Marine monitoring of carbon capture and storage: Methods, strategy, and potential impacts of excess inorganic carbon in the water column

FME SUCCESS Synthesis report Volume 5

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Carbon Capture and Storage (CCS) is considered an essential mitigation strategy in order to reduce anthropogenic CO₂ emissions. To meet the 2°C target set in the Paris Agreement, decarbonization of the global power sector by the 2030s and the heavy industry sector beyond that is critical. CCS is currently the only option for decarbonizing the steel, chemical and cement industries.

CCS is a proven method (e.g. at Sleipner, Snøhvit, In Salah, Weyburn, Boundary Dam, Quest). There are remaining technical challenges related to upscaling, however, and cost is a critical factor in large-scale deployment of CCS.

In order to stimulate relevant research, the Norwegian Research Council has established a scheme of Centers for Environment-friendly Energy Research (FME) to develop expertise and promote innovation by focusing on long-term research in selected areas of environment-friendly energy, including CCS.

**The FME SUCCESS center**

The SUCCESS center for SUbsurface CO₂ storage was awarded FME status in 2009 and was formally inaugurated on 1 January 2010.

Key to public acceptance and successful deployment of CCS, the FME SUCCESS center focuses on effective and safe storage of CO₂. To meet the regulatory requirements for Measurement, Monitoring and Verification (MMV), the SUCCESS center seeks to provide a sound scientific base for CO₂ injection, storage and monitoring in order to fill gaps in strategic knowledge, and to provide a system for learning and development of new expertise. Such knowledge is vital in order to ensure conformance (concordance between observed and predicted behavior), containment (proving storage performance in terms of security of CO₂ retention) and contingency (leakage quantification and environmental impacts).

The following objectives were defined in the FME SUCCESS application:

- To improve our understanding and ability to quantify reactions and flow in carbon storage.
- To develop advanced modeling tools for multiphase flow and reaction.
- To investigate the integrity of sealing materials, and test their retention capacity.
- To improve our understanding and develop new models for the relationship between saturation, flow and geomechanical response.
- To improve our understanding and develop new models for geochemical and geomechanical interactions.
- To improve our understanding and modeling tools for flow and reaction in faults and fractures.
- To test, calibrate and develop new monitoring techniques and instrumentation.
- To improve the understanding of shallow marine processes and the ecological impact of CO₂ exposure, and develop marine monitoring methods.
- To reduce risk and uncertainties in sub-surface CO₂ storage.
- To facilitate extensive and high-quality education on CO₂ storage.

*Field excursion Unis CO₂ lab workshop, Svalbard 2012*
One of the strengths of the FME SUCCESS center is its expertise within fundamental, theoretical research, which is internationally recognized; the center hence focuses on basic research, interpreting the results of field and laboratory experiments in order to predict the long-term effects of CO\textsubscript{2} storage. In particular, the center has used the theoretical platform to address critical and relevant scientific issues related to CO\textsubscript{2} storage.

Upon inauguration, the SUCCESS center was organized into six scientific work packages and one educational work package.

**Mid-term evaluation**

In 2013, the Norwegian Research Council conducted a mid-term evaluation of the FME centers. The mid-term evaluation of the SUCCESS center concluded that the center needed to undertake major changes in the organization and operational structure to secure integration and industry relevance.

Following the recommendations of the mid-term evaluation, the SUCCESS center reorganized the scientific activities into three work packages:

- Work Package 1: Reservoir
- Work Package 2: Containment
- Work Package 3: Monitoring

An integration Work Package, WP0, was also established for the final two year-period of the center. WP0 aimed to test and verify new knowledge and methodology developed at the SUCCESS center in connection with two case studies. The Skade and Johansen formations were originally chosen as case studies. The Johansen Formation was later replaced by the Smeaheia project case, which is the selected reservoir candidate for Norwegian full-scale demo project.

**Final reports**

As part of the center’s scientific reporting, the center’s partners and board agreed that a set of reports would be written and...
summarize the major scientific findings and achievements. These reports have been referred to as Long-term Deliverables (LTD).

Knowledge and lessons from the two field pilots, Snøhvit and Sleipner, have been synthesized in separate summary reports (Volume 6 and 7). Lessons from the Longyearbyen CO$_2$ Lab, which has been an important test site for the SUCCESS center, have been and will be published in dedicated summary volumes of scientific journals.

The case studies on the Smeaheia fault block (deep, confined reservoir) and the Skade Formation (shallow, saline aquifer) in the North Sea are presented in separate reports in order to demonstrate the value of the results achieved at the SUCCESS center and associated projects, and determine how they can be applied to better quantify the storage feasibility of untested aquifers. They allow testing of the lessons and knowledge from the Snøhvit and Sleipner field pilots, and may constrain the range and use of the methods and models developed.

**Long-term deliverables**
The LTD reports (5) include the SUCCESS center’s final report on the above-mentioned deliverables. They aim to synthesize the results and findings of the SUCCESS center, and directly address the objectives of the SUCCESS center (see the figure below).

The LTD reports cover the following topics:

- **Storage capability (Volume 1)**
  This report summarizes the SUCCESS center’s work on storage capability, which is the ability of a formation to safely store CO$_2$. An important objective of this center has been to identify geological factors and the hydro-geomechanical processes that are most important for determining storage capability. The most important factor is whether the storage reservoir is open or closed.

- **Injectivity (Volume 3)**
  This report presents experimental and computational results that have enhanced our understanding of reservoir injectivity, including a basic understanding of mechanisms, quantification of the expected impact, model calibration and case specific implications. A main outcome is a workflow that includes new computational tools, new geochemical and geomechanical experimental design/data and research-based advice.

- **Containment**

- **Conformance**

- **Contingency**

**Leakage risks (Volume 2)**
Summarizing the results from field, experimental and theoretical studies of potential leakage mechanisms and their relevance to CO$_2$ storage site risk assessment, this report demonstrates that viscous deformation of the shales can play an important role in their ability to keep CO$_2$ contained and that material properties and their dynamic behavior in response to the stress introduced by CO$_2$ injection need to be evaluated in order to safeguard operations.

- **Geophysical monitoring (Volume 4)**
The geophysical monitoring report summarizes the SUCCESS center’s work on rock physics related to pore pressure and saturation and estimating these two parameters via geophysical monitoring. By estimating their spatiotemporal distribution, we can monitor the migration of injected CO$_2$ and determine whether the containment of storage complex is secure.

- **Marine monitoring (Volume 5)**
This report synthesizes relevant knowledge and data regarding marine monitoring methods and strategies for inorganic carbon in the water column, based on modeling and observational work. A cost-effective strategy for a marine monitoring program should optimize the probability of detecting a leak.
Relevance of work
The collective work of the SUCCESS center addresses various groups of stakeholders and the reporting structure is relevant to different communities. The report on storage capability is particularly relevant to storage site selection and Norwegian CO₂ storage capacity estimates, based on better constrained trapping efficiency and immobilization potential. The leakage risks report addresses important issues regarding safe operation of CO₂ storage and risk management. The report on injectivity provides valuable knowledge on the planning of CO₂ operations and reservoir utilization. Finally, there are two reports on monitoring: the report on geophysical monitoring addresses methods for measurement, monitoring and verification (MMV) of the subsurface; while the report on marine monitoring is particularly relevant to risk management and mitigation in the event of leakage to the water column.

Future work and recommendations
CO₂ storage has been successfully demonstrated at Million-tonne scale, but needs to be ramped up to Giga-tonne scale in order to achieve global emissions reductions targets. A shown in the report on Large-scale Storage of CO₂ on the Norwegian Shelf, there are no technical showstoppers for ramping up CO₂ storage (Tangen at al., 2014). However, ramping up to Giga-tonne scale requires 1) better estimate of storage capacity, 2) better pressure management strategies, and 3) smart methods for controlling and optimizing CO₂ injection (Nettvedt, A., pers. comm. "Mission innovation workshop", 2017).

Better estimate of storage capacity requires more reliable forecasting of CO₂ migration and trapping processes, with range of uncertainties. This, in turn, requires improved physics and chemistry-based understanding of CO₂ flow and transport processes at multiple scales within heterogenous rock media.

Better pressure management strategies imply control on pressure limits at both near-well and reservoir scales and quantification of allowable pressurization. Consequently, better understanding of the effects of stress field, pressure history, reservoir/caprock heterogeneities, including faults and fractures, is needed.

Smart methods for controlling and optimizing CO₂ injection include effective control and handling of transmissivity, near-well geochemical processes, formation damage, etc. Well stimulation and next-generation well technologies need to be demonstrated to enable large-scale CO₂ injection. Future advances in CO₂ storage will likely occur at the interface between industry and academia and be coupled to the execution of ramp-up CO₂ storage projects.
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Executive Summary

For CCS (Carbon Capture and Storage) technologies to be classified as a climate change mitigation option, efficient, safe and enduring storage needs to be verified through site-specific monitoring programmes, which is mandated by national and international statutes such as the Norwegian Petroleum Activities Act and the EU Emissions Trading Scheme (EU ETS). In the case of offshore geological storage, high spatiotemporal natural variability hinders the interpretation of leakage signals above background measurements. It is therefore necessary to establish spatiotemporal natural variability through baseline studies when designing an efficient monitoring programme.

Given these complexities, the Geophysical Institute at the University of Bergen, the Department of Mathematics at the University of Bergen, Uni Research Climate, and the Norwegian Institute for Water Research have concentrated part of their research on improving the understanding of shallow marine processes and the ecological impact of CO₂ exposure, and developing marine monitoring methods and strategies, based on both modelling and observational work at the SUCCESS centre. During the project, the above-mentioned institutions were also involved in other relevant projects that produced new knowledge about the risks associated with potential exposure of the marine environment to potential leakages of stored CO₂ and how to detect such leaks through monitoring.

The CLIMIT-funded CO₂ BASE project emphasized that a proper environmental baseline is a prerequisite for detecting anomalies and serves as an assurance against unjustified accusations of adverse environmental events. The EU’s FP7 project ECO₂, which investigated Sleipner and Snøhvit, among other sites, studied the connection between subsurface and marine processes. A number of leak scenarios were considered, and the C_{seep} method was developed. This method was used to optimize deployment of fixed installations on the seabed with the highest probability of detecting potential leaks. Development of this method has continued, applying Bayesian methodology, in the Horizon 2020 project STEMM-CCS and the CLIMIT-funded BayMoDe project.

This report synthesizes relevant knowledge and data acquired during the above-mentioned projects regarding monitoring methods and strategies for inorganic carbon in the water column, based on both modelling and observational work. The following are the most important findings from the activities conducted.

- A cost-efficient strategy for a monitoring programme will optimize the chances of detecting a leak.
- Optimization of leak detection needs: (i) a map of probable leak locations and potential rates and topological features, preferably quantifying their internal relative probability at the different sites; (ii) a proper environmental baseline; and (iii) probabilistic footprint predictions of leakages through modelling.
- Monitoring programmes will ensure that real leak alarms are detected, minimizing false positives.
- The use of monitoring techniques that eliminate natural variability from the measurements (C_{seep} method) captured through the baseline may improve the threshold for leak detection; i.e. may lower the degree of anomaly needed for a leak signal to become statistically significant.
- Macrofauna is currently the first taxon choice for baseline monitoring. As the primary biological method for detecting possible leaks, a survey should be performed of the possible spatial-related behavioural responses of benthic megafauna using remote methods in the area overlying the reservoir. This should be done together with a study of the physical and/ or chemical properties of bottom water.

"It is ... necessary to establish spatiotemporal natural variability through baseline studies when designing an efficient monitoring programme."
Introduction

"When CO₂ enters the ocean, carbonic acid and eventually protons (H+) are formed, which affects the marine inorganic carbon system. The ocean gradually transforms into a more acidic reservoir, as more CO₂ dissolves and the amount of available carbonate is reduced, which is the process known as ocean acidification."

During the past decade (2006–2015), burning of fossil fuel and changes in land use have resulted in an annual emission of 10.3 GT C into the atmosphere. Approximately 25% of this has been absorbed by the ocean (Le Quéré et al., 2016). When CO₂ enters the ocean, carbonic acid and eventually protons (H+) are formed, which affects the marine inorganic carbon system. The ocean gradually transforms into a more acidic reservoir, as more CO₂ dissolves and the amount of available carbonate is reduced, which is the process known as ocean acidification (OA). At present, there is evidence of changes to the structure and functionality of marine ecosystems due to OA (e.g., Gattuso and Hansson, 2011), and there is thus no doubt that excess CO₂ entering the atmosphere and oceans, i.e. CO₂ from human perturbation, represents a challenge.

For a decade or so, the CCS (Carbon Capture and Storage) process has been put forward as a way of reducing the excess CO₂ entering the ocean and atmosphere. The effectiveness of CCS as a mitigation option (IPCC, 2005; IEA GHG, 2008) depends in part on demonstration of efficient, safe and enduring storage, verified through monitoring. In the case of offshore CCS, monitoring programmes must be planned in even greater detail than on-shore CCS sites, as marine operations are more expensive. Marine monitoring is challenging due to the spatiotemporal natural variability and the extent of the area that migrating CO₂ might leak to from the seabed. An environmental baseline, characterizing natural variability, is therefore necessary. Primary monitoring of the integrity of storage reservoirs will likely be based on seismic techniques that are capable of detecting the evolution of the CO₂ plume, and large leakage fluxes (in the order of 103 T CO₂). However, smaller, low flux leakages would only be detected near or at the seabed, suggesting a need to monitor the surface seabed and the water column above it in order to achieve complete certainty (Blackford et al., 2015).

Different leak scenarios were studied in the EU’s FP7 project ECO₂, distinguishing between large-scale flux rates over a large area through a chimney reactivation (max. flux rate of 150 T/day within a 500 m diameter circle), a blow out (100 T/day, 50 m diameter), a leaky well (20 T/day, 1 m diameter) and an elongated conduit (15 T/day, 200x2000 m). Time evolution of these scenarios was delivered as input to a model study on the footprint created by the scenarios (Alendal et al., 2014). Even though the models used varied greatly, they all indicated that the footprint of a leak would be very localized in the vicinity of the leak.

Unsurprisingly, the flux of CO₂ governs the maximum concentration and the spatial extent of the footprint. The topology of the leak (dispersed leaks over a large area vs. large flux at a point) and the bubble size distribution of the leakage also influence the footprint.

"Even though the models used varied greatly, they all indicated that the footprint of a leak would be very localized in the vicinity of the leak."
Proper and reliable predictions regarding how CO₂ reaches the seabed are hence important in order to estimate the spatiotemporal footprint of a leak. Strong currents will carry the CO₂ cloud over a larger distance in a short period of time, usually also implying higher shear, at least along the seabed, and thus stronger turbulent mixing. The varying direction of the currents also determines the bearing taken by the CO₂ cloud. Even though the mean signal will be very low when it moves away from the leak, patches of higher concentration may pass by a location.

In 2010, the Research Council of Norway granted funds for a Centre for Environment-friendly Energy Research (CEER) called SUbsurface CO₂ storage – Critical Elements and Superior Strategy (SUCCESS). The main goal of the centre was to address several areas of importance to subsea CO₂ storage: storage performance, sealing properties, injection, monitoring and consequences for the marine environment. Specifically, the objective of activity five of the centre was to improve the understanding of shallow marine processes and the ecological impact of CO₂ exposure, and to develop marine monitoring methods.

The partners in the centre were also involved in several other international and national projects that addressed the development of measurement procedures and technology for CO₂ in marine waters. For instance, the GASSNOVA-CO₂ Marine, CO₂ BASE, and the EU’s FP7 CARBOCHANGE projects involved gathering baseline data in the North Sea in order to document and understand the variations and trends in background CO₂ concentrations.

In contrast, the aforementioned EU FP7 project ECO₂ aimed to achieve a better understanding of the risks associated with CCS, e.g., the likelihood of leakage from sub-seabed storage, the effects of leakage, and monitoring strategies, using the Sleipner and Snøhvit fields as two of the study sites. The ECO₂ project ended in 2015, and its final report presented a framework of best environmental practices to guide the management of offshore CO₂ injection and storage (Wallmann et al., 2015). The ongoing STEMM-CCS project began in March 2016 and seeks to test CO₂ leakage detection, impact assessment, and decision-making support techniques that are currently at Technology Readiness Level (TRL) stages 4–5 and support their progress to a higher TRL and ultimately commercialization.

This report synthesizes relevant knowledge and data acquired during the above-mentioned projects regarding monitoring methods and strategies for inorganic carbon in the water column, based both on modelling and observational work conducted by the Geophysical Institute at the University of Bergen (GFI, UiB), the Department of Mathematics at the University of Bergen (Math, UiB), Uni Research Climate (UniRC), and the Norwegian Institute for Water Research (NIVA). Monitoring strategies are summarized in section two, observations leading to the determination (detection and/or quantification) of excess carbon in the water column are described in section three, a summary of the potential impact of CCS leakage on the structure and function of marine communities is provided in section four, and conclusions and recommendations are made in section five.

"The main goal of the centre was to address several areas of importance to subsea CO₂ storage: storage performance, sealing properties, injection, monitoring and consequences for the marine environment."
Geological CO\textsubscript{2} storage projects require an adequate monitoring programme in order to demonstrate safe and enduring storage, following regulation like the London Convention, OSPAR and EU directives. A three-phase monitoring programme has been suggested, consisting of: 1) a detection phase; 2) a confirmation and location phase; and 3) a leak quantification phase. Some authors suggest a fourth step – impact assessment (Blackford et al., 2015).

Work at the SUCCESS centre and on related projects mentioned in this report has focused on the detection phase, where the monitoring programme looks for anomalies in the environment. The major questions are as follows. How can a potential leakage be detected? Is it possible to quantify the certainty of detecting a leak? In offshore storage projects, the answers to these questions requires us to ask “Where will a leak most likely occur?”; “How will a leak trail materialize in the water column?” and “Will we be able to distinguish the signal from the background variability?”

The answers to the first two questions, “Where will a leak most likely occur?” and “How will a leak trail materialize in the water column?” are provided through site characterization. A map of probable leak locations is an intrinsic part of site characterization. Injection wells are believed to be the most probable leakage pathway, but transport of CO\textsubscript{2} within a formation might create new pathways to the surface (Oldenburg and Lewicki, 2006), possibly far from the injection well. The internal relative probability between different areas will dictate where it will be most important to search for leaks.

Leaks following weakness zones in geological structures or old wells might cause high CO\textsubscript{2} flux rates far from the injection site. Possible CO\textsubscript{2} migration through the overburden reaching the surface may create more diffusive leaks over a relatively large area. Leak scenarios will be an intrinsic component of site characterization and lay the groundwork for the risk and impact assessments that are necessary in order to obtain a CCS permit.

The answer to the third question, “Will we be able distinguish the signal from the background variability?” initially relies on establishing the natural spatiotemporal variability of the storage site through an environmental baseline study.

The answer to the third question, “Will we be able distinguish the signal from the background variability?” initially relies on establishing the natural spatiotemporal variability of the storage site through an environmental baseline study. Baseline studies will include environmental parameters such as currents, natural gas seeps and biogeochemical parameters. Long time series will capture natural seasonal variability and long-term trends. In particular, it will be important to capture the expected acidification caused by the increase in atmospheric CO\textsubscript{2} levels (Caldeira and Wickett, 2003). It is therefore necessary to combine historical data and new data collected during site characterization.

It is equally important to understand how to recognise a leak. CO\textsubscript{2} seeps shallower than 500 m will rise in the water column as gas bubbles (Alendal and Drange, 2001). Depending on the flux rate, this might create individual bubbles, bubble trains or bubble plumes. The dynamics of these regimes differ, with the plume dynamics being the most challenging to model due to the two-way coupling with the surrounding seawater.

In all cases, an increase in the CO\textsubscript{2} concentration is expected near a leak (Blackford et al., 2010), with subsequent potential environmental impacts that may cause changes to the bottom fauna and pelagic ecosystems, possibly materializing as new occurrences of bacterial mats (Wegener et al., 2008). The spatial extent of the impacted area is expected to be limited (Dewar et al., 2013, 2014), but might become severe, depending on the size of the leak and the dilution rate in the water column.

At the SUCCESS centre, we have simulated possible changes to the seasonal variability of biogeochemical parameters in the upper sediment (up to 10 cm), the benthic boundary layer (0.5 m), and the water column in various leakage scenarios using the 1D benthic-pelagic Bottom RedOx Model (BROM) (Yakushev et al., 2017). During these simulations, CO\textsubscript{2} was injected just
above the sediment-water interface, imitating the leakage through a crack or chimney. Four different leakage scenarios were considered:

1. Blowout 1: 26.8 mmolC/sec for 1 year
2. Blowout 2: 26.8 mmolC/sec for 4 years
3. Chimney reactivation 0.2 mmolC/sec for 1 year
4. Leaky well 0.045 mmolC/sec for 1 year

These are based on the scenarios simulated in the ECOS project [Alendal et al., 2014]. The rates above are purely hypothetical and are based on upper bound estimates. Blowout scenarios correspond to the formation of chimneys and pipes reaching the seabed bottom due to sediment mobilization during CO$_2$ injection described in [Yarushina et al., 2015a; Yarushina et al., 2015b]. The chimney reactivation scenario assumes that the CO$_2$ plume reaches the relict seismic chimney located near the injection site.

Abandoned wells penetrate geological formations in oil and gas exploration areas and thus break through the natural sealing layers. This results in possible pathways for migration of fluid and volatiles from deep geological formations up to the seabed. This process represents the 'leaky well' scenario. However, very little is known about the realistic leakage rates for all of the above-mentioned scenarios, and future research should cast light on the expected leakage rates.

Calculations for the leaky well (scenario 4) did not show any significant differences, compared with the baseline state; i.e. a short-lived leakage for a one year at a small rate is not detectable and causes few changes to the natural conditions. Nor does a one order of magnitude increase in the leakage rate expected for chimney reactivation considered under scenario 3 have a significant influence on the marine environment. In contrast, the short-lived blowout (scenario 1) and the long-lived blowout (scenario 2) where the leakage rate is four orders of magnitude larger than for the leaky well will result in significant changes to the marine environment. Within the first few centimetres of the sediment, the pH in the water column drops from 6 – the baseline value – to 7, which results in water acidification (see Fig. 1). Correspondingly, concentrations of calcium carbonate remain low during the whole leakage period, porewaters are undersaturated with aragonite and calcite.

The leakages expected for blowout scenarios could create dangerous conditions for the benthic ecosystem with a low pH, which will restrict the carbonate formation. This causes negative effects for the bottom ecosystem: limiting the ability of calcifying organisms to deposit their hard parts, reducing the transportation of organic carbonate to deep sediments, shifting the balance of the ‘biological carbon pump’.

The main question remains: What level of certainty will be required in order for the monitoring programme to sound the alarm? In order to reduce the cost of mobilizing the resources needed to confirm and locate a leak, it will be preferable to treat data from the monitoring programme in order to quantify the certainty of a leak alarm.

Research activities at the SUCCESS centre include studies in close collaboration with other related projects. The leak scenarios...
(Alendal et al., 2014) and the subsequent predicted footprints of a leak (Ali et al., 2016) from the ECO2 project (Figs. 2 and 3) were used as a basis for studies of optimal layout of fixed sensor installations in the vicinity of the Sleipner field (Hvidevold et al. 2015, 2016) (see Fig. 4).

The optimal placement of sensors with the highest probability of detecting a leak was determined using a map of wells in the vicinity of Sleipner from the Norwegian Petroleum Directorate (see Figure 4).

The study was expanded on in Hvidevold et al. (2016), where the concerns regarding false alarms were addressed and different methods for treating time series in order to avoid false alarms were assessed. If the average concentration in the measured time series must be above a threshold, this restricts the area monitored by a sensor,
and the time to detect a leak increases. In contrast, the area monitored will expand if a single event of increased concentration is enough to trigger an alarm regarding a potential leak in the area monitored. However, this expanded area must be balanced against the higher rate of false alarms that will likely be the result of the latter method. A method in between counts the relative time the concentration is above a threshold and, in a frequentists’ way, introduces the probability of the presence of a leak. Ali et al. (2016) documented the role of spatial dependency on the footprint and the underlying simulations used in Hvidevold et al. (2015, 2016).

This probabilistic reasoning was subsequently expanded on in Alendal et al. (2017a) by turning to the Bayes theorem. This theorem was used to quantify the uncertainties involved and show how Bayesian decision theory can be used to balance the cost of false alarms (see Fig. 5). Bayesian methodology has also been used to develop three strategies for optimal routing of Automatic Underwater Vehicles (AUV) (Alendal et al., 2017b; Witman, 2017). The threshold applied in these studies was based the stoichiometric approach developed in Botnen et al. (2015), the C\text{seep} tracer, which allows the elimination of natural variability from CO\textsubscript{2} measurements.

"The most critical factor in the detection is the accurate identification of the anomaly in the seawater CO\textsubscript{2} concentration produced by the leakage. This is challenging because the ocean exchanges CO\textsubscript{2} with both the atmosphere and the biosphere, and contains background CO\textsubscript{2} that is hugely variable, especially on shelf and coastal systems."
Geochemical methods can be used to detect and quantify CO₂ leakage in the form of extra carbon dissolved in the water resulting either from bubbles that dissolve as they rise or from dissolved CO₂ advecting with deep waters. The most critical factor in the detection is the accurate identification of the anomaly in the seawater CO₂ concentration produced by the leakage. This is challenging because the ocean exchanges CO₂ with both the atmosphere and the biosphere, and contains background CO₂ that is hugely variable, especially on shelf and coastal systems (Blackford and Gilbert, 2007).

An important prerequisite for anomaly detection is therefore the establishment of a sound baseline. For quantification purposes, an estimate of the water volume impacted by the leakage is necessary in addition to determination of the CO₂ enrichment. A combination of autonomous in situ measurements and high-sensitivity analysis methods are thus important tools for easy identification of leakage footprints. The following subsections describe the water column baseline acquired at the SUCESS centre and the analytical methods developed. The detection and quantification of leakage CO₂, familiarity with seawater carbonate system variables, and measurement of these are all important, and will be discussed first.

**Seawater carbonate system variables and measurements**

Inorganic carbon is present in seawater as bicarbonate (HCO₃⁻, 90%), carbonate (CO₃²⁻, 9%) and carbon dioxide (CO₂ gas + HCO₃⁻, <1%) and shares of these are governed by a set of equilibria called the marine inorganic carbon system, which is described by four measurable variables: DIC, TA, fCO₂, and pH. DIC is the total amount of dissolved inorganic carbon components in the seawater; total alkalinity (TA) describes the ability of the water to neutralize acid, i.e. the buffer capacity of the seawater; fCO₂ is the fugacity of CO₂; and pH expresses the proton concentration in the seawater.

If two out of these four parameters are measured, in addition to seawater temperature and salinity, the remaining two parameters can be determined (Park, 1969; Dickson et al., 2007). Additional information provided by these calculations is the carbonate concentration and the saturation state of carbonate, Ω. If Ω > 1, the seawater is oversaturated with respect to carbonate, while a value of Ω < 1 indicates undersaturation of carbonate. There are differences in the precision of each pair of parameters when estimating the carbonate concentration and Ω (see Fig. 6).
"Data are collected either by using sensors deployed at certain depths and continuously logging data or by collecting and analyzing discrete samples."

However, this view must be combined with consideration of which pair of parameters is the most feasible and cost-efficient.

The sampling and instrumentation used to analyze seawater carbonate system parameters follow international standards described in the Guide to Best Practices for Ocean CO₂ Measurements (Dickson et al., 2007). Data are collected either by using sensors deployed at certain depths and continuously logging data or by collecting and analyzing discrete samples. A third way of collecting data is using flow-through systems on ships where they measure semi-continuously in unattended operation.

The DIC and TA samples were collected by filling glass bottles with seawater from the depths of interest. The analyses were performed either on the ship or on shore, and in the latter case, the water samples required preservation in order to prevent biological activity that influenced the results. DIC measurements were conducted by first acidifying the water sample, next extracting the CO₂ and, then conducting coulometric titration and photometric detection of the CO₂. TA analyses were carried out using potentiometric titration with 0.1 N hydrochloric acid. Those measurements were performed using VINDTA 3D and 3S analytical systems (Marianda, Germany) for DIC and TA, which are bench instruments that have been used for many years. The DIC and TA values were calibrated using the Certified Reference Material (CRM) supplied by A. Dickson, Scripps Institution of Oceanography, and the measurement precision was 1 µmol kg⁻¹ for DIC and 1 µmol kg⁻¹ for TA.

While there are no available sensors for measuring the DIC and TA, both pH and pCO₂ can be determined in situ using sensor technology. One of the most commonly used pH sensors is the SAMI2-pH sensor (Submersible Autonomous Moored Instrument) from Sunburst Sensors, which can be used from surface depth down to 600 m. The SAMI2-pH sensor mixes an indicator dye with water in a flow-through cell, and the colour change, which is a function of the amount of CO₂ in the water, is detected optically. The pH of the water is then calculated. The precision of this sensor is reported to be better than 0.001 pH units, while the accuracy checked against CRMs was ± 0.003.

Semi-continuous in situ pCO₂ measurements at different depths can be performed based on similar principles as for pH, using a SAMI-CO₂ sensor (Sunburst Sensors) with indicator and optical detection. For the SAMI-CO₂ sensor, water flows close to a semi-permeable cell filled with indicator, which changes colour according on the amount of CO₂ diffusing into the cell. The colour change is detected optically, and the precision is reported as being better than 1 µatm, while the accuracy checked against US National Institute of Standards and Technology gas standards was ± 0.003.

A detailed list of inorganic carbon variables measured at the SUCCESS centre and their specifications can be found in Table 1. As mentioned previously, it is enough to know two of the marine inorganic carbon system parameters in order to calculate the other two.

Here, we used the DIC and TA together with temperature, depth (pressure), salinity, phosphate, and silicic acid in the chemical speciation equilibrium model CO₂SYS (Pierrot et al., 2006) to calculate the pH and fCO₂, in addition to aragonite and calcite saturation (ΩAr and ΩCa, respectively). For this calculation, we used the carbonate system constants from Mehrbach et al. (1973), modified by Dickson and Millero (1987), and the total pH scale (pHT) using the constant for HSO₄⁻ from Dickson (1990) at 25°C. The calcium concentration ([Ca²⁺]) was assumed to be proportional to salinity by Mucci (1983), and corrected for pressure following Ingle (1975).

"..... it is enough to know two of the marine inorganic carbon system parameters in order to calculate the other two."
Table 1 Inorganic carbon variables measured at the SUCCESS centre and their specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method of analysis</th>
<th>Response time</th>
<th>Precision</th>
<th>Accuracy</th>
<th>Calibration method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIC</td>
<td>VINDTA 3D (Mariana, Germany)</td>
<td>15 min. per sample</td>
<td>1.0 µmol kg⁻¹</td>
<td>1.0 µmol kg⁻¹</td>
<td>Comparison with CRM* (A. Dickson, Scripps)</td>
<td>Dickson et al. (2007)</td>
</tr>
<tr>
<td>TA</td>
<td>VINDTA 3S (Mariana, Germany)</td>
<td>20 min. per sample</td>
<td>1.0 µmol kg⁻¹</td>
<td>1.0 µmol kg⁻¹</td>
<td>Comparison with CRM* (A. Dickson, Scripps)</td>
<td>Dickson et al. (2007)</td>
</tr>
<tr>
<td>pH</td>
<td>Colorimetry</td>
<td>3 min.</td>
<td>&lt; 0.001</td>
<td>± 0.003</td>
<td>Using DIC, TA, and CRM*</td>
<td>DeGrandpre et al. (1995)</td>
</tr>
<tr>
<td>fCO₂</td>
<td>Colorimetry</td>
<td>5 min.</td>
<td>&lt; 1 µatm</td>
<td>± 3 µatm</td>
<td>Using DIC, TA, and CRM*</td>
<td>DeGrandpre et al. (1995)</td>
</tr>
<tr>
<td>fCO₂</td>
<td>Equilibration, NDIR</td>
<td>3 min.</td>
<td>± 2 µatm</td>
<td>3–4 standard gases</td>
<td>Pierrot et al. (2009)</td>
<td></td>
</tr>
</tbody>
</table>

* CRM= Certified Reference Material

In general, interannual variations are enhanced in the southern North Sea and during the summer/spring.

Baseline measurements

The surface seawater variability of CO₂ and pH in the North Sea have been studied using mainly continuous fCO₂ measurements from cargo ships (Trans Carrier and Nuka Arctica) (Omar et al., 2010, 2016). The findings show that in the seasonally-stratified North Sea, including the western Norwegian fjords, carbon is taken up by phytoplankton in the surface and respired in the subsurface layer. The area is therefore undersaturated with respect to CO₂ throughout the year, driving a flux of CO₂ into the ocean.

There are also great seasonal variations (Table 2) driven by (in descending order) biological activity and mixing, temperature changes, and air–sea CO₂ exchange. The interannual variations are also significant and their magnitude seems to be dependent on the area and the season. In general, interannual variations are enhanced in the southern North Sea and during the summer/spring. The long-term trends are still poorly quantified due to a lack of proper long time series, but low-resolution repeated measurements published indicate that the increase in atmospheric CO₂ is driving a secular increase in the CO₂ in surface waters of the North Sea (Omar et al., 2010; Clargo et al., 2015). This is supported by high-resolution time series data for the period 2004–2014 acquired by the authors (Omar et al., 2017 in prep.). Moreover, Salt et al. (2013) reported that the CO₂ system in the North Sea responds to external and internal expressions of the North Atlantic Oscillation index. All of the surface CO₂ data from the container ships (Trans Carrier and Nuka Arctica) are available in the SOCAT database (www.socat.info).

Table 2 Summary of mean values and variability in the Northern North Sea (data from Glodap v2; Key et al., 2015; Olsen et al., 2016).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Surface (≤10 m)</th>
<th>Bottom (≤ 50 m above bottom depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Winter</td>
</tr>
<tr>
<td>DIC (µmol kg⁻¹)</td>
<td>2.045 (1927–2128)</td>
<td>2.103 (2021–2122)</td>
</tr>
<tr>
<td>TA (µmol kg⁻¹)</td>
<td>2.293 (2099–2357)</td>
<td>2.291 (2235–2320)</td>
</tr>
<tr>
<td>fCO₂ (µatm)</td>
<td>288.5 (184.6–360–5)</td>
<td>358.5 (296.3–397.9)</td>
</tr>
<tr>
<td>T (ºC)</td>
<td>11.91 (6.97–17.80)</td>
<td>8.70 (5.12–12.50)</td>
</tr>
</tbody>
</table>

*pHTis indicates pH at total scale and 25 ºC.
Background CO₂ variations in the water column were studied using discrete CTD sampling from three locations: the area around Sleipner, the Jan Mayen natural venting fields (JMVF) in the Norwegian Sea, and in Isfjorden in Svalbard. The first two areas were surveyed during a summer expedition on board the research vessel G. O. Sars as part of the EU’s ECO² project. Carbon measurements during the first leg of the expedition were performed in order to map the background variations on the Sleipner subsea CO₂ storage complex. Seawater samples taken from CTD bottles at 20 stations were analysed for DIC, TA, and pH using the methods described in section 2.1. Preliminary analyses of these data indicate that the observed variability of background concentrations is governed by freshwater dilution and biology.

At the JMVF, carbon measurements were performed in order to study the effect of the venting CO₂ on seawater carbon concentrations. The DIC, TA, and nutrients were ascertained at 10 CTD stations and a few samples were taken with a ROV from the ‘chimney’ and adjacent bottom water. The latter samples showed extremely high DIC values (>3 000 µmol kg⁻¹). Higher up in the water column, the DIC and TA concentrations measured were mainly impacted by water mass mixing and biological activity, although the DIC concentrations around the vents appeared to be slightly higher than at the reference station. A new sensitive tracer for CO₂ seepage was developed (Cseep) and successfully tested in order to quantify the extent of CO₂ enrichment due to the venting of CO₂ (Botnen et al., 2015). There is a brief discussion of the Cseep tracer, which ascertains the impact of venting-related CO₂ on water chemistry, in the following section.

High-frequency in situ pH measurements have been attempted on several occasions, mainly as part of the testing of newly-purchased SAMI₂-pH and SAMI-CO₂ sensors. The SAMI₂-pH sensor was deployed to the bottom water for 12 hours during the 2012 G. O. Sars expedition in the North Sea. The sensor was attached to a bottom lander, which was submerged to 100 m depth for 12 hours. The half-hourly pH data recorded by the sensor revealed significant short-term variations, with a magnitude of 0.3 pH units, which is nearly 50% of the seasonal variation in the bottom water over the Sleipner storage complex. Such high short-term background variation illustrates the huge challenge involved in identifying leakage CO₂ using simple concentration measurements.

The SAMI sensors were also deployed in other oceanic environments that are more extreme than the North Sea (see left photo below). In 2014–2015, a one-year deep mooring deployment of the sensors was carried out at 800 m depth in the coastal Red Sea (19.720°N, 37.395°E). A SAMI-CO₂ sensor was placed on the upper part of the mooring (34–37 m) and acquired high-quality hourly pCO₂ data throughout the year despite the extreme Red Sea environment, with high temperatures, high salinity, and heavy biofouling (see Fig. 7).

Figure 7: Half-hourly bottom water pH data (above) recorded by a SAMI₂-pH sensor attached to a bottom lander (left) in the North Sea in June 2012. Hourly pCO₂ data in uatm (below) recorded by a SAMI-CO₂ sensor (right) in the extreme environment of the Red Sea, October 2015–October 2016.
"The CO₂ content of seawater is highly dynamic due to natural processes, and varies between seasons and from year to year."

Another one-year deployment of SAMI pH and CO₂ sensors was carried out on a 100 m depth mooring in the Arctic environment of Dicksonfjorden, Svalbard (October 2016–September 2017). Preliminary quality checks showed that the sensors worked satisfactorily during the deployment, and the resulting data is expected to yield insights into the natural variability of the marine inorganic system related to changes in sea ice.

**Excess carbon determination using the C\text{seep} method**

The CO₂ content of seawater is highly dynamic due to natural processes, and varies between seasons and from year to year. It is therefore challenging to quantify the natural variability of the near-seabed CO₂ system. In order to address and minimize this problem, we customized an existing technique that was designed to estimate the oceanic uptake of excess CO₂ from the atmosphere in order to ascertain the amount of excess CO₂ originating from a submarine leak. The new C\text{seep} tracer separates the natural variability from the leakage signal (Botnen et al., 2015) based on the back-calculation technique used to estimate the oceanic uptake of atmospheric CO₂ of anthropogenic origin (e.g. Gruber et al., 1996).

In order to optimize the method for variables that can be measured at high frequency and in an autonomous mode, we are assessing the effect of variables on the performance of the method by computing the C\text{seep} tracer twice: first using discrete DIC and TA, and second using pCO₂ and pH (García-Ibáñez et al., 2017). The results show that the C\text{seep} tracer increases the signal to noise ratios ten times, compared to the raw measurement data, regardless of the variables used. C\text{seep} findings can hence be automated using in situ sensor-based measurements of pCO₂, pH, and dissolved oxygen, together with algorithms that compute C\text{seep}. Baseline and monitoring surveys should thus seek to measure pCO₂, pH, salinity and oxygen, and apply these data in order to determine the concentration of the C\text{seep} tracer in ambient bottom waters above the storage complex, which should cluster at values close to zero prior to the onset of the storage operation.

Sources of uncertainty when computing the C\text{seep} tracer are changes in the air-sea CO₂ fluxes, changes in the Redfield ratios used to estimate the biologically-mediated changes in CO₂, and changes in water masses between the reference station and the area monitored. Assessment of the changes in air-sea CO₂ fluxes during a monitoring expedition has determined that they are smaller than a few ppm and can therefore be disregarded. The uptake of anthropogenic CO₂ via the air–sea interface induces a continuous increase in background CO₂. Measurements at the reference station away from the storage site can be used to assess this effect during the operational phase.

Evaluation of the spatiotemporal changes in the Redfield ratios in the Sleipner area leads to an estimated C\text{seep} tracer uncertainty of 20 ppm. Assessment of the changes in water masses between the reference station and the area monitored covers both changes in salinity/TA and changes in the Redfield ratios. Changes in salinity/TA caused by differences in the water mass distribution lead to poor detection of leakage signals. Water mass characterization is therefore a critical factor when choosing the location of a reference station.

The C\text{seep} method can be a powerful technique if automated measurements can be performed from mobile platforms. There is therefore a need for instrumentation for continuous monitoring of the marine inorganic carbon system. Accurate sensors for continuous monitoring of the four measurable variables of the marine inorganic carbon system (DIC, TA, fCO₂, and pH) are being developed within the framework of the EU’s STEMM-CCS project.

The successful development of such instrumentation will lead to more accurate separation between natural variability and leakage signals in the marine inorganic carbon system. This will improve the detection threshold of programmes to monitor offshore CCS storage sites.

"The C\text{seep} method can be a powerful technique if automated measurements can be performed from mobile platforms."
Potential impacts of CCS leakage on the structure and functions of marine communities

The biological studies in the North Sea within the frames of the SUCCESS centre were devised in conjunction with similar studies in the FP7 ECO2 project, which are presented in detail on the project's website (http://www.eco2-project.eu/).

A variety of methods and approaches have been used to assess the potential impacts of CCS leakage on the structure and function of marine communities, allowing us to identify generic patterns and paradigms that are independent of the recognised, method-specific weakness associated with single approach studies. Tightly-controlled mesocosm-based studies allow us to demonstrate cause and effect between specific environmental drivers (such as pH, hypoxia and salinity) and key biological responses. A large mesocosm facility has been used to examine the potential impacts of CCS leakage on typical Northern European soft sediment biological communities and processes. Concurrently with these experiments, there have been field studies of the ecosystems, communities, species and their functions. By comparing mesocosm results with observations from field sites which are naturally exposed to elevated levels of CO₂, we can determine if experimental responses are seen in more complex, natural, marine systems.

Experimental set-up

A high CO₂ exposure system was built at the NIVA marine research station in Solbergstrand in Oslofjorden in Norway. It was used to perform an exposure experiment (2012/2013) where 5 CO₂ concentration treatments were used (control (400 ppm), 1 000, 2 000, 5 000 and 20 000 ppm of CO₂) to investigate the impacts of a leakage from a CCS injection site or pipeline on benthic communities and processes. Sampling took place after 2 and 20 weeks of exposure, in order to identify the potential short and medium-term impacts.

The severity and speed of impact on the diversity and structure of the micro, meio and macrobenthic communities were established. Moreover, the impact on benthic ecosystem processes was also determined at each time point by measuring changes in bioturbation activity (i.e. mixing of sediment particulates by burrowing infauna), bioirrigation (i.e. flushing of benthic sediment by burrowing fauna through burrow ventilation), and community respiration, which were all expected to reflect the physiological impact of environmental stressors.

A variety of biogeochemical parameters and processes were also measured in order to identify potential changes in sedimentary nutrient and organic matter cycling. These included sedimentary pH profiles, fluxes of nutrients (PO₄, NH₄, SiO₄, NO₂, NO₃), and the rate of ammonia oxidation in the seawater and sediment in connection with experimental treatments. Seawater total alkalinity, total inorganic carbon, temperature, salinity, seawater and sedimentary pH were
also monitored. Sedimentary properties, including particle size distributions and porosity, were also measured.

Another mesocosm experiment was devised to assess the short-term impact of the release of hypoxic brine from formation waters during a sub-seabed CO₂ injection. The high-CO₂ mesocosm system was thus modified to accommodate this work, and this experiment ran at the end of the summer of 2013. As we were interested in the impact of hypoxic brine, we also investigated the individual effects of hypoxia and high salinity on benthic biota and processes in order to disentangle the potential contributions of each stressor to potential changes in the benthos.

A fourth impact scenario was considered, with simulation of tidal flushing of a brine plume by standard seawater. This experiment therefore gauged five experimental treatments: control, high salinity (48 g/l NaCl), hypoxia (1.4 g/l O₂), mixed (48 g/l NaCl and 1.4 g/l O₂), and tidal (see section 2.1.2 for details). These exposures lasted for 2 weeks. In order to assess the impact on the benthic community structure and processes, the same end points were measured as for the high-CO₂ experiment. Additional measurements were carried out for sedimentary sulphide and redox profiles.

### Biological responses to high CO₂ exposure

The studies performed by comparing experimental data and observations on the natural seeps near Panarea Island showed that the effect of CO₂ seabed emission was clearly visible on porewater chemistry in the form of pH reduction, increase of DIC and alkalinity, and enhanced chemical weathering (high concentration of iron, manganese and silicate) along the sediment profile of CO₂-impacted sites. The total organic carbon (TOC) and total nitrogen content (TN) in the sediment and C:N ratios did not differ between the seep and control areas. The following effects on the biological characteristics are described below (Berge, 2015).

**Macrofauna.** Although diversity did not differ, the macrofauna composition at CO₂ seep sites differed from the reference site based on the occurrence of more oligochaetes and amphipods and less polychaetes and gastropods at the seep sites. Grazing marks by the sea urchin Paracentrotus lividus were less abundant at the impacted sites, compared to the reference site. Grazing marks by the fish Sarpa salpa were more abundant at the impacted sites. Meanwhile, the macrofauna density was the lowest in the event of weak CO₂ supply compared with high CO₂ and the reference site.

**Meiofauna** densities were significantly higher in the control sediments at the reference site compared to the CO₂ seep, while the opposite was true in the seagrass shoots. Where CO₂ seepage occurred, meiofauna densities were highest in the first 2 cm of the sediment and showed a steep decline with depth. At the control site, there was a more gradual decline in densities with depth. Nematode species richness was significantly lower in the CO₂-impacted sites, compared to the non-impacted sites. In the seagrass (leaves and shoots), no significant seepage-related differences were detected in the meiofauna taxa, copepod species and nematode species assemblages.

Grazing marks by the sea urchin Paracentrotus lividus were less abundant at the impacted sites, compared to the reference site. Grazing marks by the fish Sarpa salpa were more abundant at the impacted sites. Meanwhile, the macrofauna density was the lowest in the event of weak CO₂ supply compared with high CO₂ and the reference site.

**Microphytobenthos/Bacteria** showed the consistently highest densities at high-CO₂ sites; about four times higher than the abundance observed at the reference site. In the water column and on the seagrass leaves, there were no significant differences in the bacterial community structure in the sites investigated. Conversely, bacterial community analyses of recovered sediments showed differences in the CO₂-impacted sites and the reference site without seepage. The results also provided evidence of a reduction in the bacterial diversity in seep sites compared to the background site.

The results from planktonic communities indicate that natural CO₂ emissions at the sites investigated do not appear to have any clear influence on the phytoplankton and microzooplankton communities.
"In order to be effective, it should be possible to apply the detection method for monitoring to large areas over a relatively short period of time."

Best practice on biological monitoring at the SUCCESS centre

Responses to CO₂ leakage can basically be broken down into those that act at the level of the individual and those that act at the level of the community. Individual biomarkers/bioindicators can be behavioural (e.g. animals coming to the surface) or physiological/biochemical. At the community level, there are 3–6 main potential response candidates, depending on how different types of organisms are classified by taxonomy and size: bacteria/Archaea, meiofauna/nanobenthos, and macrofauna/megafauna. Macrofaunal communities have long been used by industry and regulators as an effective environmental monitoring tool for a variety of potential stressors in the marine environment and are also an agreed tool pursuant to the EU’s Water Framework Directive.

Macrofauna are an appropriate tool for detecting the effects of stressors related to organic enrichment and reduced oxygen concentrations in bottom water, but this group does not seem to be optimal for detecting the effects of industrial effluents like metal effluents (Oug, 2013).

Although it has been shown that bacteria, meiofauna, and macrofauna communities can be affected by CO₂ under certain experimental conditions, these effects cannot be directly used for the purposes of detecting and monitoring CO₂ leakage. There will also be a question of the objective of the monitoring.

There is a considerable difference between the methods that are suitable for detecting a leak in the first place and methods that are suitable for monitoring the effects of a leak in space and time after it has been detected or before a potential leak has taken place (baseline survey).
In order to be effective, it should be possible to apply the detection method for monitoring to large areas over a relatively short period of time. The method should not require the taking of samples for later treatment. In most cases, detailed physical sampling for species identification will therefore not be a practical method for detecting a leakage, but can be a useful and relevant tool for more detailed mapping of the effects after a leakage has been identified by other means. Modelling indicates that the spatial footprint of a CO$_2$ leak covers a small area. However, this also implies that it is difficult to locate a leak. The methods for characterization of biological communities are time-consuming and expensive (especially as regards macro, meio and microbiota) and the results are only available after some delay, depending on the sample treatment time.

The behavioural responses of megafauna may be detected more easily, however, if good automatic methods are available, which does not appear to be the case (see above). Physical and chemical properties, like acoustics and pH measurements, are instant measurements that are more specific to CO$_2$ and can be applied over relatively large areas (surveying along parallel lines) with less effort than using most biological methods. It is suggested that the combination of surveying physical and chemical properties and biological responses of megafauna (remote methods) is the best method for detecting a new leak. One should nonetheless bear in mind that traces of emerging megafauna tend to disappear over time due to degradation, at least in cases where the end point of the behavioural response is mortality.

The following recommendations made in the FP7 ECO$_2$ report (Berge, 2015) thus remain relevant to biological monitoring.

1. **Biological baseline monitoring.** Macro fauna is at present the first taxon choice for baseline monitoring. Meio and microbiota should not be completely omitted, however, but should be included if this is consistent with the objective of collecting sufficient data in order to be able to design a comprehensive programme for monitoring the effects of an observed leak and recovery at a later stage (see below). The baseline monitoring should cover all of the main types of sediment areas (sand, clay, etc.) overlaying the reservoir and should encompass typical depth intervals. The orientation of the station network should depend on the shape of the reservoir and possible weak zones in the sedimentary overburden (some sort of grid is most relevant). Expected dispersal patterns for leaks and benthic conditions should also be taken into consideration.

2. **Detecting a new leak.** As the primary method for detecting possible leaks, a survey of possible spatial-related behavioural responses of benthic megafauna should be conducted using remote methods in the area overlying the reservoir. This should include the physical and/or chemical properties of bottom water. If a leak is suspected, the area should be monitored using physical and/or chemical and biological (megafauna) methods in greater detail, in order to locate the epicentre of the leak. When the epicentre is identified, a more detailed monitoring programme should be designed in order to identify the effects.

"It is suggested that the combination of surveying physical and chemical properties and biological responses of megafauna (remote methods) is the best method for detecting a new leak."
Conclusions and best practice recommendations

A cost-efficient strategy for a monitoring programme will initially seek to detect anomalies using a minimum number of techniques and measurements across a wide area (Blackford et al., 2015). The monitoring programme will seek to optimize the probability of detecting a leak. Three main components are necessary in order to optimize the probability of detecting a leak (Ali et al., 2016; Greenwood et al., 2015; Hvidevold et al., 2015): (i) a map of probable leak locations and potential rates and topological features, preferably quantifying the internal relative probability between the different sites; (ii) a proper environmental baseline; and (iii) probabilistic footprint predictions of a leak- age achieved through modelling. Once an anomaly is detected, statistical methods will help design monitoring programmes that ensure that leak alarms are real, minimizing the incidence of false positives (Alendal et al., 2017a), in accordance with relevant national/international regulation.

The use of monitoring techniques that eliminate natural variability (captured through the baseline) from measurements (Botnen et al., 2015; García-Ibáñez et al., 2017) may improve the threshold for leak detection, i.e. may lower the requirements regarding the degree of anomaly in order for a leak signal to become statistically significant.

There is a need to align marine monitoring research with other activities. Subsurface risk assessments provide important input in order to establish monitoring programmes, which should combine subsurface and marine methods in a cost-efficient way and in accordance with regulation. In short, the following are required.

- Align subsurface monitoring and risk assessments with marine monitoring and potential impact.
- Study the relationship between legislation and monitoring/risk assessments.
- Align CCS marine research with other activities. For example, in order to obtain a baseline in collaboration with other marine monitoring programmes like ICOS, MAREANO, INTAROS, SO-CAT, etc.
- Align CCS with ecosystem-based marine management as a result of IOC implementation, for example in the EU and Norway.

"There is a need to align marine monitoring research with other activities. Subsurface risk assessments provide important input in order to establish monitoring programmes, which should combine subsurface and marine methods in a cost-efficient way and in accordance with regulation."
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