QICS has shown that:

- The appearance, form and impacts of CO₂ in the marine environment can be complex.
- No one potential indicator of leakage or impact is likely to tell the whole story.
- A leakage footprint is likely to be small in comparison with the storage area that requires monitoring.
- Successful monitoring may need to distinguish weak signals against a background of considerable natural variability.

Consequently, we advocate a multivariate approach to monitoring: geophysical, acoustic, chemical and biological - supported by baseline surveys that characterise the spatial and temporal dynamics of all relevant processes. Our recommended strategy for baseline surveys is described in fact sheet 3.

**Geophysical baseline**

Sediments and sea floor systems in shelf seas can be spatially complex. Many features that could be used to identify leakage are commonly present for a variety of other reasons. For example natural seabed fractures or pockmarks resulting from shallow sediment biogenic gas production, could both be mistaken for leakage signals.

The spatial extent of the target area should be established by predictive modelling of the migration of CO₂ injected at the storage site;

- Systematic and repeated profiles of bathymetric and seismic profile data, sea bed features and sea bed reflectance should establish natural annual, seasonal and tidal variation before injection starts (see right).
- It is important to record fissures, pock marks and geological discontinuities predating storage.
- Repeat surveys should be acquired on common 2D or 3D grids to ensure surveys are comparable.
- Deep core sampling of the unconsolidated sediment layers is important to assess carbonate content of the sediments across the complex, this will indicate the potential for buffering of leaked CO₂.
- Spatial rather than temporal coverage is the key requirement.

**Acoustic baseline**

Shelf seas are acoustically complex (for example, from shipping and marine traffic, or storms and waves, or seal deterrents), yet listening for bubble streams has promise for both detection and quantification of leakage (see left):

- The background noise field must be quantified using an acoustic array before CO₂ injection starts;
- An acoustic array should be deployed to capture all seasonal components of background noise and be planned with respect to known shipping lanes.
Geochemical baseline

The key parameters are dissolved carbon dioxide or DIC, pH, pCO$_2$ and total alkalinity. This suite of measurements is needed as seawater is a complex buffering solution for CO$_2$ and no one parameter varies linearly with increased carbon dioxide. Measures of oxygen, temperature, salinity and pressure are also necessary to permit the discrimination of abnormal changes in CO$_2$ from natural processes. Covariance relationships between geochemical parameters should be established as deviations from these 'normal relationships' can be more powerful indicators than absolute changes from the mean value of a single measurement.

Measurements taken from surface sediments and in the lower part of the water column are essential to determine the background flux of dissolved inorganic carbon (DIC) between the sediment and overlying water, as expulsion of dissolved CO$_2$ is possible. Other parameters might include nutrient elements, and metals, the latter especially in areas already contaminated by other activities.

Geochemical data must be collected at least monthly and at periods corresponding with intense biological activity, weekly and even hourly sampling might be necessary to constrain variability completely. In shallow highly unconsolidated sediment, additional high temporal resolution sampling should be considered to establish tidal variation in sediment geochemistry.

Biological baseline

While biological baselines are primarily useful in impact assessment, they may have a monitoring utility. For example in assessing ratios of sensitive to non-sensitive species, or observing unusual behaviours (see left). Further there is evidence that microbial populations can be sensitive to additional CO$_2$.

Sample coring for macrofaunal and microbial abundance, coupled with visual records of the sediment surface with at least monthly discrimination are the essential elements of the biological baseline. Weekly frequency sampling during high activity periods may provide added certainty.

If leakage occurs, additional sampling at similar multiple un-impacted control sites will be necessary to provide proper statistical discrimination of any biological effect.

Key points

• The marine environment is constantly changing and there is no unequivocal absolute indicator of a leak.
• Leak detection will depend upon determining changes to a system that exceed the natural normal variation.
• To establish normal variation requires an extensive baseline of data acquired before storage starts, to underpin later monitoring.
• Thorough baseline understanding is paramount to reduce the risk of false positives and false negatives which could be highly detrimental to the future of CCS and/or the environment.