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Abstract

RISCS is a 4-year, EU and industry project which aims to improve understanding of the possible environmental impacts of geological storage of CO_2. There are 24 organisations participating in the project including research institutions, industry environmental associations and the International Energy Agency Greenhouse Gas R & D Programme. The project is designed to study a wide range of potential impacts, thus providing information relevant to the development of legislation and helping to ensure the safe management of CO_2 storage sites. Research is being undertaken through field work, laboratory studies and the development and validation of mathematical models.

Facilities for the geological storage of carbon dioxide (CO_2) as part of carbon capture and storage (CCS) schemes will be designed to prevent leakage back to the surface. However, it is important to be able to assess the consequences of any such leakage should it occur, and the RISCS programme is concerned with research into the potential environmental impacts that might be associated with hypothetical leakage in a European context. The importance of assessing the potential for environmental impacts should any leaks occur is recognized by the EC Directive on storage and other sources of guidance such as the OSPAR Framework, USEPA Vulnerability Evaluation Framework and the CO2QUALSTORE Guideline. Research within the RISCS programme is focused on receptor impacts and related monitoring.

A set of reference European receptor environments has been defined as an input to research together with associated high-level impact scenario descriptions. These high-level scenarios provide the basis for mathematical modelling studies that will be undertaken later in the project, and provide input to experimental studies in both terrestrial and marine environments.

This document summarises the output of work undertaken to date in this area for interested parties both inside and outside the RISCS project. Much of the information presented derives from an expert workshop held in Brussels in May 2010.

The baseline 'most likely' scenario is for a storage system to evolve as designed, with no leaks occurring. In other words, potential receptors, such as organisms and groundwater resources, will evolve as they

would in the absence of any CO_2 storage project. It is important to explore this baseline scenario to understand the impacts that could be associated with any leaks. 'Impact' scenarios are therefore potential low likelihood 'alternative evolution' scenarios. Alternative evolution scenarios identified for terrestrial systems include those involving impacts to animals and plants arising from direct releases to the atmosphere following well seal failure, and localized releases of CO_2 in the near-surface environment. Localized releases to aquifers that may be exploited as drinking or irrigation water resources are also considered. Impacts to human receptors are considered through the definition of a scenario based upon releases within an urban environment. In each case, relevant release and exposure mechanisms have been described. Equivalent scenarios for marine systems include impacts to marine biota, habitats and other sensitive receptors in both the biologically active sediments and overlying water column caused by different types of release.

Based on simplified scoping calculations and a review of published literature concerning natural CO_2 seepages and modelled CO_2 behaviour, illustrative CO_2 leakage fluxes and areas that would be plausible for the alternative leakage scenarios are presented.

TABLE OF CONTENTS

Page

1 INTRODUCTION

Facilities for the geological storage of carbon dioxide (CO_2) as part of carbon capture and storage (CCS) schemes will be designed to prevent any leakage back to the surface. However, it is important to be able to assess the consequences of any leakage in the unlikely event that it should occur. RISCS is a project funded by the European Commission and industry under Framework Programme 7 concerned with research into the potential environmental impacts that might be associated with hypothetical leakage in a European context. The importance of assessing the potential for environmental impacts from CO_2 storage is recognized by regulations, such as the EC Directive on storage (EC, 2009) and the OSPAR Framework (OSPAR, 2007), and other sources of guidance such as the USEPA Vulnerability Evaluation Framework (USEPA, 2008) and the CO2QUALSTORE Guideline (DNV, 2009).

A set of reference European receptor environments have been defined as an aid to research with associated high-level impact scenario descriptions. These high-level scenarios provide input to experimental studies in both terrestrial and marine environments and the basis for mathematical modelling that will be undertaken later in the project.

This document summarises work undertaken to date in this area for interested parties both inside and outside the RISCS project, including workers and regulators in the field of CCS. Much of the information presented derives from an expert workshop held in Brussels in May 2010 (RISCS, 2010). The participating organisations at that workshop were: British Geological Survey, BGS; Norwegian Institute for Agricultural and Environmental Research, Bioforsk; Center for Research and Technology Hellas, CERTH; EON, United Kingdom; International Energy Agency Greenhouse Gas Research Programme, IEAGHG; The National Institute of Oceanography and Experimental Geophysics, Italy, OGS; Plymouth Marine Laboratory, United Kingdom, PML; Sapienza University of Rome; Institute for Marine Resources and Ecosystem Studies, Netherlands, IMARES; Stiftelsen for industriell og teknisk forskning, Norway, SINTEF; University of Nottingham; Vattenfall Research and Development; Zero Emission Research Organisation, Norway, ZERO; and Quintessa Ltd, United Kingdom.

The remainder of this document is structured as follows.

- Section 2 provides brief background information on CCS;
- Section 3 provides an overview of the aims of scenario analysis;
- Section 4 discusses international guidance and terminology relevant to scenario analysis;
- Section 5 gives details of the scenarios that have been derived; and, finally
- Section 7 includes a brief discussion of potential impacts from CO_2 leakage and the use of the impact scenarios.

In all technical areas specialist terminology is used, and it is important that this terminology is employed consistently. A list of definitions of relevant technical terms used in RISCS and which are referred to in this document is given in Table 1-1. As far as possible definitions used are taken from the EC Directive (marked EC) and / or the OSPAR framework (marked O), with the Directive taking precedence. Additional clarifications of those terms, and other definitions are employed based upon experience gained in other CCS projects and associated studies.

Table 1-1: Terminology.

Term *	Definition *and additional notes*
Cessation of control	The point at which activities by the site operator, such as monitoring, cease and responsibility for the site, including any further monitoring, passes to the relevant competent authority. The 'post-closure' phase follows. The competent authority may wish to continue monitoring for a time during this phase.
Closure	The definitive cessation of CO_2 injection into that *storage site*. (EC)
Conceptual model	A detailed statement of the status of a *system* and its evolution, typically mapped against a specific evolution *scenario*.
Contaminants	Any non- CO_2 substance associated with the stored CO_2 and any associated leaks, including any *impurities* that might be associated with the injected CO_2 stream, and any substances that might be released or formed as a result of sub-surface storage and / or leakage of CO_2.
FEP	A Feature that represents a component of a storage system or an Event or Process relevant to its evolution. The term includes 'external' FEPs or EFEPs that are part of the global system but external to the storage *system*; the EFEPs may however act upon the *system* to alter its evolution (e.g. seismic effects). Together, the FEPs of the *system* describe *conceptual models* that may be related to *scenarios* for *system evolution*.
Impact	An effect (positive or negative) on a defined human or environmental receptor that may occur as a result of *leakage* of CO_2 and / or associated impurities from a storage system.
Impact Scenario	A plausible *conceptual model* describing how a leak from a *storage system* could lead to *impacts* on one or more *receptors*.
Impurities	Substances other than CO_2 that may be present in the injected CO_2 stream.
Leakage	Any release of CO_2 from the *storage complex*. (EC)
Long-term	The term (period) following cessation of operation of the CO_2 storage site. This could extend to several thousand years into the future. (O)
Migration	The movement of CO_2 within the *storage complex*. (EC)
Post-closure	The period after the *cessation of control* of a storage site, i.e. after the transfer of responsibility to the competent authority. (EC)
Receptor	Any component of the environmental system that could be subject to adverse (or positive) *impacts* as a result of *leakage*, e.g. human populations, ecosystems, groundwater or other resources, and relevant aspects of the wider environment.
Risk assessment	Part of a risk-management system, consisting of exposure assessment, effect assessment and *risk characterisation*. (O)
Risk characterisation	Risk characterisation is the step in the *risk assessment* process which determines the likelihood *and* severity of impacts on the (marine) environment. (O)
Safety	The prevention of negative health and safety impacts on human populations
Scenario	A plausible description of the potential evolution of a system according to the nature of the features, events and processes that might act within and upon it.
Short-term	The term (period) prior to closure of the CO_2 *storage site*. This could extend to one hundred years into the future. (O)
Significant irregularity	Any irregularity in the injection or storage operations or in the condition of the *storage complex* itself, which implies the risk of a *leakage* or risk to the environment or human health. (EC)
Storage complex	The storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, including any secondary containment formations. (EC)
Storage site	A defined volume within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities. (EC)
(Storage) system	The *storage complex* and the surrounding environment with which it may interact.

2 CARBON CAPTURE AND STORAGE

Many argue that climate change is one of the greatest challenges humanity has ever faced, and urgent measures are needed to achieve the CO_2 emissions reduction required to stabilise and reduce atmospheric concentrations of greenhouse gases. Contributions to the stabilisation of CO_2 emissions can be made by measures such as improved energy efficiency, increased use of energy sources that do not produce CO_2 and the decarbonisation of heavy industries and power generation from fossil fuels through CO_2 capture and storage (CCS).

The basic concept of CO_2 storage is to prevent CO_2 emissions being released into the atmosphere by injecting it into deep porous geological formations so that it remains permanently trapped. The CO_2 gas can be captured at a power station or other industrial plant after or before the fuel is burnt (pre- or post-combustion capture). After the CO_2 is captured it can be compressed and transported by pipelines to a suitable geological storage site, either on- or off-shore where it is then pumped deep underground (Figure 2-1). Several projects have used different types of storage formation including depleted oil and gas fields and saline aquifers (see, for example, Torp and Gale, 2003; Wilson and Monea, 2004; Riddiford et al., 2005). These sites have been monitored before, during and after CO_2 injection and have generally been shown to be performing as expected.

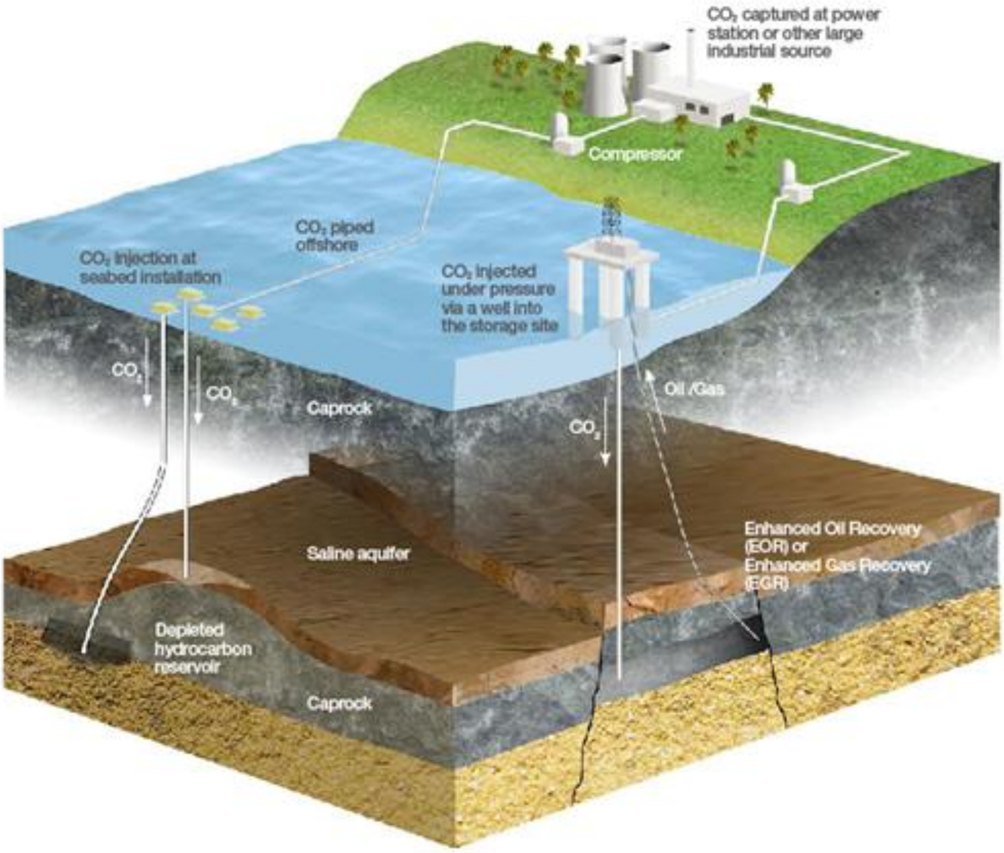


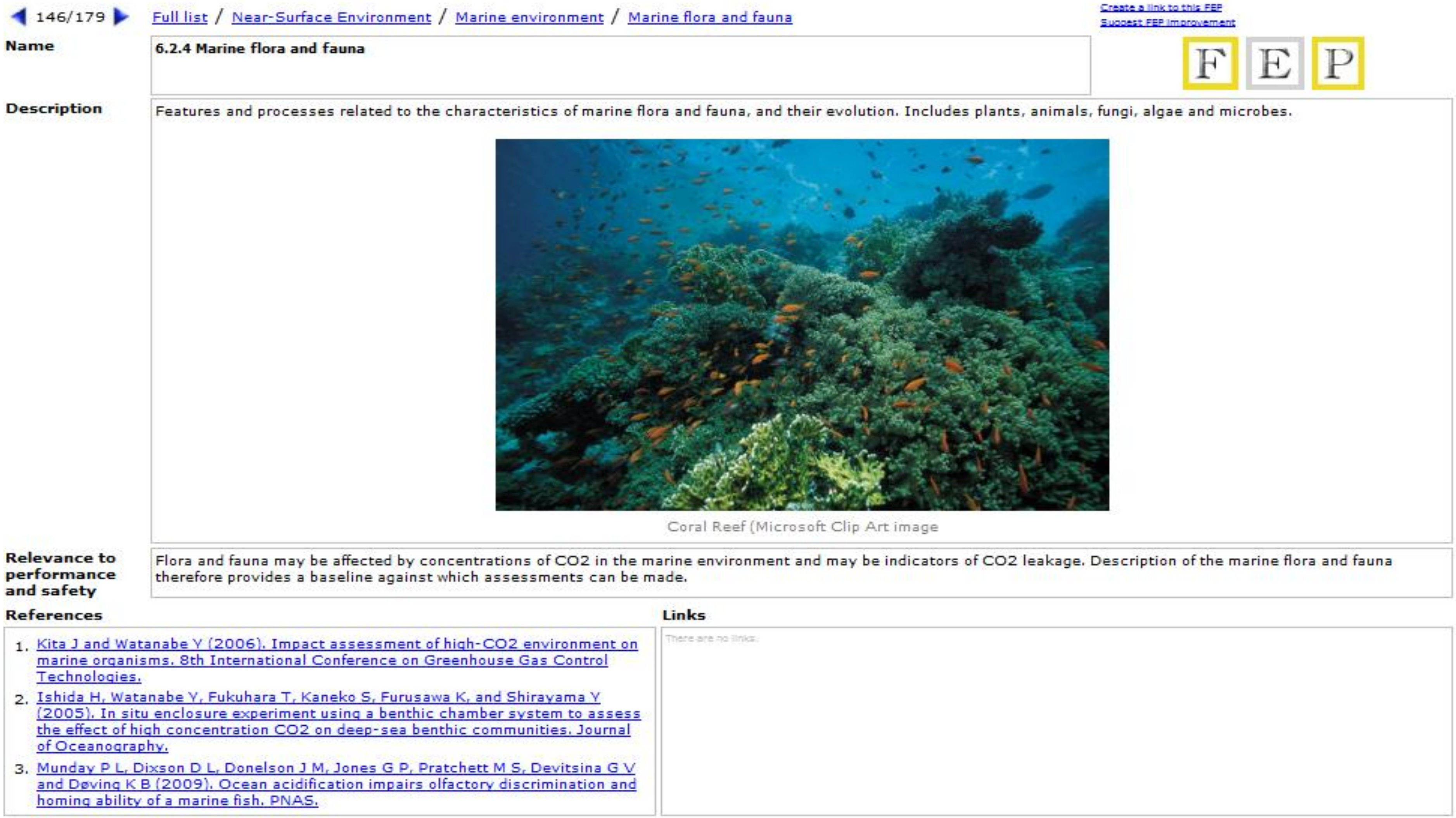
Figure 2-1 Schematic illustration of the concept of geological storage of CO_2. The figure is not to scale; the depth for CO_2 injection will normally be at least 800 m.

Storage sites need to be chosen carefully on the basis of their geological characteristics. For safe storage the storage site must have:

- a good reservoir at a depth of greater than about 800 metres (where CO_2 will be in the dense or 'supercritical' phase under typical subsurface conditions of temperature and pressure);
- a geological trap;
- a good seal above the reservoir (typically mudrock or salt, usually hundreds of metres thick); and
- a geologically stable area.

Much research has been carried out to assess the storage potential across Europe which has been funded mostly by the European Commission. The first Europe-wide study was the Joule II project (Holloway, 1994) which assessed the potential for reducing CO_2 emissions from the atmosphere and included a European inventory of storage capacity (including Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain and the UK). This was followed in 1999 by the GESTCO project (Assessing European potential for Geological Storage of CO_2 from fossil fuel combustion) (Christensen and Holloway, 2004) which provided an overall assessment to the viability of geological storage at selected sites within Europe (including Belgium, Denmark, France, Germany, Greece, the Netherlands, Norway and the UK). These and subsequent studies have shown that in most European countries there is significant capacity to store CO_2 in saline aquifers, hydrocarbon fields, and coal fields.

When assessing the performance of a storage system it is useful to consider relevant Features, Events and Processes (FEPs), which are different factors affecting the evolution of the storage system. A generic FEP database has been produced (Quintessa, 2010) that can be freely accessed at www.quintessa.org/co2fepdb/. Figure 2-2 shows part of an example page from this database.


146/179 [Full list](#) / [Near-Surface Environment](#) / [Marine environment](#) / [Marine flora and fauna](#)

Create a link to this FEP
Suggest FEP improvement

F E P

Name	**6.2.4 Marine flora and fauna**
Description	Features and processes related to the characteristics of marine flora and fauna, and their evolution. Includes plants, animals, fungi, algae and microbes.
	Coral Reef (Microsoft Clip Art image
Relevance to performance and safety	Flora and fauna may be affected by concentrations of CO2 in the marine environment and may be indicators of CO2 leakage. Description of the marine flora and fauna therefore provides a baseline against which assessments can be made.

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2. Ishida H, Watanabe Y, Fukuhara T, Kaneko S, Furusawa K, and Shirayama Y (2005). In situ enclosure experiment using a benthic chamber system to assess the effect of high concentration CO2 on deep-sea benthic communities. Journal of Oceanography.
3. Munday P L, Dixson D L, Donelson J M, Jones G P, Pratchett M S, Devitsina G V and Døving K B (2009). Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. PNAS.

Links

There are no links.

Figure 2-2 Part of a page from the generic FEP database.

3 IMPACT SCENARIO ANALYSIS

The focus of the RISCS programme is on the potential impacts that might result from CO_2 leakage from the storage complex, however unlikely it is that any leaks will occur.

In addition to leakage, there are two further possible impact mechanisms:

- Even if there is no leakage, pressurisation of the storage complex could lead to unintended displacement of fluids with the potential for subsequent interactions between saline waters and sensitive environments such as near-surface aquifers. Such impacts are not considered directly in the present document, although there is a large amount of literature that is relevant to such potential impacts, for example publications concerning the effects of saline intrusion into groundwater aquifers (e.g. Edmunds and Milne, 2001; Ball and Campbell, 2006; Al-Hanbali and Kondoh, 2008). The focus of the RISCS project is on potential impacts from CO_2 leakage, where such impacts are less well understood.
- Pipeline failures during operations could lead to impacts of a similar nature to those associated with some forms of leakage from the storage complex.

The term 'scenario' is used in a number of different ways in different fields of study. For the RISCS project, the definition employed is:

A plausible description of the potential evolution of a system according to the nature of the features, events and processes (FEPs) that might act within and upon it.

The analysis is concerned with exploring how leaks, if they occur, could lead to environmental impacts.

The identification of impact scenarios needs to address the following:

- the identification of plausible temporal and spatial leakage patterns;
- an understanding of the mechanisms by which such leaks could lead to environmental impacts; and
- an appreciation of the main features of, and differences between, example reference environments, including different types of marine and terrestrial systems.

Consistent with the aims of the RISCS project, the reference environments have been identified to illustrate all the main types of impact that need to be considered within the project.

A small number of scenarios are required that are broadly representative of the main types of impacts that could occur. Identification of scenarios and impact mechanisms that are particularly unlikely to occur (even if a leak does happen), and which can therefore be 'screened out' from further analysis, is also an important part of the process.

4 INTERNATIONAL GUIDANCE AND TERMINOLOGY

The EC Directive on storage (EC, 2009), and other regulations or sources of guidance such as the OSPAR Framework, USEPA guidance and the CO2QUALSTORE Guideline (OSPAR, 2007; USEPA, 2008; DNV, 2009) all recognize that the primary issue to be assessed and demonstrated for CCS sites is long-term containment. However, they all also recognize the importance of assessing the potential for environmental impacts should there be any leaks. A brief summary of key documents is provided here.

4.1 EC Directive on the Geological Storage of Carbon Dioxide

The EC Directive (EC, 2009) describes requirements and guidance relevant to CCS. A number of specific statements are relevant to assessments of the potential impacts of any leakage from storage systems. The Directive states that Member States shall require operators to monitor the storage complex and the surrounding environment for the purpose of:

- detecting 'significant irregularities';
- detecting migration of CO_2;
- detecting leakage of CO_2;
- detecting significant adverse effects for the surrounding environment;
- assessing the effectiveness of any corrective measures taken; and
- updating the assessment of the safety and integrity of the storage complex in the short and long term, including the assessment of whether the stored CO_2 will be completely and permanently contained'.

Additionally, the separate EC Environmental Impact Assessment (EIA) Directive (Directive 85/337/EEC, as amended by Directives 97/11/EC and 2003/35/EC), requires that an EIA should be carried out by the developer of a potential CO_2 storage site, before a license to operate the site can be granted. According to this Directive, an EIA is required to: 'identify, describe and assess in an appropriate manner, in the light of each individual case….the direct and indirect effects of a project on the following factors:

- human beings, fauna and flora;
- soil, water, air, climate and the landscape;
- material assets and the cultural heritage; and
- the interactions between the factors...'

In addition, closure of the site will require preparation of a *'post-closure plan'* that will take account of *'risk analysis, best practice and technological improvements'* prior to submission to a competent authority (such as a national government or an agency appointed by a national government) for approval. This risk analysis will require:

- a *'hazard characterisation'* stage, including identification of potential leakage pathways, the potential magnitude of leakage events for those pathways, and any factors that could cause a hazard to human health or the environment;
- an *'exposure assessment'* based upon the characteristics of the environment and human populations that may be subject to any leaks and associated impacts;

- an *'effects assessment'* considering the sensitivity of particular species, communities and habitats to any leakage events (including consideration of any impurities that might be associated with CO_2 leakage); and
- *'Risk characterisation'*, integrating the above steps into an overall short- and long-term assessment of system safety and integrity, including the risk of leakage assuming the 'proposed conditions of use' of the site, and any 'worst case' environment and health impacts.

4.2 OSPAR Guidelines

The OSPAR guidance includes an overview of the use of a Framework for Risk Assessment and Management (FRAM) of storage of CO_2 streams in geological formations *'in the sub-soil of the OSPAR maritime area'*, developed noting the framework of the London Convention / Protocol. The guidelines '*encompass the iterative process described in the FRAM … that should be used for continual improvement of the management of a CO_2 storage project during the project life cycle, in accordance with the principles of internationally- recognized environmental management standards'*.

The six stages of the FRAM are defined as:

1. *'Problem formulation: critical scoping step, describing the boundaries of the assessment;*
2. *Site selection and characterisation: collection and evaluations of data concerning the site;*
3. *Exposure assessment: characterisation and movement of the CO_2 stream;*
4. *Effects assessment: assembly of information to describe the response of receptors;*
5. *Risk characterisation; integration of exposure and effect data to estimate the likely impact; and*
6. *Risk management: including monitoring, mitigation and remediation measures'.*

These stages are to be undertaken in an iterative process, revisiting appropriate stages as a result of advances in system design and understanding, or impacts estimates. All these stages are of relevance to RISCS. Stages 3 to 6 are reflected in the requirements of the (subsequently developed) EC Directive. The OSPAR guidelines provide significant additional guidance relating to these stages for a marine environment.

4.3 CO2QUALSTORE

The CO2QUALSTORE Guideline (DNV, 2009) also provides useful guidance on the importance of impacts assessment. It states that, while the fundamental aim of the 'qualification' process is to establish that a site will meet requirements for injectivity, capacity and containment, the following additional issues are relevant to the evaluation of candidate storage sites:

- 'Have the most relevant secondary effects of the storage project that may have adverse impact on human health or the environment been considered, including effects of displaced formation fluids and release of heavy metals or other substances with the potential to contaminate vulnerable zones?'

- 'Are there any other factors which could pose a hazard to human health or the environment (e.g., physical structures associated with the project)?'

4.4 The EPA Vulnerability Evaluation Framework

The USEPA *'vulnerability evaluation framework'* document (USEPA, 2008) provides a further useful resource that includes an exploration of potential impacts that might be associated with CO_2 storage, and how those impacts might be evaluated within a vulnerability assessment.

The 'vulnerability' term is used to reflect a separate (if related) concept from 'risk assessment'. The framework is used to *'systematically identify those conditions that could increase the potential for adverse impacts from geological storage, regardless of likelihood or broad applicability'* within an iterative process. Its role therefore is in '*framing key site-specific considerations and in identifying key areas that require in-depth evaluation for project design, site-specific risk assessment, monitoring, and management*.' As the framework does not reflect site-specific requirements a generic 'conceptual model' has been developed. This provides a useful indication of the sorts of impacts considered relevant by the USEPA (see Figure 4-1). The document contains, amongst other supporting information, a range of further details exploring potential processes that can lead to impacts associated with the identified receptors.

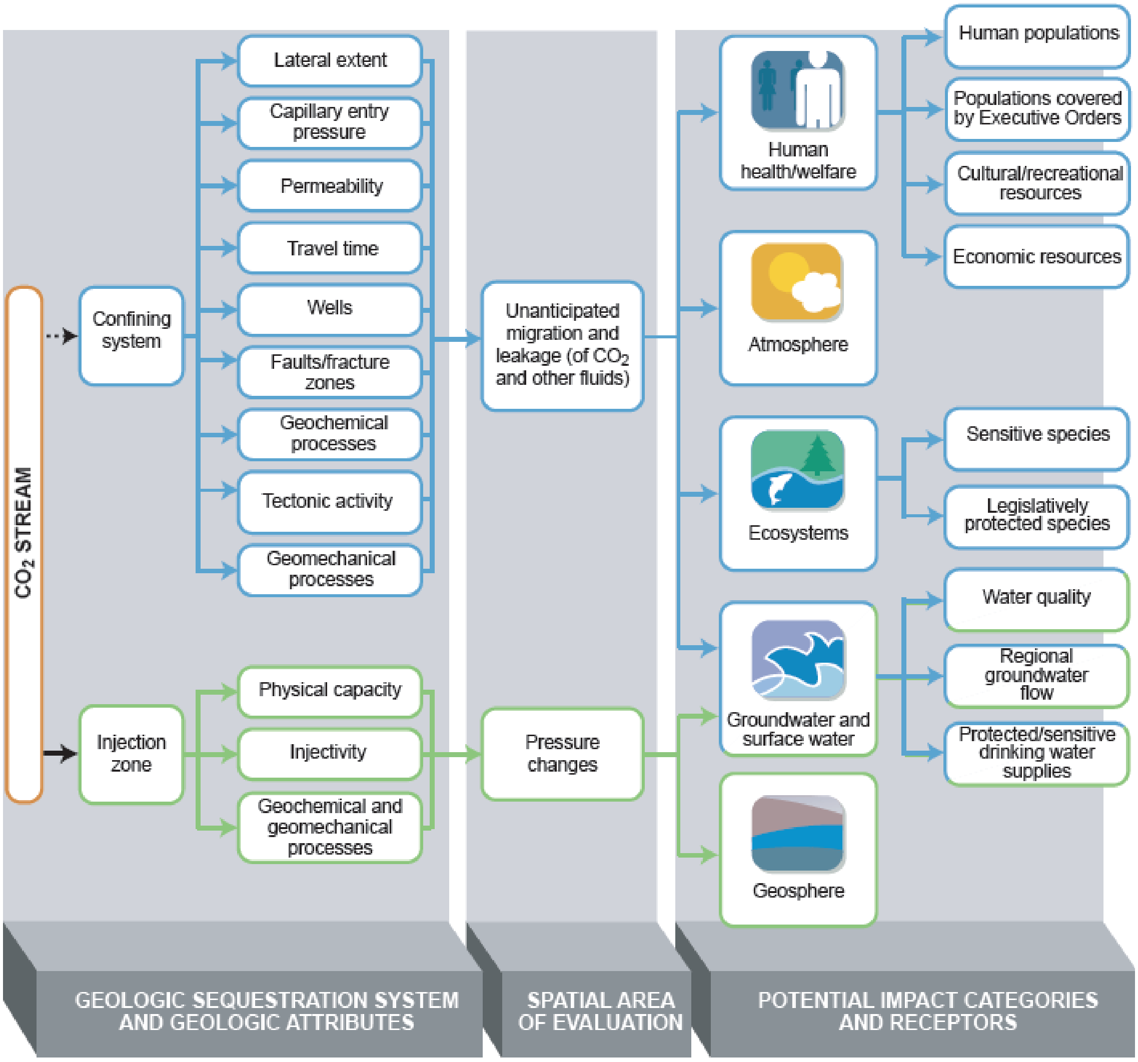

Figure 4-1: Vulnerability Evaluation Framework Conceptual Model (after USEPA, 2008).

4.5 Timescales

An important aspect for the identification of scenarios for the RISCS programme is to consider the timescales over which different types of impact might apply. The following considerations are relevant.

- The main risks of impacts to human health and safety for many sites may be associated with potential impacts to workers during the operational time period.
- The EC Directive and OSPAR framework require a long-term analysis of the risk of potential post-closure impacts to a range of receptors.
- Stakeholder views on the relative importance of different risks will vary with timescales. For example, a low-impact risk that is reasonably likely to occur in the next 50 years may (or may not) be considered to be more important than a higher-

impact risk that is less certain to occur and would be associated with a 500 year time frame.

For the purposes of defining scenarios, it is useful to consider a range of indicative timescale categories that help frame assessment of the types of impacts that might be relevant. The following time periods are relevant:

- an ‘operational’ assessment time period (typically of the order of a few decades, up to cessation of injection operations);
- a ‘closure / monitoring’ assessment time period (perhaps a further 20 to 100 years, up to the cessation of monitoring and other controls); and
- a ‘long-term’ assessment time period (including a post-closure period of a perhaps a further 100 to several 1000 years).

5 IMPACT SCENARIO DERIVATION

The Brussels workshop enabled information to be obtained from experts in the field. This was followed by an audit against the generic FEP database to demonstrate completeness.

5.1 Reference Environments

The RISCS project needs to address the full range of CCS projects that may be undertaken in the EU region at some point in the future. Therefore it is important that the impact scenarios identified are not site-specific. It is also recognized that to develop guidance that will provide a meaningful contribution to the analysis of possible impacts associated with specific sites, the scenarios should not be too generic.

A small number of reference environments have been identified for both the 'marine' and 'terrestrial' environments, providing an input to research activities. The environments together encompass a representative range of receptor classes within the two main categories, to give an indication of the range of different types of FEPs that need to be included in the overall analysis.

Key points in the specification of scenarios are:

- The environments should reflect European conditions, consistent with the focus of RISCS.
- The fundamental difference is between marine and terrestrial environments.
- Within each of these types of environment, receptor types and habits will vary according to climate (terrestrial environments) and depth, salinity and temperature of water (marine environments), although other factors will also apply.
- Variations in geology / sediment types and related characteristics are site-specific issues and therefore not considered directly in the list of reference environments.
- Tectonic activity is not considered a key control on the choice of reference environments. The influence of tectonic activity is considered in terms of the nature and likelihood of occurrence of processes such as fault / fracture widening.
- Humans, and the resources they utilise, correspond to specific classes of receptors that could be present across all terrestrial environment types. To consider environmental (i.e. non-operational) processes that could lead to impacts on human populations, a specific environment was identified to consider a storage system located under an urban settlement.
- Freshwater systems such as lakes and wetlands are potential features that might be present in all terrestrial environments.
- There are large disparities in tidal range and hydrodynamic mixing in different marine environments, which influence both the nature of biota and the dispersion of any CO_2 that leaks into the environment. The Baltic Sea and Mediterranean Sea have relatively small tidal ranges compared to, for example, the North Sea.
- Estuaries, intertidal and near coastal regions are very different from marine and terrestrial environments. Diurnal changes in salinity / tides could have effects not represented in the other environments. However, many of the influences will be site-specific. A specific 'estuary reference environment' was not defined because 'typical' properties cannot be defined. Receptor communities in estuaries are adapted

to extreme ranges of salinity and therefore would respond differently to CO_2 compared to communities that are adapted to more stable salinity conditions, for example fully marine or Baltic seawater conditions (Baltic seawater is typically only 20% - 30% as saline as fully marine water).

- Consideration was only given to environments that are representative of European areas that could reasonably be expected to provide candidate sites for CO_2 storage in the future. Therefore, it is not necessary to consider:

  - terrestrial environments with true Arctic conditions;
  - very deep seas, e.g. off the continental shelf; or
  - very mountainous regions.

The reference environment types that have been defined are shown in Table 5-1. These are intended to cover the different types of environment relevant to the RISCS project. Figure 5-1 illustrates the first type of terrestrial environment and Figure 5-2 shows the locations of some of the regions considered in the specification of marine environments.

It should be noted that there is no ‘warm deep’ marine environment. Potential CO_2 storage environments of this type are present in Europe; in the Mediterranean, there are potential storage sites with a wide range of water depths, from a few tens of metres to a few hundreds of metres. However, the addition of such an environment to the list of reference environments would simply cause duplication of the issues to be considered; the main environmental factors to be considered when developing impact scenarios (notably depth, temperature, salinity) are already encompassed by the four marine environments.

Table 5-1: Reference environments.

Class	Reference Environments	Notes
Terrestrial	Maritime Temperate	Representative of a northern central European, cool climate (e.g. UK and the Netherlands).
	Continental	Climate associated with northern (but not Arctic) European continental land mass countries.
	Mediterranean	Representative of warmer, more arid, southern European climates
	Generic Urban	Specifically designed to explore potential impacts on humans should a storage system be located close to a large urban centre.
Marine	Cool, temperate, deep	Continental shelf remote from shoreline influences where the water depth is greater than 60 m, and typically over one hundred metres. Tides significantly influence mixing and currents but not water depth. The site is not Arctic (no sea ice), but bottom water is cool (around 5°C). The moderately nutrient rich water is seasonally stratified, surface temperatures varying from around 4°C to around 15°C annually. Such an environment may be in the northern North Sea, or to the west of Norway.
	Cool, temperate, shallow	Land is relatively close and the water depth is a few tens of metres. A comparatively large tidal range could cause significant changes in water depth and strong mixing. Some seasonal stratification may occur but normally the water column is fully mixed. The temperature varies from around 4°C to around 15°C annually. Nutrient rich (eutrophic) water may be impacted by riverine water. Such a site could be in the southern North Sea
	Warm shallow	Land is relatively close and water is a few tens of metres deep. The tidal range is small. Variable seasonal runoff from adjacent land masses may be significant. The temperature is a minimum of 5°C at the seabed and varies annually from 6°C to 25 °C, with a mean of 10 - 12 °C, at the sea surface. Such a site could be in the Adriatic Sea.
	Low salinity (saline, but substantially lower than mean ocean salinity)	Land is relatively close and water is a few tens of metres deep. The tidal range is small. Water salinity is much lower than that of open ocean water (which is present at the other marine sites), but varies depending upon the proximity of the coast and open ocean. Biodiversity is much less than in the open-ocean. Such a site would be in the Baltic Sea.

Figure 5-1 Typical marine temperate agricultural mix.

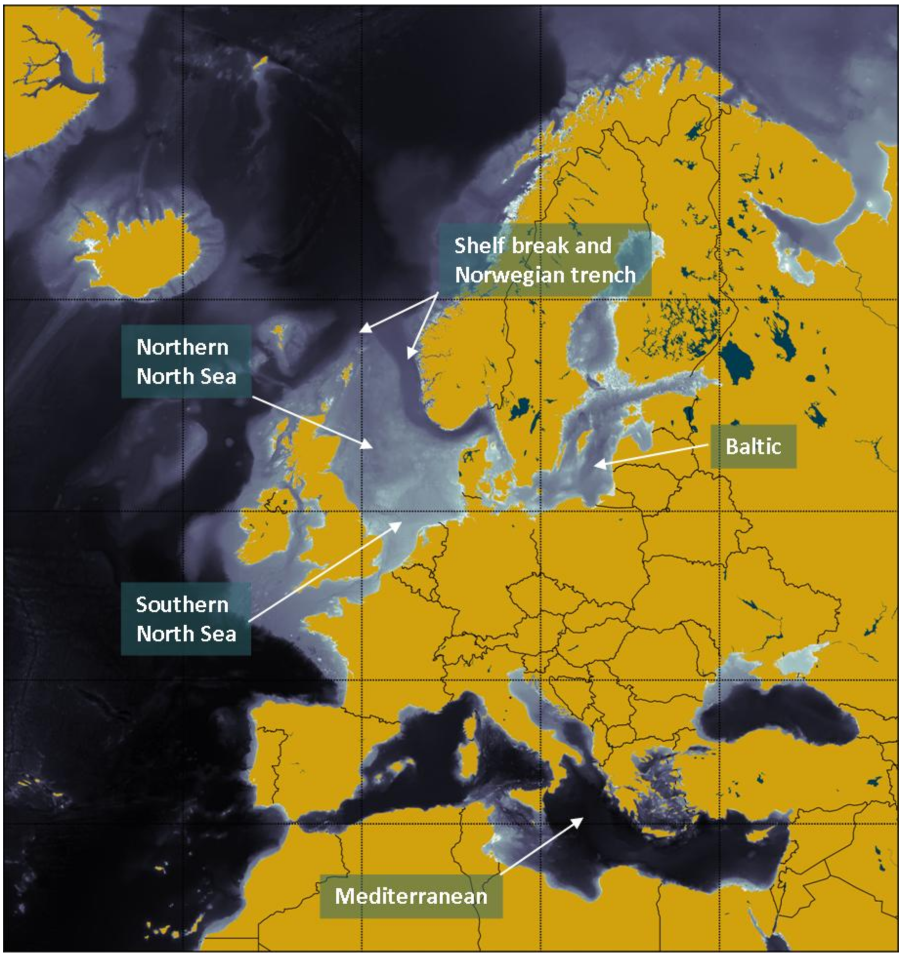

Figure 5-2 European marine regions.

5.2 Leakage Patterns

5.2.1 Terrestrial Environments

When considering the different possible types of leakage the following points are relevant:

- Features that are most likely to be associated with leakage include wells (for example following well seal failure) and faults and fractures (for example as a result of fault / fracture widening through induced or natural seismicity, or interaction of the storage complex with a fault that had not previously been mapped) (IPCC, 2005).
- Potential diffusion through the rock matrix would be very slow, and would probably only reach the surface if it intersects a fracture.
- Although individual faults and fractures are essentially planar features, in the event of leakage they are likely to lead to localized CO_2 releases to the atmosphere (essentially point sources), rather than more diffuse releases, as seen at the Latera site in Italy where there are large natural fluxes of CO_2 to the surface (Annunziatellis et al., 2008). Where a fault intersects the ground surface, these point sources are likely to have an approximately linear distribution along the length of the fault.
- CO_2 that leaks along faults / fractures is likely to reach the atmosphere either where the fault / fracture intersects the ground surface, or through the rock matrix and / or unconsolidated deposits that intersect with but overlie the fault. The leakage of CO_2 through these media will occur via discontinuities, or through the matrix of the media concerned. Migration of the CO_2 through these relatively near-surface media above a fault will be accompanied by some dispersion and hence broadening of the zone through which CO_2 is eventually released to the atmosphere. However, zones of release will be relatively localized and a general diffuse release is much less likely to occur.
- Overall the leakage pattern most likely to lead to significant impacts would be a point source, localized release via wells, faults or fractures, individually or through a combination of linked features.
- Release fluxes and timescales will vary according to the nature of the system and the leak. Releases could occur relatively quickly, i.e. on the order of days or weeks, unless the system is very large and is full of supercritical CO_2, in which case the release could occur over a much longer timescale (Bachu and Watson, 2009; Celia et al., 2009 and Pawar et al., 2009). The 'worst case' leakage would be if a closed well completely fails; in extreme circumstances this could lead to releases of the order of 100 tonnes a day, although a few hundred tonnes per year is more likely.
- Evidence from natural analogue studies suggests that impacts from point source releases will be localized around a radius of the order of metres to tens of metres from the source (Beaubien et al., 2008; Vodnik et al., 2006; Krüger et al., 2009, 2011).
- Experience from natural analogues also suggests that while leaks from comparatively near-surface gas containing systems can take very little time to travel to the surface, leaks from deeper systems typically take much longer, sometimes taking several years.

- In considering leakage patterns to different domains it is important to define depths and other important aspects pertinent to different features.
  - The primary storage reservoir within a storage complex will generally be located at a depth of greater than eight hundred metres, where the CO_2 would typically be at sufficiently high pressures and temperatures to remain in a supercritical phase.
  - Potential receptors within the storage complex are out of the scope of RISCS, as they will have been 'deliberately' impacted upon by the act of storage, rather than representing unintended impacts as a result of leakage.
  - Aquifers that may be considered to have the potential to be exploited as drinking water or low salinity irrigation water resources represent receptors in their own right. Typically such resources are likely to be located within a few hundred metres of the surface, and the nearer they are to the surface, the more likely they are to be exploited as a resource. It is also relevant to note that even some higher salinity aquifers may be considered a resource, via desalination, in water-stressed areas.

The list of plausible leakage mechanisms / patterns considered is therefore:

- localized release to the surface through well failure;
- localized release to the surface through fractures;
- localized release to aquifers that have the potential to be exploited as water resources through a well failure;
- localized release to aquifers that have the potential to be exploited as water resources through fractures; and
- diffuse effects following fracture / well transport to the surface / aquifers.

In this list, localized releases to the sub-surface or aquifers from wells or fractures can be treated together, as the leakage patterns are similar. Whilst diffuse effects are noted for completeness, they are less likely to occur, or at least less likely to be associated with significant levels of impact. Any impacts that could occur would be lower in magnitude than the point source equivalent. Evidence in support of this arises from studies of analogues that show where chronic long-term diffuse leakage does occur, impacts are generally low. Therefore, diffuse leakage is not considered further.

5.2.2 Marine Environments

The following aspects of leakage that could affect ecosystems need to be noted (Alendal and Drange, 2001; Biglake et al., 2008; Blackford et al., 2008; Blackford et al., 2009; Blackford et al., 2010 Brewer et al., 2002; Chen et al., 2007; Chen et al., 2009; Hall-Spence et al., 2008; Shirayama and Thornton, 2004):

- Fast passage of CO_2 through benthic (sea floor) system may result in the benthic system in the immediate vicinity of the leak being little affected.
- Impacts on pelagic ecology (away from the sea floor) in the region of the leakage site could be important.

- The physical effects of leaking CO_2 on the behaviour of seawater could be important. The degree to which CO_2 dissolves in water before leaking to the seabed, or close to the seabed following leakage of a discrete CO_2 phase, will determine whether or not a plume of dense CO_2-charged water forms. Such a plume would impact upon benthic organisms.
- Hydrodynamic mixing and density variations due to CO_2 dissolution will control the pH profile that develops in the water column. The impacts may depend partly upon whether acidified, CO_2-charged water is applied to the benthos from above (when dense CO_2 solution sinks) or beneath (when acidified water rises).
- Acidification of porewater in the sediment column beneath the seabed, as well as that of the water column above the seabed, is important in controlling impacts.
- Mobilisation of organic compounds from the storage reservoir, shallower strata (overburden) and shallow sediments as a result of CO_2 leakage may influence the impacts.
- Mobilisation of inorganic contaminants (e.g. heavy metals) from the storage reservoir, overburden and shallow sediments as a result of CO_2 leakage may influence the impacts.
- Displacement of saline water could occur as a result of CO_2 leakage. However, formation water with salinity much greater than that of seawater is likely to be encountered only at great depth. Displacement of formation fluids could also occur separately from actual CO_2 leakage. For example, the CO_2 itself may not leave the storage complex, but the pressure changes caused by CO_2 injection could cause the movement of formation fluids beyond the storage complex. These formation fluids could include hydrocarbons (including gas pockets) and saline water / brine.

The geometry of any CO_2 emission at the seabed whether as a discrete CO_2 phase or as CO_2-charged water, would influence the spatial distribution of potential impacts. Three different geometries are considered to be plausible:

- point emissions;
- linear emissions; and
- diffuse emissions over a wide area.

Expert judgement expressed at the Brussels workshop was that truly linear emissions, in which CO_2 or CO_2-charged water is released along the length of a linear feature on the seabed, is unlikely to occur. It is more likely that there will be single emission points, or groups of emission points, that are approximately aligned with one another (as considered for terrestrial environments). The alignments of these emission points could reflect the existence of structures such as faults and fracture zones in the underlying rock.

Similarly, expert judgement at the Brussels workshop was that a diffuse emission over a wide area, without any change in seabed topography, is unlikely to develop; it is more likely that pock marks would form within seabed sediments. However, the fact that such emissions have not been observed at natural analogue sites could reflect the difficulty of detecting this kind of emission, and so this possibility cannot be totally ruled out. If CO_2 dissolved in water within the sediment column immediately below the seabed, then the resulting dense, low-pH water might spread laterally over a wide area and diffuse upwards to the seabed.

The actual kinds of sub-surface leakage path that could give rise to these different patterns of emission at the seabed are similar to those considered for terrestrial environments, and leakage could potentially occur through a combination of different kinds of pathways.

5.3 Receptors

5.3.1 Terrestrial

The receptor classes identified as being important for assessments of impacts associated with terrestrial systems are summarised in Table 5-2.

Receptor characteristics will vary across receptor environments according to differences in climate:

- The nature and proportions of plant and animal types associated with natural ecosystems will vary with climate.
- Human land uses will vary with climate and this will influence plants and animals associated with agricultural ecosystems.
- Some locally adapted species may be more tolerant of variations in conditions than others. Therefore impacts could change the type and distribution of species, and influence natural competition effects.
- Site-specific conditions, e.g. geology, soil type, land use, proximity to surface water resources etc. will have a major influence on the nature and sensitivity of flora and fauna receptors, and so it is not possible to provide a detailed analysis of the likely impacts of changes in climate at a generic level.
- Very cold conditions, in particular those involving a significant ice load on the environment, and very hot arid conditions could lead to very significant deviations from the situation for maritime environment receptors. Given the areas of Europe where storage projects are most likely to be located, it is more relevant, however, to consider the implications of less extreme variations in climate.

The main differences between maritime, continental and Mediterranean climate types are that the nature and distributions of plant and animal types will vary. However, under colder or more arid conditions, many plants will already be subject to stress, and so will be more sensitive to additional stresses that may result from CO_2 leakage. It is therefore more likely that plants in such conditions will suffer a loss of productivity / quality or death. Degradation of food and / or habitat quality may in turn have an impact on animal receptors.

Table 5-2: Receptor classes for terrestrial systems.

Receptor Class	Potential Impact Mechanisms
Plants associated with agricultural ecosystems Crops and grasses **Plants associated with natural systems** Plants associated with forest, moorland, heath, wetland, and alpine ecosystems	Stress / death as a result of the effects of CO_2 concentrations on roots. Stress / death as a result of CO_2 ponding and impacts on the canopy. Stress / death as a result of degradation of soil quality (acidification, toxicity etc.).
Animals that inhabit agricultural or natural ecosystems Invertebrates (e.g. insects) Vertebrates (including mammals, amphibians, birds) Microbiota	Death (of animals unable to move away from a localized surface ponding event). Potential for chronic low-concentration exposure effects e.g. on skeletal structure or other effects (some burrowing animals may have reduced sensitivity). Impacts due to a reduction in feed quality and availability. Habitat damage / loss (see impacts on plant receptor classes).
Terrestrial freshwater bodies / resources (lakes, rivers, springs) Surface water resources as receptors in their own right Aquatic plants e.g. algae Vertebrates (e.g. fish) Invertebrates (e.g. mosquito larvae)	Surface water body acidification / toxicity. Stress / death on aquatic plants as a result of CO_2 concentrations. Impacts on animals due to a reduction in feed quality and availability. Habitat damage / loss (see impacts on plant receptor classes above). It is necessary to distinguish between stratified and more homogeneous lakes.
Aquifers that may be exploited as drinking or irrigation water resources Aquifer water resources as receptors in their own right Microbes that might inhabit the aquifer	Degradation of water quality as a result of biogeochemical processes leading to acidification / toxicity etc. (it is not possible to be more specific without site-specific geochemical information). Microbial populations could be regarded as receptors in their own right, in addition to contributing to biogeochemical processes.
Humans Defined as non-operators who might be exposed to impacts as a result of CO_2 leak / migration to and through the environment	Death as a result of sudden releases to and accumulation within basements / subsurface features. Impact on urban environment (gardens, other structures and resources). It is extremely unlikely that a storage system would be built sufficiently close to a large urban population, that releases could then occur to a basement, and that the release would be acute enough to lead to death. Similarly it is unlikely that any leak would happen to interact with basements associated with a less laterally extensive settlement. Related scenarios must therefore be, by definition, high impact (in that death could occur) but very low likelihood.

5.3.2 Marine

The receptor classes identified as being important for assessments of impacts associated with maritime systems are summarised in Table 5-3.

Table 5-3: Receptor classes for marine systems.

Receptor Class	Potential Impact Mechanisms
Benthic biota Micro-biota Multi-cellular fauna and flora	Benthic organisms include all those in or on the sediments. They will be influenced by the changes in dissolved carbon chemistry (pH, pCO_2, bicarbonate and carbonate concentrations) that occur upon exposure to CO_2. The primary factors that affect impacts to benthic biota include: • Different communities are found in muddy and sandy sediments. • Calcified organisms are likely to be most affected because CO_2 influences calcite solubility. • Soft bodied animals are most resistant because they have no calcified structures and a high capacity to regulate their chemical environment. Benthic effects of leakage are likely to remain local to the leakage site. The dispersal potential of the organisms being affected will determine the domain over which leakage effects occur.
Pelagic biota Larval forms of benthic organisms Fish larvae Phytoplankton	Like benthic organisms, pelagic organisms will be influenced by the changes in dissolved carbon chemistry (pH, pCO_2, bicarbonate and carbonate concentrations) that occur upon exposure to CO_2. The structure of the phytoplankton community is potentially sensitive. Organisms with calcified skeletons will be more affected than those with silica skeletons. Calcification is inhibited under high CO_2. Effects on zooplankton might lead to indirect impacts on phytoplankton. Pelagic effects will not remain localized. The hydrodynamic mixing rates coupled with the dispersal potential of the organisms being affected, coupled with their recovery rates will determine the domain over which leakage effects occur.
Biogenic calcifying habitats Cold water coral Maerl beds Mussel beds	Marine organisms that are important not only because they calcify, but also because they provide habitats
Localized sensitive populations	The impact will depend upon the spatial ranges of communities, which are in turn controlled by the habitat provided by sediments (e.g. whether sandy or muddy sediments are present). Communities that have adapted to a specific habitat with a restricted spatial range will tend to be impacted more significantly than communities that are less specialised with respect to the local environments.
Biogeochemical cycles Biogeochemical cycles such as the nitrogen cycle	Nitrogen cycling involves various groups of bacteria, the balance of which impacts upon the nitrogen cycle. Several aspects of the nitrogen cycle are sensitive to high CO_2 concentrations, especially nitrification. Release of CO_2 can change the micro-biota within the sediment, which then impacts upon cycling of other chemicals. Sediment type (and rock type) would also influence contaminants that could be mobilised with the CO_2 (e.g. heavy metals and hydrogen sulphide). Impacts on bioturbating organisms would affect the sediment habitat and pelagic-benthic coupling.

The receptor characteristics and potential impacts upon them would vary according to a number of factors:

Sediment types

Different communities of organisms in different sediment types show different degrees of resistance to elevated CO_2 concentrations (Widdicombe et al., 2009). However, the reasons for these differences are not fully understood. Possibly, the differing pH-buffering capability of different kinds of sediment may be important. Muddy environments are more pH-buffered than sand. Uplift and subsidence could be accompanied by erosion and sedimentation respectively, which could change the nature of the substrates upon / within which ecosystems develop. Hence uplift and / or subsidence could influence the nature of the communities that are impacted by CO_2.

Water column depth

The degree to which benthic and sea surface systems are coupled decreases with increasing water depth. Shallower environments will be in the photic zone (the layer of a body of water that is penetrated by sufficient sunlight for photosynthesis to take place, also called the euphotic or limnetic zone); deeper environments will not be in the photic zone. Plants, including sea grass and algae, will grow in the photic zone, but not below this zone. The depth of this zone varies with latitude and water quality, from ~10 m or less in parts of the North Sea to 100 m in parts of the Mediterranean for example.

Water temperature

This will influence the nature of the organisms that are present and their vulnerability to CO_2 leakage. For example, corals can be present in both shallow warm water (for example in the Mediterranean) or in cool temperate waters. However, there would be different ecosystems associated with warm water- and cold water- corals.

Water salinity

The salinity of the seawater will impact upon the nature of organisms that will be present and the biodiversity. In the Baltic Sea, which has much lower salinity than open-ocean water (around 20%-30% of fully marine water in near-surface waters near the middle of the Baltic), there is very low biodiversity compared to fully marine environments. Potentially this low biodiversity could increase the vulnerability of the organisms present. Relatively large and rapid environmental changes are more likely in lower salinity marine environments, which tend to occur in confined basins and in relatively close proximity to shorelines. In such environments, relatively small degrees of uplift or subsidence could have a relatively large impact upon salinity and water chemistry. As a result, organisms could be stressed. If salinity changes (e.g. due to change in freshwater input near a coastline) then there would be an impact on responses of organisms to CO_2.

Water chemistry

In lower salinity water, the behaviour of dissolved carbon is very different from that in higher salinity water. In fully marine water, solid carbonate phases such as calcite and aragonite are close to saturation, whereas in lower-salinity water, these solid phases are undersaturated. Increasing CO_2 concentrations may cause fully-marine waters to become undersaturated, but more dilute waters will remain undersaturated. However, lower salinity waters also have lower alkalinity than higher salinity waters. A consequence is that in less saline environments it is more difficult for organisms to calcify than in fully marine environments. For these reasons it is likely that the response to CO_2 leakage of organisms in lower salinity waters, like those of the Baltic, will be different from the response of fully marine organisms. On balance, there will be a larger sensitivity of pH to leakage of CO_2 than in a fully marine environment.

Water chemistry may vary in response to annual hydrogeological cycles. For example, the flow of water from the Mediterranean via the Straits of Gibraltar varies over an annual cycle, leading to annual variations in the alkalinity of Mediterranean water. In contrast, in the North Sea, there are regional variations in alkalinity due to variable river inputs, but not annual changes to the same extent. Variable alkalinity of marine waters is important only because it reflects the overall geochemical characteristics, rather than because it influences the behaviour of CO_2.

Another aspect of water chemistry is the presence of pollutants. Smaller and / or confined water bodies are more likely to be polluted. For example, parts of the Baltic Sea and Mediterranean Sea are relatively heavily polluted. This pollution will stress ecosystems potentially making them more vulnerable to leaking CO_2.

5.4 Impact Scenarios

5.4.1 Introduction

The previous sections have identified key receptor classes and processes that might influence impacts upon them, and variations in receptors and processes across reference environments and associated climate states have been mapped to the leakage mechanism / patterns. This enables a range of plausible impact scenarios to be specified.

The scenarios are not intended to represent all the combinations of receptors and processes that could occur. Instead, the scenarios together illustrate the key issues and the range of receptor impacts that could occur.

5.4.2 Terrestrial Impact Scenarios

The impact scenarios are summarised in Table 5-4.

The scenarios representing impacts to ecological receptors apply across the maritime, continental and Mediterranean reference environments, noting the differences in receptor characteristics. The 'release to the urban environment' scenario is specifically relevant to the 'generic urban' reference environment.

Table 5-4: Impact scenarios for terrestrial systems.

Scenario	Description
Normal Evolution scenario	The baseline, 'most likely' scenario is for the system to evolve as designed, i.e. consistent with the principles of containment, with no leaks occurring.
Direct release to atmosphere, via a well (high flux for a relatively short time period – e.g. days)	This scenario considers failure of a well seal, leading to direct release to the atmosphere, followed by the potential for CO_2 ponding in the vicinity of the release. This could present a risk to animals in the vicinity, but it is highly likely that larger animals capable of moving away from the zone of release would be able to escape unharmed. However, this may not be possible for smaller less mobile animals, and local plants are likely to suffer stress or even death. Effects would be localized, within a few metres to tens of metres of the release. The release would only last while pressurisation is maintained. Moreover if such an event occurred during the operational or monitoring periods, it can be assumed that remedial action would be taken. Indeed even post-closure, any humans who may habitually utilise resources in the vicinity would observe what is occurring and mitigate impacts by moving livestock, setting up warning signs or even organising remediation. For impacts of any significance to occur, a combination of well failure, locally depressed topography, local receptor habits and lasting pressurisation effects would be required. Significant impacts would therefore be unlikely, even if leakage does occur.
Localized release to soil as a result of wells / faults / fractures, leading to high concentrations of CO_2 in the near surface	This release could occur through a well, or through another linear feature such as a fault. The primary impacts that could occur are plant stress or death as a result of soil acidification or toxicity, and / or the direct influence of CO_2 concentrations in the rooting zone. This could lead to secondary impacts on productivity, crop quality, species competition etc. The leak could also have a direct impact on animal receptors associated with the sub-surface. In turn, degradation or death of plant or subsurface animal-based foodstuffs and habitats could have an impact on surface-based animals. Should high concentrations of CO_2 build up in the near-surface (either as a result of significant CO_2 fluxes, or accumulation of CO_2 as a result of lower-level fluxes) impacts to plants, in particular, would be likely to occur, as such high concentrations could be maintained for months or longer. However, some species may be able to adapt and recover within this timescale. Some species are also more tolerant of soil chemistry changes than others. The probability of faults / fractures providing pathways relevant to this and other scenarios depends upon, amongst other factors, the probability that sufficiently transmissive features are present (but, perhaps, not previously identified) at site closure, and intersect a sufficiently pressurised zone within the storage complex. Natural or induced seismicity processes could cause such features to be created following injection.
Localized release to soils as a result of wells / faults / fractures, leading to long-term low concentrations of CO_2 in near surface	This scenario considers lower-level fluxes of CO_2 that could lead to long-term 'chronic' impacts on near-surface and surface-based receptors. Plant death could occur, but gradual plant quality degradation as a result of prolonged exposure may be the primary impact of concern here, together with secondary effects on habitats, food quality, species competition etc. At the lower end of the CO_2 concentration spectrum positive impacts (fertilisation) could be seen.

Scenario	Description
Localized release to freshwater lakes via fractures / faults	The main impact associated with this scenario is likely to be acidification of a lake, and its consequences. If the lake is a resource e.g. for drinking water or irrigation purposes, then the water body is a receptor in its own right. In addition, acidification could lead to impacts on plant and animal species living within or otherwise dependent on the lake. This scenario is considered to be particularly unlikely to occur. It requires a storage system to be located close to such a water body, for a fault / fracture to intersect both the storage complex and the lake, and for a sufficiently large flux to be transported to the lake to lead to a degree of acidification that is greater than that seen naturally in seasonal variations. In addition the latter effect would only be likely to occur for a small or very stratified lake, and the impacts would be localized. The sudden release of free CO_2 due to the 'turn-over' of CO_2-charged water, as in the Lake Nyos disaster (Kling et al., 1987) is even less likely to occur, as it requires very unusual conditions in the lake.
Diffuse releases to surface and near-surface systems	This class of scenario is included for completeness. However, diffuse leakages are considered unlikely to occur compared to localized equivalents, and would, in any case, result in lower impacts.
Localized release to aquifers that may be exploited as drinking or irrigation water resources	The most acute effects would be local to any release from a well or fault/fracture structure. The interface zone relevant to the release may be a point source, or associated with a linear vertical source tracking the intersection of a well or fault / fracture with the aquifer. The primary impact of concern is degradation of resource quality as a result of biogeochemical effects such as acidification and leaching of heavy metals. The nature and magnitude of such effects would be highly site-specific, dependent on the aquifer geochemical environment, and so is not discussed in any more detail here. There is also the potential for impacts to microbes that might inhabit the aquifer.
Release to an urban environment	Impacts could be 'high', in that there is the potential for adverse or fatal consequences for humans as a result of exposure due to accumulation of CO_2 in basement structures. It is considered extremely unlikely that such impacts would occur. Other impacts could include those on the urban environment e.g. gardens and other resources.

5.4.3 Marine Impact Scenarios

The impact scenarios identified for marine environments are summarised in Table 5-5. Individual scenarios cannot represent long-term climate change explicitly. However, the different reference environments that have been chosen collectively represent the main environmental conditions that might occur at any particular site as a result of climate change.

Table 5-5: Impact scenarios for marine systems.

Scenario	Description
Normal Evolution scenario	This is the scenario which describes the expected evolution of the site in the absence of CO_2 leakage. That is, this scenario describes how the site would behave naturally, in the absence of any CO_2 storage. Populations of marine organisms may vary naturally over a wide range of timescales, from very short-term (e.g. diurnal changes due to tides) to long-term (e.g. slow silting of a marine basin over many hundreds to thousands of years). These variations need to be understood in order to recognize any superimposed population variations due to CO_2 leakage. An understanding of other stresses, for example pollution, is also needed in order to distinguish the effects of CO_2 leakage from the effects of other processes.
Localized direct release of free CO_2 via the sediment or directly to the water column above the sea bed via a point source	This scenario would correspond to well seal failure. However, the scenario also encompasses leakage from features such as faults and fractures, since channelling of CO_2 flow along these features will result in leakage being expressed in clusters / alignments of point releases on the sea bed. The extent to which impacts will be localized will depend upon the degree to which CO_2 dissolves in and subsequently mixes with the upper sediment porewaters and / or the water column near to the seabed. This dissolution will in turn depend upon the rate of discharge, the rate at which seawater moves across the discharge site (by factors such as water depth, wave regime, tides and currents), water pressure (which depends upon depth), water temperature and salinity. Dissolution of the free CO_2 may produce a plume of relatively dense water, which will either sink to the seabed from higher in the water column (if dissolution occurs mostly above the seabed) or spread along the seabed from the point of release (if dissolution occurs effectively immediately following discharge). The impacts will depend to a large extent upon whether such a plume forms, whether it sinks from above or spreads laterally along the seabed, and the areal extent and thickness of the plume.
Diffuse direct release of free CO_2 via the sediment or directly to the water column over a wide area	This scenario is less likely to occur than the other alternative evolution scenarios and there is little evidence from natural analogues that it could occur. Diffuse leaks that percolated through the sea floor sediments could impact benthic ecosystems and biogeochemistry in a different way from impacts from plumes spreading along the bottom water.
Localized release of CO_2-charged water through the sediment or directly to the water column via a point source	This scenario would most likely correspond to either: • relatively low-flux leakage via a well in which partial seal failure had occurred, allowing leaking CO_2 to mix with water during relatively slow transport; • leakage along faults / fractures through which CO_2 is transported along tortuous pathways, allowing high degrees of mixing with surrounding formation water; or • the primary localized leakage path (either a leaking well or a pathway within a fault / fracture) being overlain by seabed sediments, through which CO_2 travels to the seabed via the sediment's matrix, mixing with seawater as it does so. This scenario has some similarities to the release of free CO_2 from the seabed, followed by dissolution very close to the seabed, leading to the development of a dense CO_2 plume; the CO_2-charged water is expected to spread laterally across the seabed from the discharge point. However, the localized release of CO_2-charged water is also likely to be accompanied by the development of a relatively thick plume of dense CO_2-charged porewater in the sediment / rock beneath the seabed around the discharge point. This plume will be thicker than the relatively shallow zone of CO_2-charged porewater that will develop beneath any plume of bottom-hugging dense CO_2-charged waters that might develop around a discharge point of free CO_2. Thus, if the localized release of CO_2-charged water occurs, there may be greater impacts on sub-seabed biota than in the scenario where free CO_2 is discharged.

Scenario	Description
Diffuse release of CO_2-charged water through the sediment and subsequently to the water column over a wide area	This scenario is most likely to occur where leaking CO_2 dissolves in porewater at depth and then spreads laterally within the rock and / or sub-seabed sediment without being emitted at a discrete discharge point. Such a process would result in the sediment and / or rock below the seabed being charged with CO_2 over a wide area. Diffusion of CO_2 could then occur upwards to the seabed over this wide area. Thus, there are potentially impacts to biota within the sediment, to the rock beneath the seabed and subsequently to pelagic ecosystems.

5.4.4 Other Impact Scenarios

A number of other scenarios could be considered, and some are summarised in Table 5-6. Scenarios for terrestrial and marine systems are presented together as significant commonalities were observed in the relevant scenario lists. These scenarios will not be taken forward in the RISCS project for the reasons indicated in the table, but several can be considered as variants of the scenarios that will be directly considered.

Table 5-6: Other impact scenarios.

Scenario	Description
Displacement of saline formation water due to storage activities (marine environments)	Some aspects of this scenario can be taken into account by considering variants of the scenarios describing '***Localized release of CO_2-charged water to the water column above the sea bed via a point source'*** and '***Diffuse release of CO_2-charged water to the water column above the sea bed over a wide area'.*** These variants would consider the impacts on ecosystems of water constituents besides CO_2. In some cases saline formation water might be produced deliberately during injection operations. Such water would need to be disposed of, potentially leading to impacts. Water produced from hydrocarbon reservoirs during the exploitation of hydrocarbon resources is often re-injected and discharged.
Impacts through inadvertent human intrusion (marine environments)	Although the main focus of RISCS concerns consideration of impacts that might be associated with unplanned leakage, inadvertent human intrusion into the storage system could also lead to impacts. This would be more likely to occur in areas where there are significant remaining natural resources than in areas where there are no such resources or where resources have previously been depleted. The most likely offshore resources to be targeted by future activities are hydrocarbons. However, 'fossil' offshore freshwater aquifers occur adjacent to several countries and there have been suggestions that in future such reservoirs could be exploited for water resources. Human intrusion scenarios were considered to be of lower priority for assessment than the other scenarios. Any future activities in the offshore environment would require significant technological capabilities at least comparable with those of present industries. These capabilities imply an ability to avoid CO_2 storage accumulations and / or to take remedial actions were leakage from such an environment to be caused by human activities. In any case, the main effects of human intrusion would be captured by the scenarios that have been defined. For example, if human intrusion took the form of borehole drilling into a storage reservoir, then the effects of the resulting CO_2 leakage on the seabed biosphere would be similar to the effects of leakage of free CO_2 or CO_2-charged water at a point on the seabed.

Scenario	Description
Potential for impacts through inadvertent human intrusion (terrestrial environments)	Similar arguments apply to terrestrial environments. Consideration of 'deliberate' intrusions is outside the scope of RISCS. The risks involved would be the responsibility of the organisation responsible for the exploration. In addition, any such organisation can be expected to be at least as technologically advanced as present-day equivalents and so the likelihood is that they would be aware of the presence of the storage system even if planning documentation etc. is for some reason unavailable. Finally, impacts associated with any leakage that could result from drilling activities can be considered to be adequately represented by the impact scenarios that are directly addressed.
Sudden releases of free CO_2 due to the 'turn-over' of CO_2-charged seawater in the marine environments	This scenario is considered unlikely to occur, because it requires there to be accumulations of stagnant water on the seabed. Marine water will mostly be moving across the seabed, thereby preventing sufficient accumulation of CO_2-charged water. However, there are some environments where such CO_2-charged water accumulations might occur. For example, within some fjords there are deep-water basins within which water circulation is restricted. This scenario is considered to be of sufficiently low likelihood that it should not be analysed explicitly.
Releases related to earthquake / seismic activity (marine environments)	This scenario is of great concern to stakeholders in many countries, particularly in southern European nations such as Greece and Italy. However, the impacts of leakage due to earthquake / seismic activity can be considered to be taken into account by variants of the scenarios describing '***Localized direct release of free CO_2 to the water column above the sea bed via a point source'*** and '***Localized release of CO_2-charged water to the water column above the sea bed via a point source'***. These scenario variants will need to consider the short-term release of potentially large quantities of CO_2, either as a discrete phase or dissolved in water, at a point source.
Releases related to earthquake / seismic activity (terrestrial environments)	The influence of tectonic activity in terms of characterisation of the nature and relative likelihood of occurrence of processes such as fault / fracture widening, is addressed by '***Localized release to soil as a result of wells / faults / fractures, leading to high concentrations of CO_2 in near surface', 'Localized release to soils as a result of well / faults / fractures, leading to long-term low concentrations of CO_2 in near surface', Localized release to freshwater lakes via fractures / faults', 'Diffuse releases to surface and near-surface systems',*** and ***'Localized release to aquifers that may be exploited as drinking or irrigation water resources'*** scenarios.
Induced seismicity caused by CO_2 injection (marine and terrestrial environments)	The impacts of seismicity that is induced by CO_2 injection will be similar to natural seismicity. Similarly, the impacts of any CO_2 leakage that occurs as a result of induced seismicity will be similar to the impacts of CO_2 leakage caused by natural seismicity; these impacts can be evaluated by variants of other scenarios.
Sudden leakage of CO_2 caused by over-pressuring during operations (marine and terrestrial)	During operations, over-pressuring might lead to unplanned leakage of CO_2. However, the effects of such leakage could be covered by variants of a range of scenarios equivalent to those listed above for 'seismic activity'.
Heat shock to organisms surrounding a leakage site (marine and terrestrial)	Leakage of CO_2 could be accompanied by an elevated geothermal gradient if it occurs sufficiently rapidly. There could then be a thermal shock to organisms near to the leakage site. This shock, if it occurred, would be very localized. Furthermore, this possibility could be taken into account by variants of the localized release scenarios described.

6 ILLUSTRATIVE LEAKAGE FLUXES AND AREAS

6.1 Purpose of Illustrative Leakage Fluxes and Areas

The illustrative leakage fluxes and areas that are presented in this section aim to:

- help readers form a view as to the plausible characteristics of CO_2 leakage in the various low-likelihood impact scenarios described in Section 5.4; and
- contribute to a context for interpreting and communicating the experimental and modelling results of the RISCS project.

Here CO_2 leakage fluxes and areas in any particular low-likelihood scenario are considered 'plausible' if they do not violate fundamental physical or chemical principles / laws and there is a high level of agreement among researchers that they are conceivable.

It is emphasized that this section does ***not*** aim to ***predict*** CO_2 leakage in these scenarios. Furthermore the presented fluxes and areas should not be considered as 'worst-case'. This term is not meaningful when applied to the very general specifications of low-likelihood alternative impact scenarios presented in Section 5.4, because:

- For each scenario a wide range of values could be assigned plausibly to each of the various parameters that would influence CO_2 movement in the sub-surface and hence leakage (pressure, permeability, dispersivity etc.). In principle it is possible to define parameter values that individually are plausible and that collectively would result in a maximum possible flux and impacted area for the considered scenario. However, in such a case there would be little confidence that the chosen combination of parameter values could actually occur at a real site. Conversely, at an actual site it is unlikely that simultaneously all relevant parameters would have values near the extremes of their plausible ranges. Consequently, almost certainly the highest fluxes and impacted areas that could occur at an actual site would be less than the highest fluxes and impacted areas that could be calculated for a generic scenario.
- These parameters influence CO_2 behaviour in complex and coupled ways. Hence, without detailed numerical analysis, which is outside the scope of the present work, it would not be apparent what combinations of parameter values would result in the greatest leakage fluxes and impacted areas.
- It cannot be stated whether a particular leakage flux and area is truly 'worst case' without predicting the impacts of the CO_2 leakage. For example, it would be necessary to predict impacts in order to determine whether a larger leakage flux over a smaller area is 'worse' than a smaller leakage flux over a larger area. Since the RISCS project aims to research possible impacts, to comment on plausible impacts in the present document would pre-empt the findings of the project.

6.2 Approach to Specifying Illustrative Leakage Fluxes and Areas

Here, the approach is to quote CO_2 fluxes and areas that are consistent with published values or RISCS project outputs concerning modelled, natural or experimental situations that correspond to each low-likelihood CO_2 leakage scenario described in Section 5.4. Furthermore, the CO_2 fluxes and areas have been specified to be consistent among the different scenarios. For example, localized releases have been chosen to have greater fluxes than more diffuse releases. However, it is recognized that none of these situations correspond exactly to any of the scenarios. Therefore, the fluxes and areas quoted for any scenario are reported together with explanations of their relevance. It is also important that the plausible leakage fluxes in each scenario can be viewed in the context of natural background CO_2 fluxes from soil and vegetation. Therefore, illustrative natural fluxes are also given for each scenario.

The processes that control the release of CO_2 in terrestrial and marine environments are first summarized in Section 6.3. The information available to support the specification of CO_2 fluxes and areas is then reviewed in Section 6.4. Illustrative fluxes and areas are subsequently tabulated in Section 6.5.

6.3 Processes Influencing CO_2 Releases in Terrestrial and Marine Environments

The processes by which CO_2 will disperse near the upper boundary of the solid earth differ in different environments are described in IEA Greenhouse Gas R&D Programme (2006). In this source and in other literature, two main kinds of seepage at the solid earth's surface are reported: localized seeps; and diffuse seeps. However, there is no clear distinction between these two kinds of seepage. Both terms generally refer to seepage of free CO_2, rather than to diffusion of dissolved CO_2 from a CO_2-charged water body at depth towards a water body with low CO_2 concentrations (lake or ocean water) above the surface of the solid earth. However, whether in terrestrial or submarine environments, a localized seepage usually occurs over a small area (a few metres to a few tens of metres across) and is typically associated with a physical feature, such as a depression in the earth's surface. In contrast 'diffuse seepage' is used to describe seepage that is distributed spatially over several tens of metres or more and that is unassociated with any obvious physical surface feature. Terrestrial diffuse seeps can be recognized only by their effects (if any) on biota, by measuring CO_2 fluxes directly, or by measuring, for example, the pH of porewaters. In sub-aqueous systems diffuse seeps may be recognized by fields of bubbles that are spatially distributed over areas of several tens of metres. In the cases of both localized seeps and diffuse seeps, the ultimate origin of the CO_2 could be either CO_2 that has been transported from depth as a free phase, or CO_2 that has been transported in aqueous solution and then degassed at shallower depths.

In terrestrial environments other than permanent lakes and rivers, typically the zone immediately below the earth's solid surface will be either permanently or periodically (e.g. seasonally) non-water saturated. Evidence from natural CO_2 seepage sites and experimental sites suggests that the pore space in this unsaturated zone becomes saturated with CO_2 at fluxes that are lower than the maximum that could conceivably occur in a low-likelihood leakage scenario. For example, Beaubien et al. (2008) report that at Latera, Italy, significant biosphere impacts occur only where CO_2 fluxes are greater than c.5 x 10^{-4} mol m^{-2} s^{-1} to c.8 x 10^{-4} mol m^{-2} s^{-1}, in which case the porosity of the soil is >95% CO_2-saturated. Similar results have been reported for vents near the shore of the Laacher See in Germany (Krüger, 2009, 2011). Within the unsaturated zone, free CO_2 that is released from greater depth, for example via a borehole or fracture, could potentially migrate laterally and then diffuse upwards over a wide area. Alternatively, CO_2-charged water could ascend to the water table, driven by processes such as artesian flow, and then migrate laterally, degassing as it does so. These mechanisms could give rise to diffuse release of CO_2 at the surface which is ultimately an expression of localized release at greater depth.

In contrast, in marine environments, and in permanent lacustrine and riverine terrestrial environments, the zone beneath the solid earth's surface would become un-saturated with water only if the flux of CO_2 is sufficiently high. The mechanisms by which CO_2 is released to the water column in these environments have been reviewed by Oldenburg and Lewicki (2005). The CO_2 would either exist as a free phase, or else dissolved in the water. The degree to which the CO_2 dissolves will be influenced strongly by the height of the water column and its salinity. The spatial distribution of the free CO_2 phase and / or the CO_2-charged water would be controlled partly by the advection of the water phase. This advection would be controlled in turn by many factors, including winds, density variations in the water and tides. Once discharged at the base of the free water column, the CO_2, whether dissolved in water or remaining as a free phase, would disperse. The impact of the CO_2 on the sea (or lake or river) would depend on the vigour and spatial extent of mixing between CO_2 / CO_2-charged water and water that is not CO_2-charged. Oldenburg and Lewicki (2005) concluded ebullition (bubble formation from a gas-supersaturated liquid), followed by bubble flow, will be the dominant form of gas transport in surface water except for very small seepage fluxes or shallow water bodies.

Near-coastal environments represent transitions between terrestrial and marine environments and therefore processes by which CO_2 will disperse will be to some degree intermediate between terrestrial and marine environments. The extent to which a non-water saturated zone will develop in a near-coastal environment will depend not only on seasonal factors, but also on tides. Over time, the transition between the marine and terrestrial environments will also typically change its location and width, reflecting marine transgression (coastline recession due to erosion, for example), or marine regression (coastline aggradation owing to sediment deposition, for example).

6.4 Available Information to Illustrate Leakage Fluxes and Areas

6.4.1 Application of Information from Natural CO_2 Seepages

Many natural CO_2 seepages have been studied in recent years (e.g. Stevens et al., 2001; Shipton et al., 2004; Haszeldine et al., 2005; IEA Greenhouse Gas R&D Programme, 2006, 2009; Kuuskraa and Godec, 2007; Lewicki et al., 2007; Beaubien et al., 2008; Lombardi et al., 2009; Krüger et al., 2011; McGinnis et al., 2011). These seepages are mostly related to on-going magmatism or ancient, natural sub-surface CO_2 accumulations in sedimentary basins.

In areas where there is magmatism, there may be degassing of CO_2 directly from magma, or else the high associated heat flows may cause thermal decomposition of carbonate-bearing rocks and the consequent release of CO_2. The magmatism may or may not have a surface expression in volcanic activity. In volcanic areas diffuse degassing of CO_2 may be the principal release mechanism, although there may also be emissions from localized vents and via fault pathways (IEA Greenhouse Gas R&D Programme, 2006). In sedimentary basins natural CO_2 may seep from permeable rocks, or from localized zones along faults, while shallow degassing of groundwater that has been charged with CO_2 at greater depths in the subsurface may occur over relatively wide areas (IEA Greenhouse Gas R&D Programme, 2006). Natural seepages that occur away from volcanic areas are mostly fault-related, even if this may not be apparent from the characteristics of the seeps; fault pathways tend to conduct CO_2 for at least part of its journey to the surface of the solid earth.

Volcanically and / or seismically active areas and / or sites with fault pathways between a reservoir formation and the surface would be avoided when choosing locations to store CO_2. Furthermore, many of the reported natural seepages occur in locations where the CO_2 has a magmatic origin (e.g. Mammoth Lakes, California (Lewicki et al., 2007)) or a metamorphic origin (e.g. thermal decomposition of limestone at Latera, Italy (Lewicki et al., 2007; Lombardi et al., 2009)), where CO_2 may be produced continuously at the present. It may be concluded, therefore, that although many natural CO_2 seepages are often referred to as 'natural analogues', in fact few of them occur in settings that are similar to those that would be chosen for CO_2 storage.

There are no good analogues for CO_2 leakage through relatively permeable zones within otherwise impermeable caprocks, such as might be represented by gas chimneys or sand lenses. Additionally, natural seepages do not shed light on the plausible fluxes that might occur should the seals in a borehole fail, or should a poorly sealed borehole be encountered by a plume of CO_2 migrating within a reservoir.

A further limitation with natural seepages is that the published literature does not report fluxes and areas consistently, which often makes it impossible to compare different natural releases confidently. For example, it may be stated that a certain flux occurs within a particular area, but the actual proportion of the stated area in which emissions actually occur is not recorded. This limitation in reported information gives rise to inconsistencies between fluxes and areas reported for different kinds of releases in different areas. At Solfatara in Italy, for instance, *diffuse* release has been reported to occur with a flux of 8×10^{-4} mol m^{-2} s^{-1} (Lewicki et al. 2007). However, this flux is higher than the value of 2×10^{-4} mol m^{-2} s^{-1} reported for *localized* releases along the Little Grand Wash Fault Zone, Utah (Allis et al. 2004). If a diffuse release flux as high as 8×10^{-4} mol m^{-2} s^{-1} is possible, then logically an even higher localized release flux should be possible. On the other hand, no such higher fluxes have been identified in the literature, although there are reports of localized releases with a similar flux, for example at Latera (Lombardi et al. 2009).

An additional complication is that terminology is often unclear; the difference between truly diffuse emissions of CO_2 and large 'point' emissions is usually indistinct. These factors lead to difficulties in specifying areas over which fluxes are applicable. For example, in scoping calculations to investigate the possible impacts of diffuse CO_2 emissions at the sea bed, Blackford et al. (2009) used a flux of 4.45×10^{-8} mol m^{-2} s^{-1}, based on the uppermost published values for CO_2 seeps in Colorado. However, this value is smaller than most natural soil CO_2 fluxes (IPCC, 2005). Possibly, the low Colorado fluxes are caused by the measured CO_2 emissions being averaged over a larger area than that over which emissions actually occur.

For these reasons, the fluxes that have been reported for natural CO_2 seeps must be used cautiously to support estimates of plausible leakage fluxes in the low-likelihood scenarios presented in Section 5.4. In these scenarios, CO_2 leakage fluxes conceivably could be lower than fluxes that have been observed at natural seepage sites. However, natural seepages do illustrate the general processes of CO_2 dispersion that might be expected during CO_2 migration through faulted rock. It is noteworthy that in many such sites emissions are limited to very localized areas, which must be borne in mind when upscaling natural observations to estimate fluxes over wider areas or even regions.

The natural seepages can also be used to build confidence that illustrative leakage fluxes in the low-likelihood scenarios with more diffuse leakage are plausible. It is also pertinent to note that shallow injection experiments using similar fluxes to natural systems have produced small areas of seepage rather than wide areas of diffuse seepage (e.g. the ZERT and CO2Field lab projects).

More terrestrial natural seepages of CO_2 leakage have been studied than submarine seepages. Consequently, there is relatively abundant analogue information with which to estimate plausible leakage fluxes and areas of leakage in terrestrial environments, but a relative paucity of information for marine seepages.

6.4.2 Application of Information from Accidental CO_2 and Natural Gas Releases

There have been several cases where natural CO_2 has been released accidentally when boreholes have penetrated a natural CO_2 accumulation or CO_2-charged water (Gouveia et al., 2005; Gouveia, and Friedmann, 2006; Barberi et al., 2007; Kuuskraa and Godec, 2007). Generally, these CO_2 releases have occurred as a consequence of poor understanding of sub-surface geology combined with the heterogeneous distribution of CO_2, leading to boreholes unexpectedly penetrating the CO_2 accumulation. In an actual CO_2 storage project, it is highly likely that there would be better geological understanding prior to injecting CO_2. Nevertheless, these past accidental releases do serve to illustrate the kinds of CO_2 releases that are plausible (in the sense noted in Section 6.1).

Perhaps the best known example of natural CO_2 being released from a borehole is Crystal Geyser in Utah (Gouveia et al., 2005; Gouveia, and Friedmann, 2006; Lewicki et al., 2007). Here, CO_2 is released from an abandoned oil exploration well that was drilled to a depth of 801 m in 1935. The well was left without seals after failing to encounter oil, although Shipton et al., (2004) report that in 2004 only the uppermost 130 m were believed to be open, various attempts having been made to seal the well at unspecified times in the past. The well episodically emits CO_2-charged water to a height of c. 20 m every 4 – 12 hours (Shipton et al., 2004).

The source of the CO_2 is uncertain, but it has been suggested that it originates in clay-carbonate reactions in mid-to-upper Palaeozoic strata at temperatures of 100-200°C (Shipton et al., 2004). Whatever its origin, the CO_2 has migrated upwards through faults to charge water within a shallower sandstone formation, the Navajo Sandstone. Since groundwater flow in the area is artesian, the CO_2-charged water tends to rise naturally in the abandoned oil exploration well leading to a decrease in pressure and consequent exsolution of CO_2. The gas volume increase that occurs during this process then drives a cold eruption, which continues until pressure diminishes.

Gouveia et al. (2005) used aerometric measurements to estimate the quantity of CO_2 emitted from Crystal Geyser during five CO_2 eruptions. They found that different eruptions had widely varying CO_2 fluxes, durations of CO_2 emission and total emitted CO_2 quantities. However, the duration of an eruption correlated positively with the elapsed time since the previous eruption. These authors reported CO_2 emission rates varying between 2.6 kg s^{-1} and 5.8 kg s^{-1} (59 mol s^{-1}

to 132 mol^{-1} s^{-1}). The longest studied eruption lasted for two hours and emitted 41 tonnes of CO_2, which equates to an average rate of 4.7 kg s^{-1} (107 mol s^{-1}). Gouveia et al. (2005) estimated that there is an annual CO_2 emission from Crystal Geyser of 12000 tonnes, which is equivalent to an average emission rate of 3.81 x 10^{-4} kg s^{-1} (8.7 x 10^{-3} mol s^{-1})

Unfortunately, the precise area over which emissions occurred was not reported and the diameter of the casing is not given, although it is known that during the early 2000's the near-surface casing was changed to one that is wider than the original casing (Glennon and Pfaff, 2005). Assuming for illustrative purposes that the well is 0.18 m (7 inches) in diameter, the above transient emission rates equate to 2320 mol m^{-2} s^{-1} and 5180 mol m^{-2} s^{-1}. Making the same assumption about the emission area, the mean annual flux is 3.40 x 10^{-1} mol m^{-2} s^{-1}.

An important observation at Crystal Geyser is that emissions have gradually declined since the well was drilled in 1935, as indicated by a decrease in the height to which eruptions extend. This observation is consistent with theoretical understanding since, over time, emissions of CO_2 would be accompanied by a pressure reduction in the reservoir. It is reasonable to conclude that even in the absence of remediation, CO_2 leakage from a well at a storage site could diminish over time.

A well blowout in the Sheep Mountain natural CO_2 field of southern Colorado has also been proposed as an analogue for CO_2 leakage from a storage site via a borehole pathway (Kuuskraa and Godec, 2007, quoting Stevens, 2005). The CO_2 field is exploited as a source of CO_2 for enhanced oil recovery (EOR). In 1982 an inclined borehole, 11.4 cm in diameter, blew out while coring was being undertaken. The well then flowed for 18 days, emitting up to c. 11,000 tonnes of CO_2 per day or c. 190,000 tonnes in total, equivalent to an average flux of approximately 2.72 x 10^{5} mol m^{-2} s^{-1}. However, the blowout was successfully controlled by injection of dense fluid ($CaCl_2$) and there were no significant adverse environmental impacts.

It has also been suggested that rare cases of natural gas (dominantly methane) leakage from underground storage sites can be used as analogues of CO_2 leakage from storage sites (e.g. Kuuskraa and Godec, 2007). However, most reported leakage incidents have involved natural gas stored in underground caverns, typically produced by dissolving rock salt (Evans, 2008). This kind of natural gas storage is so dissimilar to CO_2 storage in a porous rock formation that is not a relevant analogue. It should be noted, however, that invariably natural gas leaks from storage caverns have been mitigated. Therefore these natural gas leakage incidents illustrate generally the fact that mitigation technologies and methods are available for use during gas storage operations, and by implication CO_2 storage.

More relevant to CO_2 storage is natural gas storage in porous rock formations, such as depleted oil reservoirs. Reports of leakage from such sites are mostly related to well problems during operations, although there have been some reports that can be attributed to over-filling of a facility, or to over-pressuring of the reservoir, leading to the opening of leakage paths through caprocks (Evans, 2008). However, there are few data concerning leakage fluxes, or the areas impacted. As in cases of natural gas leakage from underground excavated cavities, these kinds of natural gas leakage have always been mitigated.

It should be born in mind that underground natural gas storage of all types differs from CO_2 storage for several reasons, notably:

- Underground gas storage at any site is a short-term activity, typically planned to last for only a few tens of years. After storage operations have been completed as much natural gas as possible will be removed from a storage facility, partly for reasons of safety, but to a large extent because the stored gas has economic value. In contrast, the intention is that stored CO_2 will remain in the chosen reservoir effectively forever. This difference means that, while underground natural gas storage in porous rock formations has some similarities to CO_2 storage during the period of CO_2 injection, such natural gas storage cannot be used as an analogue for CO_2 storage following operations.
- Natural gas (dominantly methane) is much less soluble in water than CO_2 and the small proportion of stored natural gas that does dissolve in formation water does not produce a low-pH reactive solution. Consequently, there are fewer processes by which methane will be retained within a rock formation. Whereas CO_2 can dissolve in water and then be retained in the resulting dense solution, or dissolve and then react with rock, thereby being permanently locked up in carbonate minerals, natural gas will remain almost entirely in the gaseous phase.
- Unlike CO_2 storage, in which CO_2 is injected into an underground reservoir with the intention that it should remain there permanently, during the operation of a natural gas storage site gas pressures vary through gas injection and extraction cycles, which are usually short (e.g. daily).

For these reasons, underground natural gas storage is of limited value as an analogue of post-operational leakage of CO_2 from a storage site.

6.4.3 Application of Numerical Model Results

In recent years there have been many theoretical studies of CO_2 behaviour in the sub-surface, several of which have simulated leakage scenarios (e.g. Oldenburg et al., 2003; Celia et al. 2005a,b, 2009; Pruess, 2005, 2008; Zhou et al., 2005; Aines et al., 2009; Humez et al., 2011; Tao et al., 2011). Leakage of CO_2 through faults and boreholes have been considered by these studies, but there have been few theoretical studies of other plausible leakage pathways, such as interconnected higher-permeability strata (e.g. sand bodies) within generally low-permeability caprock, or upwards migration of CO_2 along dipping permeable reservoirs. Reflecting this bias, modelling studies of CO_2 release mechanisms at the surface of the solid earth mostly concern localized releases, from single point sources such as boreholes, or from alignments of point sources along faults. There are very few numerical studies of diffuse release.

The published numerical studies have demonstrated that CO_2 leakage fluxes and impacted areas would be controlled by a wide variety of factors, which are coupled to varying degrees. Overall, the results therefore provide justification for not specifying here ‘limiting’ or ‘worst case’ leakage fluxes for the low-likelihood scenarios described in Section 5.4. For example, Pruess (2005) simulated CO_2 leakage through an idealized representation of a fault zone, consisting of a 1 m wide homogeneous permeable medium with planar, orthogonal boundaries between impermeable wall rocks. The model fault zone extended for 1,000 m vertically, and had a lateral extent (parallel to the walls of the fault) of 200 m. The fault zone was assigned a uniform permeability of 10^{-12} m^2, and porosity of 0.35. The CO_2 was specified to be present continuously at one margin of the fault at a depth of 710 m and the fault zone was filled initially with water. All boundaries of the model except the top were no-flow boundaries. The simulations showed that CO_2 fluxes in the fault plane depended upon the phase relations of the CO_2 (whether liquid and gaseous CO_2 were present in addition to water, or whether just gaseous CO_2 and water were present). These phase relations in turn depended upon the temperature and thermal conductivity of the rock, the temperature being coupled to the rate of heat removal by fluid flow. The strong coupling between fluid flow and heat flow was found to limit CO_2 fluxes since the volume change caused by the heat transfer and consequent phase changes of the CO_2 influenced flow strongly. The net result was a quasi-periodic variation in fluxes, which prevented self-enhancing discharge of the CO_2 at the modelled land surface. Furthermore, at any time fluxes varied along the length of the intersection between the fault zone and the surface. The peak calculated flux was c. 400 mol m^{-2} s^{-1} vertically above the CO_2 source, but this flux was not sustained and fluxes decreased with increasing distance from the CO_2 source. Additionally, the fluxes depended strongly upon the parameterization of the model. At a real CO_2 storage site, the relevant parameters would most likely have values considerably different from those used in these simulations.

A similar conclusion that a wide variety of coupled processes will control any CO_2 leakage via wells can be drawn from reported numerical models. Celia et al. (2007) pointed out that the quantity of leaking CO_2 that reaches the land surface via a well will depend partly upon the permeabilities of all the lithologies that form the overburden. In a limiting case where there is no casing or other effective engineered barrier to CO_2 entering the formation, CO_2 will tend to enter more permeable rock formations that are penetrated by the well and hence the flux of CO_2 to the surface will be diminished. In practice there will almost always be some engineered barriers, such as casings and cement plugs that will restrict the quantity of CO_2 that is able to enter the formation. Thus, simulations of well leakage fluxes need to take into account the properties of all the engineered materials used in well construction and all the rock formations penetrated by the well. Consequently the well must be treated as a heterogeneous feature.

Aines et al. (2009) described a model for leakage of CO_2 along a wellbore and calculated a maximum flow rate at which supercritical CO_2 stored at a depth of 1500 m could leak along an open borehole 0.18 m (7 inches) in diameter. It was assumed that the well was fully cased so that no CO_2 could enter the rock formation and that CO_2 flowed at the speed of sound (theoretically the maximum speed that could be attained). This scenario produced a flow rate of 20,000 tonnes per day, equivalent to 2 x 10^5 moles m^{-2} s^{-1}. This flux is similar to the flux actually reported for a well blowout in the Sheep Mountain natural CO_2 field (see Section 6.4.2).

While an open-borehole scenario does enable an upper limit to be placed on CO_2 fluxes for a given set of assumptions (CO_2 storage depth, formation pressure, geothermal gradient, overburden properties etc.), scenarios in which the borehole contains some barriers to CO_2 flow are much more likely. Even if mechanically and / or chemically degraded, barriers such as cement plugs or cement seals between casings and wall rocks will still retard CO_2 flow.
Tao et al. (2011) presented a model of wellbore leakage in which the leakage pathway is a defect such as a fracture, microannulus or gas channel in the steel, cement or rock wall components of a well. To obtain maximum flux estimates they assumed single phase CO_2 flow along a continuous pathway with a constant aperture. The properties of the CO_2 were allowed to vary along the pathway according to the Peng-Robinson equation of state with a specified temperature variation along the well. Using different pathway geometries Tao et al. (2011) obtained a range of CO_2 fluxes for various boundary conditions. For example, through a well

containing a leakage pathway 1500 m long with an effective permeability of 50 μD, a CO_2 flux of 5 x 10^{-5} mol m^2 s^{-1} would leak from the formation, if it were stored at hydrostatic pressure.

As part of the RISCS project, simulations were undertaken to explore the plausible near-surface CO_2 flux if CO_2 that leaks through a heterogeneous overburden rock sequence is remediated soon after being detected (Grimstad and Vuillaume, 2012). The mechanism by which CO_2 leaks from the storage reservoir was not specified. Rather, the aim was to investigate situations in which CO_2 travels through the overburden by a pathway with vertical and sub-horizontal sections, along which the CO_2 accumulates at intermediate locations beneath low-permeability rock formations. The simulations are relevant to the operational period of a CO_2 storage project, a few tens of years.

The approach of Grimstad and Vuillaume (2012) involved carrying out multiple numerical simulations to investigate a scenario in which supercritical CO_2 leaks through a sequence of rocks containing both aquifers and partial sealing formations. The CO_2 was specified to enter the base of the model at a depth of 850 m below the seabed, which was 100 m below sea level. The strata above the caprock included three aquifers separated by secondary partial seals at 700 m and 500 m below the seabed. These partial seals were domed slightly, with their highest points in the middle of the modelled domain. Each partial seal was entirely impermeable except for a localized permeable area 50 m x 50 m through which CO_2 could flow. During each simulation these permeable areas and the influx of CO_2 to the base of the model were placed randomly and offset laterally relative to one another. The porosity of the rocks between the barriers and in the higher permeability zones was selected randomly from the range 0.2 – 0.3, while the permeability was generated from a log-normal distribution with a mean ~250 mD. In each simulation the influx of CO_2 to the base of the model was specified to occur through a 50 m x 50 m area at a rate between 1.87 tonne per day (equivalent to 2 x 10^{-4} mol m^2 s^{-1}) and 580 tonne per day (6 x 10^{-2} mol m^2 s^{-1}). These rates were specified to be within the range of those reported for natural surface seepage sites.

In each simulation the leaking CO_2 moved predominantly vertically, but also dispersed laterally to some extent and tended to rise towards the centre of the model under each partial seal. The CO_2 was allowed to accumulate beneath each of these partial seals, but was able to leak upwards if it contacted the specified permeable area. The inflow of CO_2 to the base of the model continued unless 4000 m^3 of CO_2 had accumulated anywhere in the model under in-situ conditions and a specified period of between 1 and 2 years had subsequently elapsed. It was assumed that any larger CO_2 accumulation would be detected by seismic surveys and that subsequent mitigation would stop the leak. The delay between a CO_2 accumulation being detected and leakage ceasing represented the time needed to implement mitigating measures.

Only simulation cases with CO_2 influx rates near to the higher end of the specified range resulted in CO_2 reaching the seabed. In other cases, once the CO_2 influx to the model's base had been stopped after 4000 m^3 CO_2 had accumulated beneath the deepest partial seal, the upward fluxes of CO_2 were sufficiently small for dispersion and dissolution to prevent CO_2 breaking through to the seabed.

The maximum flux to the seabed occurred when there was a maximum CO_2 influx to the base of the model of 580 tonnes per day and leaking zones in the partial seals were positioned above the CO_2 inflow point and aligned with one another. In this case, the maximum inflow to the top 100 m of the model was around 3 tonnes per day. After cessation of the inflow to the base of the model, the flow at the top then declined to zero over a simulated period of about 18 years. Sensitivity studies were undertaken that showed that the fluxes to the near-surface zone were very sensitive to dispersion of CO_2 as it travels through the overburden.

The modelled fluxes to the surface of the solid earth are extremely sensitive to the permeability distribution in the overburden above a caprock to a CO_2 storage reservoir. The number, frequency and spatial distributions of impermeable layers and the locations and dimensions of permeable leakage pathways through them are important controls, as are the petrophysical properties (permeability, porosity, dispersivity) of the more permeable rock formations. Once again, therefore, the modelling illustrates that site-specific information is required to estimate maximal leakage fluxes and impacted areas for a given low-likelihood leakage scenario. However, the model also illustrates that the geosphere in practice is likely to have a high ability to retard and retain CO_2 even in the event that leakage through a primary caprock is able to occur.

Oldenburg et al. (2003) report simulations of diffuse seepage to the earth's surface. Their modelled domain was 1000 m x 1 m in area and 35 m thick and parameter values were reasonable for near-surface sediments. Fluxes of CO_2 into a 100 m section of the modelled domain's base, centred on the middle of the domain, were specified arbitrarily to correspond to annual losses of 0.001%, 0.01% and 0.1% by mass of a 4 x 10^9 kg CO_2 storage reservoir. When these fluxes are averaged over an area of 100 m radius they are equivalent to 9.2 x 10^{-7} mol m^2 s^{-1}, 9.2 x 10^{-6} mol m^2 s^{-1} and 9.2 x 10^{-5} mol m^2 s^{-1} respectively.

Oldenburg et al. (2003) found that near-surface CO_2 concentrations in soil and sediments could rise to high values even when the fluxes to the base of the model are of the same order of magnitude as fluxes from natural CO_2 production by soil ecosystems. For their base case sediment and rock properties, when the CO_2 influx was 9.2 x 10^{-5} mol m^2 s^{-1} the seepage flux at the surface reached a similar value at steady state and caused simulated CO_2 concentrations in soil gas to reach 95% CO_2. In contrast, for the lowest investigated influx of 9.2 x 10^{-7} mol m^2 s^{-1}, the soil CO_2 concentration was calculated to be as low as 4%. It was noted by Oldenburg et al. (2003) that this low concentration may be difficult to distinguish from CO_2 concentrations that occur naturally in the soil zone.

The factors controlling sub-aqueous seepage of CO_2 were appraised by Oldenburg and Lewicki (2005). They showed that, whether seepage occurs in the form of bubbles (transport driven by buoyancy forces) or in channels (transport driven by a pressure gradient) will depend upon both the CO_2 flux and the fluid flow properties of the rock or sediment through which the CO_2 migrates. For a given flux, bubble seepage will be favoured by coarser sediments or rocks with larger, well-connected pore spaces. In these cases, CO_2 bubbles can migrate relatively freely. In contrast, in finer sediments or rocks with smaller pore spaces and narrower pore throats, CO_2 bubbles will tend to be retained by capillary forces. This process will cause CO_2 to accumulate until a connected pathway is formed, at which point channelized CO_2 release will occur.

6.4.4 Durations of Leakage Fluxes and Temporal Variations in Areas

The impacts of a given leakage flux over a given area will depend partly upon the duration of the flux. However, this duration will be very site-specific and storage project-specific, depending on factors including:

- the volume of CO_2 that is stored;
- the initial pressure conditions in the reservoir and overburden;
- the evolution of pressure conditions in the reservoir and overburden;
- the potential for leakage mitigation (noting that a leak that is easily mitigated will probably last for a shorter period of time than one that is harder to mitigate since action will more likely be taken to stop an easily mitigated leak);
- hydrodynamic mixing within the reservoir and overburden; and
- chemical processes that will remove free CO_2 (e.g. precipitation of carbonate mineral phases).

For these reasons, it is not possible to specify an illustrative duration corresponding to the illustrative fluxes. However, it can be stated that even if any leakage were to be prolonged, it would be likely to occur at a progressively diminishing rate, reflecting the progressive drawdown in reservoir pressure as CO_2 escapes.

6.5 Illustrative Leakage Fluxes and Areas

Illustrative leakage fluxes and impacted areas for each of the low-likelihood scenarios are tabulated in Table 6-1 and Table 6-2 respectively.

Many inter-related factors could cause higher or lower leakage fluxes and areas than those proposed as illustrations in the table. These factors include:

- depth of the CO_2 reservoir;
- reservoir pressure;
- thermal and hydraulic properties of the rocks between the reservoir and the earth's solid surface, through which CO_2 must migrate;
- geothermal gradient;
- the size of the leakage path (e.g. borehole diameter, fault width);
- leakage path geometry (e.g. borehole inclination, variations in fault orientations); and
- presence of seals (e.g. seals within a borehole, even if degraded, mineral fillings within faults).

Were leakage to occur, then higher fluxes are more likely during operations than during the post-operational period, because after injection has ceased pressure gradients driving flow of CO_2 in the reservoir will decrease. Since it is expected that any leakage fluxes during an operational period would be recognized and remedied, higher leakage fluxes are likely to be of shorter duration than smaller leakage fluxes in the longer term (c.f. remediation within 18 days at Sheep Mountain (Kuuskraa and Godec, 2007).

Table 6-1: Illustrative fluxes of free CO_2 and impacted areas for terrestrial environments.

Scenario	Illustrative Baseline Natural Flux[1]		Illustrative Leakage Flux		Illustrative Area of Leakage		Relevance of Available Information
	Flux (mol m^{-2} s^{-1})	Justification	Flux (mol m^{-2} s^{-1})	Justification	Area (m^2)	Justification	
Normal Evolution scenario	2.5E-6	The mean natural flux reported for Ketzin (Pilz et al. 2011), close to the lower end of the range of natural fluxes reported in IPCC (2005), although it should be noted that the actual value will vary seasonally at any site and could be a an order of magnitude lower to a few times higher than this mean flux.	Not Applicable	Not Applicable	Not Applicable	Not Applicable.	CO_2 permanently contained.
Direct release to atmosphere, via a well (high flux for a relatively short time period – e.g. days)	2.5E-6	The mean natural flux reported for Ketzin (Pilz et al. 2011), close to lower end of range of natural fluxes reported in IPCC (2005).	2E+5	Limiting flux of CO_2 in an open borehole modelled by Aines et al. (2009). Similar to peak flux in a blowout in a natural CO_2 accumulation at Sheep Mountain (Kuuskraa and Godec, 2007).	0.03	Area of a typical well (180 mm diameter).	Theoretical studies of borehole leakage and reports of borehole blowouts are directly relevant. However, many inter-related factors control how CO_2 could leak from a borehole. Additionally, no two boreholes are identical. Consequently fluxes could differ considerably from the value suggested (although most likely fluxes would be lower, not least because truly open-hole conditions would be very

[1] Note that in IPCC (2005) the range of natural fluxes is given as 2.6 x 10^{-6} mol m^{-1} s^{-1} to 2.6 x 10^{-5} mol m^{-1} s^{-1}. The upper value is similar to the flux that is reported for localized seepage along faults in the Paradox Basin, Utah (Lewicki et al., 2007), although it should be noted that under the climatic conditions of the Paradox Basin, natural biogenic CO_2 fluxes will be much lower than the maximum natural fluxes reported in IPCC (2005). The fact that detectable natural seeps of CO_2 may have CO_2 fluxes only a small multiple of the background biogenic fluxes is supported by modelling reported by Oldenburg et al. (2003).

Scenario	Illustrative Baseline Natural Flux[1]		Illustrative Leakage Flux		Illustrative Area of Leakage		Relevance of Available Information
	Flux (mol m^{-2} s^{-1})	Justification	Flux (mol m^{-2} s^{-1})	Justification	Area (m^2)	Justification	
							unlikely to occur even if a borehole does leak).
Localized release to soil as a result of wells / faults / fractures, leading to high concentrations of CO_2 in the near surface	2.5E-6	The mean natural flux reported for Ketzin (Pilz et al. 2011), close to lower end of range of natural fluxes reported in IPCC (2005).	5E-4	Chosen to be consistent with maintaining near-100% saturation of soil with CO_2, based on modelling results reported by Oldenburg et al. (2003) and observations at sites such as Latera (see Beaubien et al. 2008).	5 point sources, each 6 m in diameter within an area of 50,000 m^2 (1000 m x 50 m) Point sources approximately aligned if along a fault	Frequency of vents selected to be similar to that in the area of the Little Grand Wash Fault Zone, Utah (Allis et al. 2004). Each vent diameter is similar to that reported for Latera, Panarea and Laacher See (e.g. Beaubien et al. 2008; Lombardi, 2010; Gal et al., 2011).	Theoretical studies of fault leakage and reports of natural seeps along faults in non-volcanic areas are relevant. However, there are many inter-related factors that control how CO_2 could leak from a fault. The physical characteristics of faults (widths, geometries, permeabilities etc.) will vary markedly from site to site and consequently fluxes and areas could differ considerably from the values suggested.
Localized release to soils as a result of wells / faults / fractures, leading to long-term low concentrations of CO_2 in near surface	2.5E-6	The mean natural flux reported for Ketzin (Pilz et al. 2011), close to lower end of range of natural fluxes reported in IPCC (2005).	5E-5	Chosen to be an order of magnitude lower than the flux for high concentrations in the near surface. Value is the same as modelled flux of CO_2 in a wellbore with defective seals presented by Tao et al. (2011). The leakage pathway is a defect such as a fracture, microannulus or gas channel in the steel, cement or rock wall components of a well. The value is similar to the flux reported for seepage from natural CO_2 accumulations in the Paradox Basin, Utah (Lewicki et al. 2007).	5 point sources, each 6 m in diameter within an area of 50,000 m^2 (1000 m x 50 m) Point sources approximately aligned if along a fault	Frequency of vents selected to be similar to that in the area of the Little Grand Wash Fault Zone, Utah (Allis et al. 2004). Each vent diameter is similar to that reported for Latera and Panarea (e.g. Beaubien et al. 2008; Lombardi, 2010).	Theoretical studies of borehole and fault leakage and reports of natural seeps along faults in non-volcanic areas are relevant. However, there are many inter-related factors that control how CO_2 could leak from a borehole or fault. The physical characteristics of boreholes and faults (widths, geometries, permeabilities etc.) will vary markedly from site to site and consequently fluxes and areas could differ considerably from the values suggested.

Scenario	Illustrative Baseline Natural Flux[1]		Illustrative Leakage Flux		Illustrative Area of Leakage		Relevance of Available Information
	Flux (mol m^{-2} s^{-1})	**Justification**	**Flux (mol m^{-2} s^{-1})**	**Justification**	**Area (m^2)**	**Justification**	
Localized release to freshwater lakes via fractures / faults	4.5E-8	Mean annual natural biogenic flux reported for sediments in the oligotrophic (nutrient-poor) Lake Pääjärvi in Finland is 4.5E-8 mol m^{-2} s^{-1} (Bergström et al., 2010). This value is likely to be smaller than for warmer, more nutrient-rich lakes elsewhere in Europe. Flux of biogenic CO_2 from lake water to atmosphere reported for a small lake in the English Lake District is 4.6E-7 mol m^{-2} s^{-1} (Caspar et al., 2000).	5E-4	Same value as the value for localized release to soil as a result of wells / faults / fractures, leading to high concentrations of CO_2 in the near surface. Value is similar to that adjacent to Mammoth Lake (>1.3E-4 mol m^{-2} s^{-1}) and 2 orders greater than flux of 1E-6 mol m^{-2} s^{-1} reported for the Laacher See, Germany (Lewicki et al. 2007).	Several point sources, each a few m in diameter within an area of 50,000 m^2 (1000 m x 50 m)	Frequency of vents selected to be the same as that reported for Panarea. Each vent diameter is similar to that reported for Latera, Panarea and Laacher See (e.g. Beaubien et al. 2008; Lombardi, 2010; Gal et al., 2011). The Laacher See has an area of 3.31 km^2, within which there are two areas c. 250 m across where emissions are suspected and 2 areas around the shore where vents have been identified, 2 locations where elevated CO_2 has been measured in air and two c. 200 m long sections of shore where soil CO_2 is elevated (Gal et al., 2011).	There is very little information upon which to base estimates of leakage fluxes and areas. The suggested values are plausible in the sense that they don't violate fundamental physical laws, as indicated by the limited information available. However, since the available information is so sparse, it is possible that fluxes and areas could differ considerably from the values suggested.
Diffuse releases to surface and near-surface systems	2.5E-6	The mean natural flux reported for Ketzin (Pilz et al. 2011), close to lower end of range of natural fluxes reported in IPCC (2005).	5E-4	As noted in Section 5.2.1 diffuse leakage is considered less likely than point leakage and little information exists with which to estimate a flux. Chosen to be consistent with maintaining near-100% saturation of soil with CO_2, based on modelling results reported by	500,000	Lewicki et al. (2007) report diffuse emissions within an area of 480,000 m^2 on Mammoth Mountain, California, although it is unclear whether diffuse fluxes occurred throughout this area.	There is very little information upon which to base estimates of leakage fluxes and areas. The suggested values are plausible in the sense that they don't violate fundamental physical laws, as indicated by the limited information available. However, since the available information is so sparse, it is possible that fluxes

Scenario	Illustrative Baseline Natural Flux[1]		Illustrative Leakage Flux		Illustrative Area of Leakage		Relevance of Available Information
	Flux (mol m^{-2} s^{-1})	Justification	Flux (mol m^{-2} s^{-1})	Justification	Area (m^2)	Justification	
				Oldenburg et al. (2003) and observations at sites such as Latera (see Beaubien et al. 2008). Value is similar to that for diffuse emissions from Mammoth Mountain, California and Solfatara, Italy (Lewicki et al. 2007).			and areas could differ considerably from the values suggested.
Localized release to aquifers that may be exploited as drinking or irrigation water resources	2.5E-6	The mean natural flux reported for Ketzin (Pilz et al. 2011), close to lower end of range of natural fluxes reported in IPCC (2005).	5E-4	Value is proposed to be the same as the value for localized emissions to lakes.	Several point sources, each a few m in diameter within an area of 50,000 m^2 (1000 m x 50 m)	Frequency of vents selected to be the same as that reported for Panarea. Each vent diameter is similar to that reported for Latera and Panarea (e.g. Beaubien et al. 2008; Lombardi, 2010). The Laacher See has an area of 3.31 km^2, within which there are two areas c. 250 m across where emissions are suspected and 2 areas around the shore where vents have been identified, 2 locations where elevated CO_2 has been measured in air and two c. 200 m long sections of shore where soil CO_2 is elevated (Gal et al., 2011).	There is very little information upon which to base estimates of leakage fluxes and areas. The suggested values are plausible in the sense that they don't violate fundamental physical laws, as indicated by the limited information available. However, since the available information is so sparse, it is possible that fluxes and areas could differ considerably from the values suggested.
Release to an urban environment	2.5E-6	The mean natural flux reported for Ketzin	1E-4	Peak value for flux to buildings at Mátraderecske, Hungary	100	No areas are reported. Assume value for	There is very little information upon which to base estimates

Scenario	Illustrative Baseline Natural Flux[1]		Illustrative Leakage Flux		Illustrative Area of Leakage		Relevance of Available Information
	Flux (mol m^{-2} s^{-1})	Justification	Flux (mol m^{-2} s^{-1})	Justification	Area (m^2)	Justification	
		(Pilz et al. 2011), close to lower end of range of natural fluxes reported in IPCC (2005).		was reported to be 1E-4 (Lewicki et al. 2007). 20% of the diffuse flux calculated by Oldenburg et al. (2003) that would cause saturation of soil pore space with CO_2. Significantly higher fluxes would likely be recognized and either remediated or avoided.		10 m x 10 m dwelling.	of leakage fluxes and areas. The suggested values are plausible in the sense that they don't violate fundamental physical laws, as indicated by the limited information available. Storage would not be undertaken near to an urban centre, which means that even in the unlikely event that leakage did occur it would be unlikely to result in large fluxes in an urban area.

Table 6-2: Illustrative fluxes of free CO_2 and impacted areas for marine environments.

Scenario	Illustrative Baseline Natural Flux[2]		Illustrative Leakage Flux		Illustrative Area of Leakage		Relevance of Available Theoretical Information and Natural Observations
	Flux (mol m^{-2} s^{-1})	Justification	Flux (mol m^{-2} s^{-1})	Justification	Area (m^2)	Justification	
Normal Evolution scenario	1E-8	The minimum baseline flux for the southern N. Sea reported by McGinnis et al. (2009) (quoting Bozec et al. 2005).	Not Applicable	Not Applicable	Not Applicable	Not Applicable	CO_2 permanently contained.
Localized direct release of free CO_2 via the sediment or directly to the water column above the sea bed via a point source	1E-8	The minimum baseline flux for the southern N. Sea reported by McGinnis et al. (2009) (quoting Bozec et al. 2005).	2E+5	Limiting flux of CO_2 in an open borehole modelled by Aines et al. (2009). Similar to peak flux in a blowout in a natural CO_2 accumulation at Sheep Mountain (Kuuskraa and Godec, 2007).	0.03	Area of a typical well (180 mm diameter).	Theoretical studies of borehole leakage and reports of borehole blowouts are mostly relevant to terrestrial leakage. The illustrative flux and area given here are based on information for terrestrial releases from boreholes and therefore may be of limited relevance. Many inter-related factors control how CO_2 could leak from a borehole. Additionally, no two boreholes are identical. Consequently fluxes could differ considerably from the value suggested (although most likely fluxes would be lower, not least because truly open-hole conditions would be very unlikely to occur even if a

[2] McGinnis et al. (2009) quote mean natural background CO_2 fluxes for the southern North Sea from Bozec et al. (2005) in the range 1 x 10^{-8} mol m^{-2} s^{-1} to 2 x 10^{-8} mol m^{-2} s^{-1}, and summer CO_2 fluxes for the same region from Prowe et al. (2009) in the range 2 x 10^{-7} mol m^{-2} s^{-1} to 6 x 10^{-7} mol m^{-2} s^{-1}.

Scenario	Illustrative Baseline Natural Flux[2]		Illustrative Leakage Flux		Illustrative Area of Leakage		Relevance of Available Theoretical Information and Natural Observations
	Flux (mol m^{-2} s^{-1})	**Justification**	**Flux (mol m^{-2} s^{-1})**	**Justification**	**Area (m^2)**	**Justification**	
							borehole does leak).
Diffuse direct release of free CO_2 via the sediment or directly to the water column over a wide area	1E-8	The minimum baseline flux for the southern North Sea reported by McGinnis et al. (2009) (quoting Bozec et al., 2005).	1E-6	As noted in Section 5.2.2 diffuse leakage is considered less likely than point leakage and little information exists with which to estimate a flux. There are no submarine data for natural diffuse seeps and few theoretical simulations. The illustrative value is set to be an order of magnitude higher than the highest baseline flux in the southern North Sea reported in McGinnis et al. (2009) , noting that theoretical factors reviewed in Oldenburg and Lewicki (2005) imply that diffuse leakage fluxes would be much less than localized leakage fluxes.	250000 m^2 (500 m x 500 m)	Theory (e.g. Oldenburg and Lewicki, 2005) implies that areas could vary widely between sites, assuming that this seepage type occurs. The areas suggested is proposed to be the same as the area within which point sources are distributed as a basis for comparison with point seepage.	There are no data with which to judge plausible fluxes and areas of diffuse submarine leakage. The suggested values are plausible in the sense that they don't violate fundamental physical laws, as indicated by the limited information available. However, since the available information is so sparse, it is possible that fluxes and areas could differ considerably from the values suggested.

Scenario	Illustrative Baseline Natural Flux[2]		Illustrative Leakage Flux		Illustrative Area of Leakage		Relevance of Available Theoretical Information and Natural Observations
	Flux (mol m^{-2} s^{-1})	Justification	Flux (mol m^{-2} s^{-1})	Justification	Area (m^2)	Justification	
Localized release of CO_2-charged water through the sediment or directly to the water column via a point source	1E-8	The minimum baseline flux for the southern N. Sea reported by McGinnis et al. (2009) (quoting Bozec et al. 2005).	5E-4	Value is proposed to be the same as the value for emissions to lakes.	Several point sources, each a few m in diameter within an area of 250000 m^2 (500 m x 500 m)	Frequency of vents similar to that reported for Panarea. Each vent diameter is similar to that reported for Latera and Panarea (e.g. Beaubien et al. 2008; Lombardi, 2010).	There are no data with which to judge plausible fluxes and areas of diffuse submarine leakage. The suggested values are plausible in the sense that they don't violate fundamental physical laws, as indicated by the limited information available. However, since the available information is so sparse, it is possible that fluxes and areas could differ considerably from the values suggested.
Diffuse release of CO_2-charged water through the sediment and subsequently to the water column over a wide area	1E-8	The minimum baseline flux for the southern N. Sea reported by McGinnis et al. (2009) (quoting Prowe et al. 2009).	1E-6	Value is reported for diffuse emissions of free CO_2 from Solfatara, Italy (Lewicki et al. 2007). Use of the terrestrial value affords comparison with terrestrial sites. Same value as for diffuse release of free CO_2 affords comparison.	250000 m^2 (500 m x 500 m)	There are no data with which to judge likely areas of diffuse leakage. Theory (e.g. Oldenburg and Lewicki, 2005) implies that areas could vary widely between sites, assuming that this seepage type occurs. The areas suggested is proposed to be the same as the area within which point sources are distributed as a basis for comparison with point seepage.	There are no data with which to judge plausible fluxes and areas of diffuse submarine leakage. The suggested values are plausible in the sense that they don't violate fundamental physical laws, as indicated by the limited information available. However, since the available information is so sparse, it is possible that fluxes and areas could differ considerably from the values suggested.

7 DISCUSSION

The sensitivities / thresholds associated with the potential for CO_2 impacts to receptors are generally uncertain. The experts present at the workshop expressed the view that impacts may be positive as well as negative with respect to the viability of particular organisms. Additionally, impacts may be direct as well as indirect. An indirect beneficial impact on one organism may be indicative of a detrimental impact on another organism. For example, in marine environments, if CO_2 leakage were to be detrimental to grazers, then plants (e.g. kelp beds) might flourish. Similarly nematode worms increase in abundance when exposed to CO_2 because larger predators are reduced in numbers. However, CO_2 is not beneficial directly to the nematodes' metabolism. In these cases, it is difficult to relate the impact on individual organisms to the overall impact on ecology.

Currently only a few terrestrial plant types, mostly herbaceous pasture species such as clover have been the subject of experimental study. These experiments provide valuable insight into potential impact mechanisms, but there is substantial uncertainty as to whether similar processes would apply for other plant species. Key issues in modelling effects on terrestrial plants is to determine whether it is the canopy or root CO_2 concentrations that matter in different situations, and whether reduced oxygen levels in the rooting zone can adversely affect the plant (Beaubien et al., 2008; Krüger et al., 2009, 2011; West et al., 2009). This underlines the importance of the experimental studies that will be undertaken in the RISCS project. Similar issues apply to sub-surface microbiota, and more broadly to the marine system.

There have been few studies of the impact of CO_2 on biodiversity in the marine environment, but all those studies that have been undertaken showed a decrease in biodiversity when communities of organisms are exposed to enhanced CO_2 (Widdicombe et al., 2009; Hall-Spencer et al., 2008). The relationship between decreased pH due to CO_2 dissolution, and bio-diversity, is uncertain. The importance of decreased pH relative to elevated dissolved carbon is not fully understood. A key question is whether loss of a species within a marine environment with low biodiversity would adversely affect other species. There is little 'functional redundancy' in such an environment.

The expert workshop highlighted that impacts of CO_2 in combination with other stresses (e.g. pollutants) are not well understood. There is some evidence to suggest that there would be at least additive effects. It is now known that elevated CO_2 will not necessarily result in decalcification of organisms, because many organisms can regulate the chemical environment around their tissues, thereby controlling the rate of calcification. However, such chemical regulation has an energy cost, which means that it may not be carried out indefinitely. As a result, there may be resistance to the effects of short-term CO_2 leakage, but less resistance to CO_2 leakage in the long-term.

Any impacts calculated for 'leakage' scenarios need to be compared with the baseline provided by the 'normal evolution' (no leakage) scenario. For example, it may be that the receptors most likely to suffer impacts if exposed to CO_2 leaks – e.g. terrestrial plants that are already stressed by climatic or poor soil conditions – are also sensitive to other potential environmental changes. For example, a prolonged drought period might lead to severe impacts on certain species, and this might be much more likely to occur than impacts from storage systems. This does not negate the principle that impacts from CO_2 need to be explored and impacts to vulnerable receptors may be considered to be particularly important, but it does provide important context to analysis of the results.

In this report, illustrative CO_2 leakage fluxes and possibly impacted areas have been proposed for each of the low-likelihood leakage scenarios, based. However, the quoted values are hypothetical and aim only to help readers form a view as to the plausible characteristics of CO_2 leakage in these scenarios and to contribute to a context for interpreting and communicating the experimental and modelling results of the RISCS project. It should be borne in mind that some natural seepage fluxes could be lower than the illustrative values presented and lower fluxes could also be appropriate for the low-likelihood leakage scenarios; reported studies of natural seepages are inevitably biased towards areas that show relatively high fluxes.

A review of theoretical studies of possible CO_2 leakage, observations made at natural CO_2 seeps and experience of accidental CO_2 releases shows that a very wide range of inter-related factors will control any CO_2 leakage fluxes and impacted areas in each of the low-likelihood leakage scenarios. To explore the bounds of feasibility more rigorously would require, for each scenario, development of complex coupled models followed by multiple simulations using realistic parameter values.

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