison, R, and Dunkley J. Comparison of Sampling Techniques for Bayesian Parameter Estimation. Monthly Notices of the Royal Astronomical Society 437 (4): 3918–28, 2014.
[23] Zhang, J. 2021. Modern Monte Carlo Methods for Efficient Uncertainty Quantification and Propagation: A Survey. WIREs Computational Statistics 13 (5): e1539, 2021.
[24] Linardatos, P. Papastefanopoulos V, and Kotsiantis S. Explainable AI: A Review of Machine Learning Interpretability Methods. Entropy 23 (1): 18, *2021*.
[25] Saltelli, A. A Short Comment on Statistical versus Mathematical Modelling. Nature Communications 10 (1): 3870, 2019.
[26] Lichtschlag, A., Pearce, C.R., Suominen, M., et al. Suitability analysis and revised strategies for marine environmental carbon capture and storage (CCS) monitoring. Int J Greenh Gas Con 112, 103510, 2021.
[27] Li, Ji, White, P, Roche, B, Bull, et al. Acoustic and optical determination of bubble size distributions - quantification of seabed gas emissions. Int J Greenh Gas Con, 108, [103313], 2021.
[28] Li, J, White, P, Bull, J, et al. Passive acoustic localisation of undersea gas seeps using beamforming. Int J Greenh Gas Con, 108, [103316], 2021.
[29] Monitoring Selection Tool - IEAGHG https://ieaghg.org/monitoring-selection-tool/

[30] STEMM-CCS Monitoring Tool https://stemm-ccs.eu/monitoring-tool/
[31] Alendal, G. Cost Efficient Environmental Survey Paths for Detecting Continuous Tracer Discharges. Journal of Geophysical Research: Oceans 122 (7): 5458–67, 2017.
[32] Torabi, P, Hemmati A, Oleynik A, and Alendal G. A Deep Reinforcement Learning Hyperheuristic for the Covering Tour Problem with Varying Coverage. Computers & Operations Research 174, 106881, 2025.
[33] Torabi, P, Oleynik A, Hemmati A, and Alendal G. Covering Tour Problem with Varying Coverage: Application to Marine Environmental Monitoring. Applied Mathematical Modelling 124, 279–99, 2023.
[34] ACTOM Decision Support Tool for monitoring strategies. https://pml.ac.uk/projects/ACTOM-Decision-Support-Tool/
[35] Broecks, K, et al. How do people perceive carbon capture and storage for industrial processes? Examining factors underlying public opinion in the Netherlands and the United Kingdom, Energy Research & Social Science, Vol. 81,102236, 2021.