Research into Impacts and Safety in CO_2 Storage (RISCS)

Identification of High-level Impact Scenarios: Including a Report of the Workshop held at Brussels on 4th - 6th May 2010

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Summary

The RISCS programme is concerned with research into the potential environmental impacts that might be associated with any CO_2 leakage from a storage site. Research within the programme is focussed on receptor impacts and related monitoring.

This document outlines a set of receptor environments and high-level impact scenario descriptions, systematically derived at an expert workshop held in Brussels on 4th - 6th May 2010. This is consistent with the overall aims of Work Package 1 (WP1) of the RISCS project, which can be summarised as:

- *'to develop descriptions of a number of reference receptor environments and associated descriptions of credible impact scenarios...'*

The workshop was held jointly with WP5 sessions on terminology, communication strategies and the proposed content of the RISCS 'Guide'. This document, however, reports the WP1 process outcomes only.

Aims

The focus of the RISCS project is on issues relating to the impacts that might result from CO_2 leakage from storage systems in the unlikely event that it occurs. The analysis therefore concerns 'impact' scenarios. That is, it explores mechanisms by which leaks, should they occur, could impact upon receptors. Issues relating to injectivity, capacity and containment are therefore out of scope.

Where potential impact mechanisms were identified that are not the result of CO_2 leakage from storage systems, such as unintentional displacement of formation brines, or leaks from pipelines during the operational phase, relevant issues were noted but not discussed in detail.

Context and Terminology

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. These sources provide context and guidance for aims and requirements for carbon storage projects, including standard definitions for key terms. Related issues were also discussed at the workshop, including a standard list of terms relevant to RISCS, and WP1 work.

Reference Environments

RISCS will produce guidance that is applicable across a full range of CCS projects that may be undertaken in the EU region at some point in the future. It is important that defined impact scenarios, however, are not too generic; it is also inappropriate that they should be site specific.

Participants identified a small number of reference environments including both 'marine' and 'terrestrial' examples. These environments together explore a representative range of receptor classes, to indicate the different types of system that need to be considered to derive a representative range of impact scenarios.

Leakage Mechanisms/Patterns

Participants considered the different physically plausible mechanisms by which CO_2 could leak from a CO_2 storage system. Hence, the leakage patterns that may be observed at the interface(s) with media associated with receptors were identified.

For both marine and terrestrial reference environments, it was considered likely that impacts would be caused by point-source, localised releases, via wells and localised channels within faults or fracture systems. The potential for diffuse releases was recognized, but judged less likely to lead to impacts than point-source releases.

Receptors and Processes Associated with Impacts to them

For both 'marine' and 'terrestrial' ecosystem types, participants identified receptor classes of potential import, and the mechanisms by which they might be impacted.

The principal terrestrial receptor classes identified are: humans, plants and animals associated with agricultural or natural ecosystems, terrestrial freshwater bodies, and aquifers that may be exploited for drinking or irrigation water. The main differences in receptors between different climates are the varied natures and distributions of plants and animals; and under colder or more arid conditions, many plants will be stressed already, and so will be more sensitive to CO_2 leakage.

Marine receptor classes identified are: benthic and pelagic biota; biogenic calcifying habitats; localised sensitive populations (such as nursery areas); and receptors associated with biogeochemical cycles that underpin the marine systems health and resilience.

FEP Audit

To build confidence that the analysis was sufficiently comprehensive, the outcomes of the process were audited against Quintessa's on-line database of Features, Events and Processes (FEPs) relevant to CO_2 storage (Quintessa, 2010).

Impact Scenarios

The baseline, by far 'most likely' scenario, is for a storage system to evolve as designed, with no leaks occurring. In other words, the receptors 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, as a deviation from the norm. 'Impact' scenarios are therefore potential very low likelihood 'alternative evolution' scenarios.

Alternative evolution scenarios identified for terrestrial systems include those involving impacts to animals and plants following direct release to the atmosphere following well seal failure, localised release to soils leading to high concentrations of CO_2 in the near-surface, and releases to soils leading to lower concentrations of CO_2. Equivalent scenarios involving more diffuse releases were also noted. Localised release to aquifers that may be exploited as drinking or irrigation water resources was also noted as a potential impact scenario. Impacts to human receptors are considered through definition of a scenario based upon release to infrastructure associated with an urban environment. In each case, the report discusses relevant release and exposure mechanisms, and the relative likelihood of each scenario class, noting that more detailed consideration of impact and likelihood would require site-specific analysis.

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: localised direct release of free CO_2 via a point source; diffuse release of free CO_2 over a wide area; localised release of CO_2-charged water via a point source; and diffuse release of CO_2-charged water over a wide area.

Issues and Uncertainties

The report presents key issues and remaining uncertainties identified during workshop discussions and subsequent audit activities. The outcomes are mapped to the planned RISCS work programme to help workpackage planning and prioritisation. Proposed next steps for work under WP1 are presented.

To aid communication of the most important outputs from each section of this document, key points are summarised throughout the main body of the report, utilising boxes of this format.

Contents

1 Introduction

1.1 This Document

The RISCS programme is concerned with research into the potential environmental impacts that might be associated with carbon capture and storage (CCS), should any leakage occur from a storage site. Research within the programme is focussed on receptor impacts and related monitoring activities.

Specifically, the overall aims of Work Package 1 (WP1) of the RISCS project can be summarised as (RISCS, 2009):

- *'to develop descriptions of a number of reference receptor environments and associated descriptions of credible impact scenarios...'*

This document presents a set of outline receptor environment and high-level impact scenario descriptions, systematically derived at an expert workshop held in Brussels on 4th - 6th May 2010. It therefore also describes issues relating to context and terminology agreed at that workshop. An audit of the outcomes against established lists of Features, Events and Processes (FEPs) relevant to storage systems was undertaken subsequently to the workshop, as was a comparison of key issues and uncertainties identified against activities planned for other project work packages. The audits and comparisons undertaken are also presented in this report.

Version 1.0 of this document was provided to workshop participants and other RISCS partners for review. The present version has been updated on the basis of feedback obtained.

1.2 Document Structure

The remainder this document is structured as follows.

- Section 2 provides an overview of the aims of the scenario analysis.
- Section 3 outlines key issues of context, and presents an agreed list of terms and definitions that are relevant to the scenario analysis.
- Section 4 summarises the process utilised, and presents the main outcomes of the analysis.

- A summary of the key issues and uncertainties identified is presented in Section 5. This includes an indication of which RISCS workpackages may be best placed to address the issues identified.

- Section 6 outlines proposed next steps.

- Appendix A presents the workshop Agenda.

- Appendix B lists workshop participants.

- Appendix C provides more details on the outcomes of the FEP audit, and of the analysis of key issues and uncertainties to help prioritise research for other work packages.

To aid communication of the most important outputs from each section of this document, key points are summarised throughout utilising boxes of this format.

2 Aims of the Impact Scenario Analysis

2.1 Main Focus

The focus of the programme is on issues relating to the impacts that might result from CO_2 leakage from the storage complex, however unlikely it is that any leaks will occur. These represent secondary but important issues, compared to the primary issues of injectivity, capacity and containment that are outside the scope of RISCS.

Two further potential impact mechanisms were also recognised.

- ▲ Even if a leak does not occur, pressurisation of the storage complex could lead to unintended displacement of fluids with the potential for subsequent interactions between saline waters and sensitive domains (e.g. aquifers, or surface effects following interactions with well-bores). This issue was not discussed at the workshop, which focussed on CO_2 leakage.
- ▲ Pipeline ruptures during operations could lead to impacts of a similar type to impacts associated with some forms of leakage from the storage complex. However operational risks are not within the scope of RISCS.

Although these issues were not directly addressed at the workshop for the reasons described, discussions that were of relevance are documented. Requirements for interactions with these issues will be considered further as the RISCS project progresses.

2.2 Scenarios

For the RISCS programme, the definition of the term 'scenario' has been agreed as follows (see also Section 3.4):

- ▲ A plausible description of the potential evolution of a system according to the nature of the FEPs that might act within and upon it.

This analysis is concerned specifically with 'impact' scenarios, i.e. exploring conceptual models describing plausible mechanisms by which leaks, if they occur, could lead to impacts to receptors.

Any process designed to identify such scenarios needs to include the following elements.

- Identification of plausible temporal and spatial leakage patterns (e.g. whether continuous or episodic, whether point sources or diffuse), based on a general understanding of the potential failure / leakage mechanisms for terrestrial and marine storage systems, including relative likelihoods of occurrence.

- An understanding of the mechanisms by which such leaks could lead to impacts to receptors, again including statements on relative likelihoods of occurrence.

- 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 programme, these environments need to be identified so to include a sufficient range of receptors to illustrate all the main types of impact to be considered within the project.

- Integration of the above to develop a suitable range of plausible impact scenarios.

It is not necessary at this stage to undertake an overly complex analysis. The primary requirement is to identify a small number of scenarios broadly representative of the main types of impacts to receptors that could occur. The analysis will inform upon the likelihoods of different scenarios, but does not involve direct estimation of the magnitudes of impacts and risks. Rather, the scenario analysis indicates the system states that may occur and provides a framework for estimating the magnitude of potential impacts.

Identification of impact mechanisms that are particularly unlikely to occur (even if a leak does happen), and can thus be 'screened out' from further analysis, represents a particularly important objective. This screening function will be particularly valuable as it will help ensure future work does not focus unduly on such low-likelihood scenarios.

3 Context and Terminology

3.1 Context

The EC Directive on storage (EC, 2009), and other sources of guidance such as the OSPAR Framework, USEPA guidance and the CO2QualStore Guideline (OSPAR, 2007; USEPA, 2008; DNV, 2009) all recognise that the primary issues to be assessed and demonstrated for CCS sites are related to demonstrating injectivity, capacity and long-term containment. However, they all also recognise the importance of assessing the potential for environmental impacts should any leaks occur. The magnitude and relative likelihood of any potential impacts to receptors can then be combined with assessments of the likelihood of leakage occurring, in order to form an overall assessment of relevant issues.

A brief summary of some of the major sources of guidance that are relevant to identifying impacts scenarios is provided below.

3.1.1 EC Directive 2009/31/EC on the Geological Storage of Carbon Dioxide

The EC Directive (EC, 2009) describes a range of requirements and guidance relevant to CCS. Of these, a number of specific statements are made that 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, including in particular on drinking water, for human populations, or for users of the surrounding biosphere;*
- *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'.*[1]

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 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.

3.1.2 OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations

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:

a. *'Problem formulation: critical scoping step, describing the boundaries of the assessment;*

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1 Italicised text indicates direct quotes from the source material.

b. *Site selection and characterisation: collection and evaluations of data concerning the site;*

c. *Exposure assessment: characterisation and movement of the CO_2 stream;*

d. *Effects assessment: assembly of information to describe the response of receptors;*

e. *Risk characterisation; integration of exposure and effect data to estimate the likely impact; and*

f. *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 a. and b. provide important contextual information, including hazard characterisation work, and f. will inform upon potential mitigation and remediation scenarios. Notably, stages c. to e. reflect the requirements of the (subsequently developed) EC Directive. The OSPAR guidelines provide significant additional guidance relating to these stages, framed by a marine-environment perspective. Of this guidance, some specific statements are noted below.

▲ '*The* (probabilities) *of the exposure processes may be assessed using appropriate techniques, including numerical modelling and simulation tools. Uncertainties should be identified, as well as sensitivity for the choice of models by comparing different simulation techniques*'.

▲ The role of 'effects' assessment is framed by the statement that '*although permanent* containment *of CO_2 streams is the ultimate objective of storage of CO_2 in geological formations, effects and risk assessment is carried out to demonstrate that, in the event of leakage, storage does not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area*'.

▲ In terms of sensitivities of receptors '*the main effects to consider in relation to the leakage of CO_2 streams are those that result from increased CO_2 concentrations in ambient marine sediments and waters and biological sensitivity to such increases*'.

▲ The OSPAR guidelines emphasise the role of the risk characterisation stage. '*Various methods for assessing the long-term passive storage phase are being developed…. These models can vary from relatively simple to very detailed models. Where significant uncertainties in model input variables are projected to exist, it is recommended that uncertainty ranges around the most likely values be applied in the assessment. Similarly, if discrete events are not certain to occur, probability values should be assigned to such events. The assessments can be executed in a deterministic way following a conservative approach or in a probabilistic manner that quantifies the uncertainties connected with* *storage of CO_2 streams.'* This is relevant as the present scenarios development process will provide a framework for the assessment of different types of storage system. In doing so it is important that the key impacts-relevant 'discrete events' are recognised and addressed by the identified scenarios, and that an appropriate description of the factors that might influence site-specific scenario probability is developed (irrespective of whether deterministic or probabilistic assessment methods may ultimately be applied to a particular site).

- The guidelines recognise the potential importance of the risk characterisation stage in informing mitigation measures.

3.1.3 CO2QUALSTORE Guideline

The CO2QUALSTORE Guideline (DNV, 2009) also provides potentially 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)?'*

3.1.4 U.S. Environmental Protection Agency: Vulnerability Evaluation Framework for Geologic Sequestration of Carbon Dioxide

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.

In its introductory section, a quote from IPCC (2005) is provided as context for the vulnerability framework. This implicitly suggests it is appropriate to consider the potential impacts of CCS systems in comparison with the level of risk typically associated with operations undertaken in other industries:

'*With appropriate site selection based on available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control* CO_2 *releases if they arise, the local health, safety and environment risks of geologic storage would be comparable to risks of current activities such as natural gas storage, [enhanced oil recovery], and deep underground disposal of acid gas*'.

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 GS, 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 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.

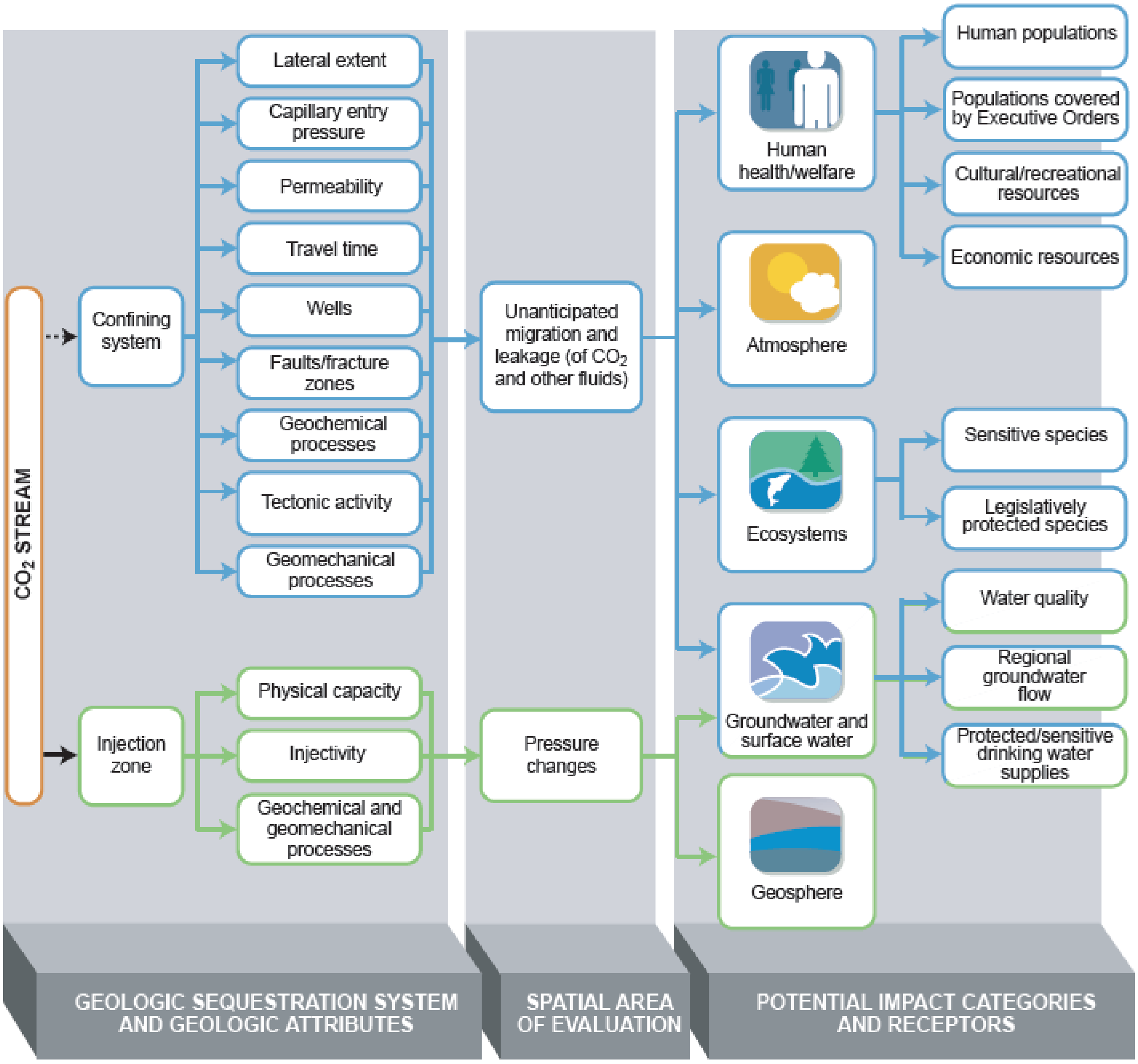
Note that the atmosphere is regarded as a receptor primarily as '*releases can reduce the climate benefits of capturing* CO_2*, thus decreasing the overall effectiveness of* (geological storage) *as a climate change mitigation strategy*'.

As the framework is not intended to explicitly estimate the magnitude or likelihood of impacts, a qualitative classification approach is followed, to identify potential factors of interest: '*low vulnerability*', whereby '*adverse impacts are not expected to be associated with the attribute or receptor under evaluation*', and '*elevated vulnerability*', whereby '*particular attention should be paid to the attribute or receptor under evaluation*' (in order to avoid any possible impacts).

3.1.5 Other Resources

A wide range of other legislative, regulatory and best-practice resources are available within the EC and wider international community. The importance of these resources is recognised, but in the interests of brevity, they are not reviewed here. In any case the basic principles from other sources of guidance are broadly consistent with the EC, OSPAR and EPA examples discussed above. In addition as RISCS is an EC funded project, EC Directives and guidance are of particular relevance.

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



3.2 Relevance to the RISCS Programme

The USEPA vulnerability evaluation framework provides a useful resource for the current RISCS programme, as it concerns exploration of similar kinds of impacts and receptors. Similarly, the role of the WP1 scenario identification process will be to frame work to be undertaken subsequently. However, the RISCS programme will consider a representative set of reference environments in order to develop an understanding of the potential likelihoods and consequences of impacts scenarios. In this respect, it is important that the approach and terminology used is consistent with the principles and approaches expressed in the EC Directive and the OSPAR framework.

3.3 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. For example, 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, amongst other best-practice guidance resources, also 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. Workshop participants agreed the following time periods to be of relevance.

- 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 (e.g. of the order of a further 50 to 100 years, up to cessation of monitoring and other controls).
- A 'long-term' assessment time period (e.g. including a post-closure period of a further 100 to several 1000 years).

3.4 Terminology

A key issue for WP1, and indeed the RISCS project as a whole, is that of terminology. Therefore, an important session at the Workshop concerned definitions of key terms. Participants were presented with a list of definitions for discussion, update and agreement. Wherever possible, a consensus on the meaning of terms was sought; any remaining issues were also noted.

The resulting list of definitions is provided in Box 1 below. As far as possible definitions used are taken from the EC Directive and/or the OSPAR framework, with the Directive taking precedence. Additional clarifications of those terms, and other definitions were proposed based upon participant experience gained from other CCS projects and associated studies.

Participants found that the terms 'geosphere' and 'biosphere' were not helpful to the construction of impact scenarios as they represent overlapping spatial domains. Therefore, the following additional definitions were agreed to provide clarity on how these domains should be treated in defining scenarios.

- **System media relevant to CO_2 transport**: Features of the system that are external to the storage complex and may provide media for CO_2 transport should any leaks occur (fractures, wells, water column, permeable caprock etc).
- **System media associated with receptors**: Features of the system that are external to the storage complex which receptors might interact with or inhabit, including features that are directly receptors in themselves (e.g. the water column, near-surface and surface soils, drinking water aquifers etc).

Box 1: Terminology

Term *	**Definition** ***and additional notes***
Biosphere	Aspects of the system relating to media that contain or interact with receptors. *This definition was reviewed at the workshop and considered to be less helpful than other terms – see 'system media relevant to CO_2 transport' and 'system media associated with receptors' definitions in the main text above. However it is retained in this list as it is utilised in the EC Directive and other resources.*
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 was noted as a two-stage process at the Workshop; hence this 'new' definition. See also the EC Directive definition of Closure below.*
Closure (EC)	The definitive cessation of CO_2 injection into that storage site. *See also 'Cessation of Control'*
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.
Environmental safety	Relates to the assessment of potential negative impacts to human and non-human receptors associated with the environment surrounding a storage system
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.
Geosphere	The subsurface component of the environmental system associated with the storage site. In addition, the geosphere may contain receptors additional to those associated with the biosphere (drinking water aquifers etc). *As for 'biosphere', this definition was reviewed at the workshop and considered to be less helpful than other terms – see 'system media relevant to CO_2 transport' and 'system media associated with receptors' definitions in the main text above. However it is retained in this list as it is utilised in the EC Directive and other resources.*
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. *At the workshop, some participants expressed the view that the term 'effect' could be usefully disaggregated from the term 'impact'. For the purposes of the current document, however, the term 'impact' has been taken to apply to all the potential consequences of leakage for receptors of interest. The terms 'impact' and 'effect' are thus considered interchangeable in the context of the current project, with the term 'impact' used to describe a significant (positive or negative) 'effect' on a domain of interest.*
Impact Scenario	For the purposes of WP1, an 'impact scenario' describes a plausible conceptual model describing how a leak from a storage system could lead to impacts on one or more receptors. The WP1 impact scenario descriptions will not consider the relative likelihood of such a leak occurring, as that is out of scope, but should provide a commentary on the important processes that need to be considered in evaluating impacts associated with a scenario, and guidance on the relative likelihoods of different impacts occurring. A range of different impact scenarios may be required to fully characterise the potential for impacts associated with a particular site. Please also see specific definitions for 'impact' and 'scenario' terms.

Term *	**Definition** ***and additional notes***
Impurities	Substances other than CO_2 that may be present in the injected CO_2 stream. See also definition of 'contaminants' above.
Leakage (EC)	Any release of CO_2 from the storage complex.
Long-term (O)	The term (period) following cessation of operation of the CO_2 storage site. This could extend to several thousand years into the future.
Migration (EC)	The movement of CO_2 within the storage complex. *Participants agreed that this process is not directly relevant to the present study, as it is forms of leak from the storage complex that are of interest. Related to this, the assumption was made that for the RISCS project, the sea-bed will not be considered to be part of the storage complex for marine systems.*
Post-closure (EC)	The period after the cessation of control of a storage site, i.e. after the transfer of responsibility to the competent authority.
Receptor	Any component of the broader 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 (O)	Part of a risk-management system, consisting of exposure assessment, effect assessment and risk characterisation. *At the workshop, participants agreed that this term, as for 'risk characterisation' below, is principally about likelihood and severity of impacts.*
Risk characterisation (O)	Risk characterisation is the step in the risk assessment process which determines the likelihood *and* severity of impacts on the (marine) environment.
Safety	Refers to the prevention of negative health and safety impacts on human populations (see also 'environmental safety' above). *Workshop participants agreed that, for the purposes of developing 'impact scenarios', the focus is on environmental impacts on humans (and other types of receptors) – that is, operational safety impacts to site operators is out of scope.*
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. Due to uncertainties in the future evolution of any system, several scenarios may be required to cover a sufficient range of potential future system states. Scenarios that are extremely unlikely to occur that could have high consequences are also typically identified.
Short-term (O)	The term (period) prior to closure of the CO_2 storage site. This could extend to one hundred years into the future.
Significant irregularity (EC)	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.
Significant risk (EC)	A combination of a probability of occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of (the EC Directive) for the storage site concerned.
Storage complex (EC)	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.
Storage site (EC)	A defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities.
(Storage) system	The storage complex and the surrounding environment with which it may interact.

*Definitions from the EC Directive are marked (EC); and those from the OSPAR guidance are denoted (O).

4 Impact Scenario Identification

4.1 Principles

The outcomes of the reference environment and impact scenarios identification processes will provide an important prioritisation tool for the RISCS programme. Therefore it is important that the analysis is appropriately comprehensive and is supported by a transparent audit trail. In addition, the use of established scenario identification approaches will help build internal, and external, confidence in the process and its outcomes.

The process was based upon a high-level systematic expert elicitation process, consistent with best practice. The elicitation process was followed by an audit against a generic FEP database to demonstrate completeness.

4.2 Process Overview

Figure 2 provides an overview of the process implemented. Those aspects of the process undertaken at the main Workshop are outlined in the Agenda provided in Appendix A.

The rationale behind the process is as follows.

- At the workshop, a suite of reference environments was identified (see Section 4.3) that together capture all the different receptor types of interest.
- In separate 'marine' and 'terrestrial' groups, participants discussed and agreed descriptions of the main mechanisms that, should any leak occur, describe how CO_2 might be subject to transport through relevant media prior to contacting receptors. For example, a fracture could lead to a linear pattern of release to terrestrial surface-based receptors etc. Where existing evidence (e.g. from analogues) or other arguments allowed, statements were made regarding the relative probabilities of different leakage patterns occurring.
- Lists of receptors, and associated features and processes by which impacts to them might occur, were elicited. These were initially defined for one reference environment. Differences in the receptor types or characteristics between the reference environment and other environments were then identified (e.g. noting differences in climatic conditions).

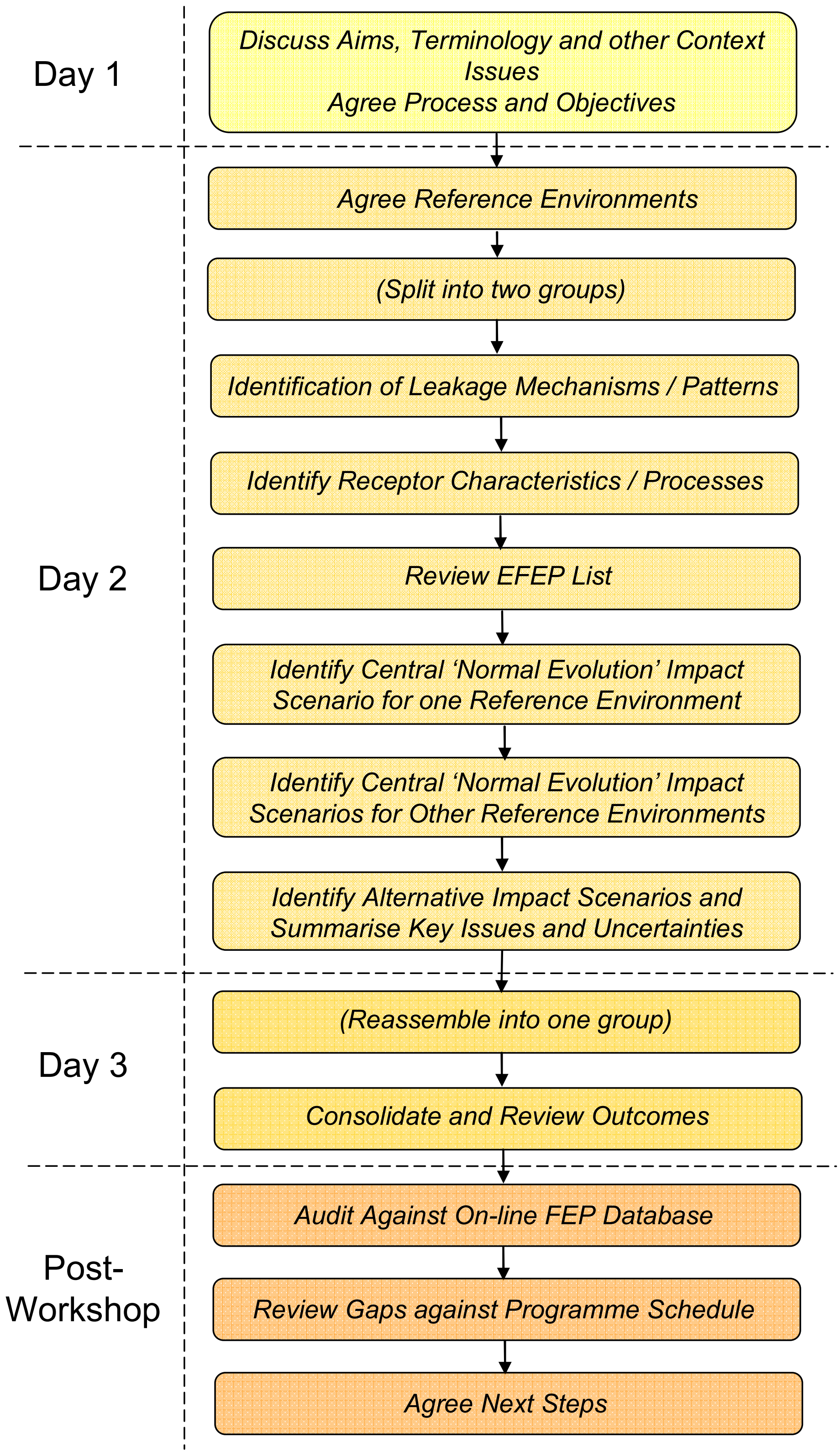
- Any other 'external' effects that could have implications for system evolution were noted (e.g. seismicity).

- The receptors identified, and the mechanisms by which impacts to them might occur, were then mapped to the leakage mechanisms / patterns previously elicited to directly identify a representative range of high-level impact scenarios.

- Following the workshop, the outputs obtained were audited against the detailed list contained in Quintessa's on-line FEP database, and a gap and uncertainty analysis was carried out, mapped to the work planned to be undertaken for each workpackage.

The following subsections detail the outputs obtained.

Figure 2: Overview of Process



4.3 Reference Environments

RISCS is charged with the production of guidance that is applicable across a 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 recognised that to develop guidance that will provide a meaningful contribution to the subsequent analysis of possible impacts associated with specific sites, the scenarios should not be too generic. The descriptions derived should, ultimately, be sufficient to underpin subsequent more detailed scenario identification processes based upon site-specific data sets. Very high-level, abstract scenarios will be of little practical help.

In discussion, it was agreed that a small number of reference environments should be identified, including both 'marine' and 'terrestrial' examples. The environments together explore a representative range of receptor classes within the two main broad categories, to give an indication of the range of different types of FEPs that need to be included in the overall analysis.

Workshop participants were asked to consider the factors that are most important in determining receptor characteristics, and thereby to identify a list of reference environments sufficient to cover the main issues. In discussion, the following key points were noted.

- It was agreed the environments should all reflect European conditions, consistent with the focus of RISCS.
- The fundamental difference is therefore between marine and terrestrial environments.
- Within each of these classes, receptor types and habits will primarily 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 thus not considered directly by this list of reference environments. However, in discussion sensitivities to variations in geology / sediment characteristics were noted.
- The importance of tectonic activity was noted. However, this was not considered a key control on the choice of reference environments. Consideration of 'containment' issues associated with potential seismicity is not within the scope of RISCS. However, the potential influence of seismic effects from an impacts

perspective does need to be addressed. An appropriate mechanism is to consider the influence of tectonic activity in terms of characterisation of the nature and relative likelihood of occurrence of processes such as fault/fracture widening. In this manner the effects of tectonic activity are considered through the scenarios derived, but it is not considered necessary to identify a specific reference environment associated with a tectonically active area.

- 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 in one place, a specific environment was identified to consider a storage system located under an urban settlement.

- Freshwater systems such as lakes and wetlands also need to be considered. It was agreed that these should be identified as potential features that might apply across the 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.

- It was noted that estuaries, intertidal and near coastal regions are very different to either marine or terrestrial environments. Diurnal changes in salinity / tides could have unique effects not represented in the other environments. However, many of the influences will be site-specific. Specific characteristics of estuaries that could influence impacts from any leakage of CO_2 are:

  - diurnal changes in salinity;
  - diurnal changes in water level;
  - adaptation of ecosystems to these changes;
  - high turbidity; and
  - interference between marine and terrestrial systems

  Nevertheless, it was considered to be inappropriate to specify a specific 'estuary reference environment' since 'typical' estuary 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. In addition, it was considered that leakage into an estuarine environment could be considered to be especially unlikely to occur.

▲ Consideration should be given only to environments that are representative of European areas that could reasonably be expected to provide candidate sites for CO_2 storage in the future. Areas which are highly unlikely to be utilised for CO_2 storage should not be considered further. Therefore, the environments elicited do not need to consider:

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

Following these discussions, the following reference environment types were defined (Box 2). These were agreed to be sufficient to bound the different types of environment and thus receptor classes relevant to RISCS.

It should be noted that in Box 2, there is no 'warm deep' marine environment. Potential CO_2 storage environments of this kind were discussed at the workshop, and it was noted that they do occur within the European area; in the Mediterranean, there are potential storage sites with a wide range of water depths, from a few 10's of metres to a few hundreds of metres. However, it was considered by the discussion group that addition of a 'warm deep' 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 in Box 2.

Box 2: Reference Environments

Class	Reference Environments	Notes
Terrestrial	▲ Maritime Temperate	Representative of a northern central European, cool climate (e.g. UK, Netherlands etc).
	▲ Continental	Considers 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 humans should a storage system be located close to a large urban centre.
Marine	▲ Cool, temperate, deep	A site with deep water (greater than c. 60 m, typically with depths of several hundred metres; note systems shallower than c. 60 m are normally completely mixed year-round) located on the continental shelf remote from shoreline influences. Tides will not be a significant influence on water depth but tidal mixing and currents are likely to be significant. The site has cool bottom water (c. 5°C), but is not Arctic (it is free from sea ice). The water is seasonally stratified with annual surface temperature variation c. 4°C – c.15°C. The water is nutrient rich (eutrophic). Cold-water corals and associated ecosystems may occur. Such a site would occur in the northern North Sea, or to the west of Norway. Note that this class includes very deep (> 300 m) waters whereby pressure effects would have a significant influence on processes governing dispersion CO_2.
	▲ Cool, temperate, shallow	A site with water depth of a few tens of metres, located relatively close to land. Tides could cause significant changes in water depth due to the comparatively high tidal range of European systems typically representative of this class of environment. Tidal mixing will be dominant, some seasonal stratification may occur but a fully mixed water column would be normal. The annual temperature variation is c. 4°C – c.15°C. The water is nutrient rich (eutrophic) and may be impacted by riverine signals. Such a site would occur in the southern North Sea.
	▲ Warm shallow	A site with water depth of a few tens of metres, located relatively close to land. Tides do not cause significant changes in water depth, because these environments occur where there is only a small tidal range. There could be significant seasonal variations in runoff from adjacent land masses. The bottom temperature minimum is c. 5°C. Surface temperatures range annually from 6°C to 25 °C, with a mean value of 10 - 12 °C. Warm water corals and associated ecosystems may occur. Such a site would occur within the Adriatic.
	▲ Low salinity (saline, but substantially lower than mean ocean salinity)	Site with water depth of a few tens of metres, located relatively close to land. Tides do not cause significant changes in water depth because these environments occur where there is only a small tidal range. Water salinity is much lower than open ocean water salinity, but is variable, depending upon the proximity of a site to the coast and connections to the open ocean; salinity

Class	Reference Environments	Notes
		will be around 30% of open ocean salinity at depth more than a few tens of kilometres from coasts, but substantially less in shallow waters and waters near to coasts. There will be much lower biodiversity than in open-ocean locations. Such a site would occur in the Baltic Sea.

4.4 Leakage Patterns

4.4.1 Terrestrial

When considering the different types of leakage mechanisms that could be envisaged from a storage system, and the leakage patterns that may be observed at the interface(s) with system media associated with receptors, participants in the 'terrestrial' environments analysis noted the following.

- System features most likely to be associated with leakage include wells (e.g. following well seal failure) and faults and fractures (e.g. as a result of fault/fracture widening through induced or natural seismicity, or interaction of the storage complex with a fault not previously mapped).

- General 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 they are likely to lead to localised CO_2 releases to the atmosphere (essentially point sources), rather than more diffuse releases. Where a fault intersects the ground surface, these point sources are likely to have an approximately linear distribution along the length of the fault. However faults are typically zones of deformation with significant width in the direction perpendicular to the direction of displacement. Hence a 2D distribution of point sources within a zone that is narrow compared to the length of the fault trace, is also possible.

- 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 general diffuse release is much less likely to occur.

- ▲ Overall, participants agreed the leakage pattern most likely to lead to impacts is that of a point source, localised 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. De-pressurisation 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. 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 localised around a radius of the order of metres to tens of metres from the source. If the location of the release is near an inhabited or farmed area, it is likely that the effect will be observed, providing an opportunity for mitigation e.g. shutting off an active nearby injection process, or at least movement of livestock etc.

- ▲ 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.

- ▲ The scope of the RISCS project does not include assessment of the potential environmental impacts that may occur should a CO_2 pipeline leak. However in discussion it was suggested that there are strong parallels between such an event and the impacts that might occur following well failure.

- ▲ In considering leakage patterns to different domains it was considered important to clearly define depths and other important aspects pertinent different features.

    - o It was agreed that probably the primary storage reservoir within a storage complex would be located at a depth of greater than eight hundred metres, and that storage would typically be at supercritical pressures.

    - o Participants considered that 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.

- o 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 couple of 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.

Participants therefore defined the following list of plausible leakage mechanisms / patterns.

Box 3: Terrestrial Leakage Mechanisms / Patterns

- ▲ Localised release to surface through well failure
- ▲ Localised release to surface through fractures
- ▲ Localised release to aquifers that have the potential to be exploited as water resources through well failure
- ▲ Localised release to aquifers that have the potential to be exploited as water resources through fractures
- ▲ Diffuse effects following fracture / well transport to surface / aquifers

In defining this list, participants noted that localised releases to the sub-surface or aquifers from wells or fractures can be treated together, as the leakage patterns are extremely similar. Participants also noted that while 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 does not need to be considered any further.

4.4.2 Marine

The discussions of the group considering marine environments focussed initially upon the aspects of CO_2 leakage that could affect ecosystems. Hence, the ways in which different spatial and temporal patterns of leakage might influence these aspects were evaluated. Finally, the possible phenomena that could cause these different patterns were determined.

The analysis of marine environments noted the following aspects of leakage that could affect ecosystems:

- Fast passage of CO_2 through benthic (sea floor) system would result in the benthic system being little affected.
- Impacts on pelagic ecology around the leakage site could be important.
- The nature of the CO_2 source term at the seabed is important. The nature of the impacts will depend upon whether release of CO_2 bubbles or acidified water occurs.
- The physical effects of leaking CO_2 on the behaviour of seawater could be significant. 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 will 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).
- Not only acidification of the water column above the seabed, but also acidification of porewater in the sediment column beneath the seabed is important in controlling impacts.
- Mobilisation of organic compounds from the storage reservoir, 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.

It was concluded that the geometry of 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 the impacts, but not these particular aspects. Three different geometries were considered plausible:

Box 4: Marine Leakage Mechanisms / Patterns

- Point emissions
- Linear emissions
- Diffuse emissions over a wide area

The general view of the group was that truly linear emissions, in which CO_2 or CO_2-charged water occurs along the length of linear feature on the seabed, is unlikely to occur. More likely there will be single emission points, or groups of emission points, that are approximately aligned with one another.

The feasibility of this third possible geometry was considered at length. The opinion was expressed 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, it was recognized by the group that there is considerable uncertainty about whether or not diffuse emissions can occur. The fact that such emissions have not been observed at natural analogue sites could reflect the difficult of detecting this kind of emission. There have been experiments in which CO_2-saturated water was introduced to the bottom of a sediment column that suggest the possibility of porewater acidification over a wide area. 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. It was noted that changes in organism behaviour would potentially indicate where diffuse release occurs.

In conclusion, the general view of the group was that diffuse emissions of discrete CO_2 or CO_2-charged water cannot be ruled out, even though there is no consensus that it does occur.

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 deduced in Section 4.4.1. As in the case of the terrestrial environments, leakage could potentially occur through a combination of different kinds of pathways.

4.5 Receptors and Processes Associated with Impacts to them

4.5.1 Terrestrial

The receptor classes identified by participants as of import for assessments of impacts associated with terrestrial systems are summarised in Box 5 below.

Box 5: Receptor Classes Identified for Terrestrial Systems.

Receptor Class	Potential Impact Mechanisms and Other Notes
Plants associated with agricultural ecosystems Crops and grasses **Plants associated with natural systems** Plants associated with forest, moorland, heath, wetland, and alpine ecosystems	The primary mechanisms by which impacts to plants may occur include: ▲ 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). ▲ Noted that existing experiments have considered a relatively small range of crops and implications for other plants are not yet well understood.
Animals that inhabit agricultural or natural ecosystems Invertebrates (e.g. insects) Vertebrates (including mammals, amphibians, birds) Microbiota	▲ Asphyxiation (of animals unable to move away from a localised surface ponding event). ▲ Potential for chronic low-concentration exposure effects e.g. on skeletal structure or other effects (it was noted that 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 above).
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 etc. ▲ 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). Participants noted the need to distinguish between stratified and more homogeneous lakes, inducing water bodies with dynamic mixing etc. Impacts are more likely to occur to stratified lakes where impacts may be concentrated. It was also noted that in order to undertake a complete assessment of aquatic systems, a complex conceptual model including water-sediment interactions etc maybe required.
Aquifers that may be exploited as drinking or irrigation water resources Aquifer water resources as receptors in their own right Microbes that might inhabit	▲ Degradation of water quality as a result of biogeochemical processes leading to acidification / toxicity etc. (Participants notes that it is not possible to be more specific without a site-specific geochemical understanding). ▲ Participants noted a general point that microbe populations that might exist associated with any system media could be regarded as receptors in their own right, in addition to contributing to

Receptor Class	Potential Impact Mechanisms and Other Notes
the aquifer	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	▲ Asphyxiation as a result of sudden releases to and ponding within basements/subsurface features. ▲ Impact on urban environment (gardens, other structures and resources). Noted that it was considered 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 was considered 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. Participants noted the possibility of 'secondary' impacts e.g. perception issues leading to house price reductions, etc, due to fear of underground carbon storage systems. This was considered outside the scope of WP1 as evaluation of such impacts is not a 'technical' issue but more related to education and communication; thus this issue may be best addressed by WP5.

Participants identified that receptor characteristics would 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, however, where storage projects are most likely to be located, it is more relevant to consider the implications of less extreme variations in climate.

A summary of participant discussions concerning the influence of different climate states on receptor characteristics is provided below.

Box 6: Influence of Different Reference Environment Climate States on Receptors

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. Therefore, it is 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.

Participants was noted that the RISCS project may wish to prioritise research on impacts to some classes of receptors over others. If so it was considered that the rationale for such decisions should be documented and ideally the subject of consultation e.g. through WP5, and that these priorities relate to value judgements that are not within the scope of WP1.

4.5.2 Marine

The receptor classes identified by participants as of import for assessments of impacts associated with maritime systems are summarised in Box 7 below.

Box 7: Receptor Classes Identified for Marine Systems.

Receptor Class	Potential Impact Mechanisms and Other Notes
Benthic biota Micro-biota Multi-cellular fauna and flora In order of vulnerability: Echinoderms (most affected), then Crustacea, then Molluscs, then Anelids Lophelia – cold water corals. Similar sensitivity to echinoderms (high)	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 found in muddy and sandy sediments. ▲ Echinoderms most affected because calcified organisms, also poor regulatory capacity ▲ Soft bodied animals most resistant because no calcified structures and good osmo-regulatory capacity. 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. The extent to which the benthic communities are impacted by a discrete CO_2 phase or by CO_2-charged water will depend upon the solubility of the CO_2, which depends in turn on water depth (and hence pressure), water temperature and salinity. Greater water depth, cooler temperatures and lower salinity generally favour greater solubility.

Receptor Class	Potential Impact Mechanisms and Other Notes
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, impacting trophic transfer of resources. Shifts from pelagic calcifiers to diatoms. Calcification is inhibited under high CO2, although short term stress responses can reverse this response. Potential promotion of dinoflagellates. Effects on zooplankton might lead to indirect impacts on phytoplankton. Pelagic effects will not remain localized. 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 Merl beds Mussel beds	Marine organisms that are important not only because they calcify, but also because provide habitats
Localised sensitive populations	Spatial scale of communities – defined by sediment habitat (e.g. whether sandy or muddy a primary control)
Biogeochemical cycles Biogeochemical cycles such as the nitrogen cycle	Nitrogen cycling involves various groups of bacteria. Balance of these microbial groups impacts upon the nitrogen cycle. Several aspects of the nitrogen cycle are sensitive to high CO_2, especially nitrification. Release of CO_2 can change the micro-biota within the sediment, which then impacts upon cycling of other chemicals. An important aspect of this cycling is the breakdown of organic matter that sinks to the seabed through the water column. Sediment type (and rock type) would also influence contaminants that could be mobilised with the CO_2 (e.g. heavy metals, H_2S etc). Impacts on bioturbating organisms would affect the sediment habitat and pelagic-benthic coupling

Participants noted the receptor characteristics and the potential impacts upon them would vary according to:

- Sediment types – Different communities of organisms in different sediment types show different degrees of resistance to elevated CO_2 concentrations. 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 head - The degree to which benthic and sea surface systems are coupled decreases with increasing water depth. Shallower environments will be in the photic[2] zone, whereas the deeper environments will not be in the photic zone. Plants, including seagrass 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 parameter will influence the nature of the organisms that occur and their vulnerability to CO_2 leakage. For example, corals can occur 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 occur 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, for example due to isostasy, 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 to 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 low 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 to the

[2] The photic zone, also called the euphotic or limnetic zone, is the layer of a body of water that is penetrated by sufficient sunlight for photosynthesis.

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. Large amounts of pollution enter the Baltic, which provide additional stresses.

It was also noted that water chemistry may vary annually, reflecting annual hydrogeological cycles. For example, flow of water from the Mediterranean via the Straights of Gibraltar varies through 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. It was noted that variable alkalinity is important only in 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.

A related issue is the quantity of organic matter that runs into the sea from nearby land masses. This quantity is variable and there is a much greater input of organic matter to the Mediterranean Sea, for example, than there is to the Baltic.

4.6 Post-workshop FEP Audit

The preceding sub-sections provide a systematic analysis of the FEPs that are relevant to consider in identifying impact scenarios. The analysis was, by its nature, high-level, with the level of detail being constrained by workshop timescales and other practicalities. Therefore, participants agreed it would be appropriate for the facilitation team to undertake a post-workshop audit of the outcomes against the impact-relevant aspects of the detailed, generic FEP list hosted by Quintessa. In particular, it was agreed that any gaps or uncertainties not addressed by the workshop discussions should be noted and considered within the final impact scenario definitions to be taken forward, and associated discussions on priorities for future RISCS work.

The audit is presented in Appendix C, which includes a table showing how the FEPs from the generic list may be considered to be addressed through the workshop discussions. Key points from the audit include the following.

- ▲ The audit did not identify any significant gaps in the workshop analysis, or any other major issues. The treatment of all major FEPs relevant to impacts was demonstrated to be appropriate.

- One minor gap in the analysis was identified; it was noted that the FEP 'Displacement of saline formation fluids' as a potential mechanism by which there might be impacts to aquifers following a CO_2 leak, e.g. via salination/displacement of water resources, or possibly even water displacement effects up to the top of any formation outcrop; such possibilities were not discussed in detail at the workshop. However, there are arguments to suggest that it is highly unlikely that any leak could lead to an effect on a sufficient scale to lead to a significant impact of this type.

- The FEP audit also identified that at the workshop, it was not directly discussed whether unintended impacts that might be associated with storage as a result of unintended saline water displacement following reservoir pressurisation (i.e. not necessarily as a result of a leak) were within scope. An appropriate clarifying statement has therefore been added in Section 2.

4.7 Impact Scenarios

4.7.1 Process

The key receptor classes, processes that might influence impacts upon them, and variations in receptors and processes across reference environments and associated climate states were mapped to the leakage mechanism / patterns previously defined. The result of this exercise was a range of plausible impact scenarios.

The scenarios identified are not intended to comprehensively represent all the combinations of receptors and processes that could occur, and thereby cover all the potential impacts that could result from CO_2 leakage. Instead, the scenarios together illustrate the key issues and the range of receptor impacts that could occur.

4.7.2 Terrestrial Impact Scenarios

The impact scenarios identified for terrestrial systems by workshop participants, and subject to the subsequent FEP audit, are summarised in Box 8 below. The scenarios representing impacts to ecological receptors apply across the maritime, continental and Mediterranean reference environments, noting the differences in receptor characteristics explored above. The 'release to the urban environment' scenario is specifically relevant to the 'generic urban' reference environment.

Box 8: Impact Scenarios Identified for Terrestrial Systems

Scenario	Notes
Normal Evolution scenario	It is important to recognise that the baseline, by far 'most likely' scenario is for the system to evolve as designed, i.e. consistent with the principles of containment, with no leaks occurring. Indeed, it is important to explore this baseline scenario to understand the level of impacts that could be associated with any leaks in context, as a deviation from the norm.
Alternative Evolution 'Impacts' scenarios	In the above context, 'impact' scenarios therefore represent potential low-likelihood 'alternative evolution' scenarios. These are listed below.
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 direct vicinity of the well. This could present an asphyxiation 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 through canopy effects. Effects would be localised, within a few meters to tens of metres of the breakthrough. 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. Overall workshop participants recognised this as an important scenario to consider, but 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, and participants therefore judged that significant impacts would be unlikely, even if leakage does occur.
Localised release to soil as a result of wells/faults/ fractures, leading to high concentrations of CO_2 in near surface	Participants also recognised a scenario involving localised release of CO_2 to the near-surface, rather than directly to the atmosphere. This release could occur through a well, or through another linear feature such as a fault; the scenarios are essentially equivalent, and were addressed as being so. The primary impacts that could occur through this scenario are plant stress or death as a result of soil acidification or toxicity increases, and/or the direct influence of CO_2 concentrations at the plant root level. 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. It was considered that should sufficient 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 – that impacts to plants, in particular, would be likely to occur, as such a high concentration could be maintained for months or longer. However, some species may be able to adapt and recover within this timescale. It was also noted that some species are more tolerant of soil chemistry changes than others. Participants noted 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 closure, and intersect a sufficiently pressurised zone within the storage complex;

Scenario	Notes
	and/or that natural or induced seismicity processes cause such a feature to be created following injection.
Localised 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. Participants noted that at the lower end of the CO_2 concentration spectrum, effects such as those observed for the Latera greenhouse situation – including positive impacts, like soil fertilisation – provide potentially useful analogues.
Localised release to freshwater lakes via fractures/faults	The main impact associated with this scenario is 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 itself. In addition, acidification could lead to impacts on plant and animal species living within or otherwise dependent on the lake. In discussion however, it was considered that this scenario is 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 sufficient flux to be transported to the lake to lead to substantial acidification. In addition the latter effect would only be likely to occur for a small or very stratified lake, and the impacts would be localised.
Diffuse releases to surface and near-surface systems	This class of scenario was recorded for completeness. However, as recorded in preceding discussions on leakage patterns, (see Section 4.4), diffuse leakages are considered unlikely to occur compared to localised equivalents, and in any case be of lower impact. Therefore, these scenarios were recognised but not discussed further.
Localised release to aquifers that may be exploited as drinking or irrigation water resources	Workshop participants recognised the potential for impacts 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. As noted in Section 4.5.1, there is also the potential for impacts to microbes that might inhabit the aquifer; indeed this principle can be extended to all environments.
Release to the urban environment	Included to consider the likelihood, and potential impacts, of releases to the human urban environment. Impacts could be 'high', in that there is the potential for death of one or more humans as a result of exposure due to sudden ponding of CO_2 in basement structures, but workshop participants considered that it is extremely unlikely that such impacts would occur (see also the discussion on human receptors presented in Section 4.5.1). Other impacts could include those on the urban environment e.g. gardens and other resources. Secondary impacts associated with perception issues and other concerns are not considered here, as they are beyond the scope of the 'technical' analysis of impacts scenarios (again, see the discussion presented in Section 4.5.1).

4.7.3 Marine Impact Scenarios

The impact scenarios identified for marine systems by workshop participants, and subject to the subsequent FEP audit, are summarised in Box 9 below.

Box 9: Impact Scenarios Identified for Marine Systems

Scenario	Notes
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. The group considered it to be essential that the baseline is adequately characterised in order to be able to determine the impact of CO_2 leakage. It was noted that 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.
Alternative Evolution 'Impacts' scenarios	In the above context, 'impact' scenarios therefore represent potential low-likelihood 'alternative evolution' scenarios. These are listed below.
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 (which in turn will depend upon factors such as water depths, wave regimes, tides and currents), water pressure (which depends upon depth), the water temperature and the 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. It was noted that this scenario will need to cover leakages in different time intervals (operation, monitoring, post abandonment etc). However, it was considered that these timescales need to be discussed when defining the context of specific examples, rather than by specifying separate scenarios. Similarly, different temporal variations in leakage need to be considered. For example, leakage could be continuous, with continuously declining flux or with constant flux, or episodic. However these (and other) temporal variations in leakage should be taken into account by variants in this scenario, rather than by defining separate scenarios.
Diffuse direct release of free CO_2 via the sediment or directly	It was noted by the group discussing marine impact scenarios that this scenario is less likely than the other alternative scenarios and there is little evidence from natural analogues that it could occur. However, this scenario cannot be entirely ruled out and

Scenario	Notes
to the water column over a wide area	therefore it is appropriate to consider the implications of this kind of CO_2 leakage should it occur. Diffuse leaks that percolated through the sea floor sediments would likely impact benthic ecosystems and biogeochemistry in a distinct way from impacts from plumes spreading along the bottom water. It was noted that this scenario will need to cover leakages in different time intervals (operation, monitoring, post abandonment etc). However, it was considered that these timescales need to be discussed when defining the context of specific examples, rather than by specifying separate scenarios.
Localised 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 relatively 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 is 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. It was noted that this scenario will need to cover leakages in different time intervals (operation, monitoring, post abandonment etc). However, it was considered that these timescales need to be discussed when defining the context of specific examples, rather than by specifying separate scenarios. Similarly, different temporal variations in leakage need to be considered. For example, leakage could be continuous, with continuously declining flux or with constant flux, or episodic. However these (and other) temporal variations in leakage should be taken into account by variants in this scenario, rather than by defining separate scenarios.
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. It was noted that this scenario will need to cover leakages in different time intervals (operation, monitoring, post abandonment etc). However, it was considered that these timescales need to be discussed when defining the context of specific examples, rather than by specifying separate scenarios.

When defining the scenarios to be taken forward in the project, the group discussing marine impacts also noted the following issues:

- Individual scenarios cannot practicably 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.
- The potential for CO_2 leaks in the far future will depend upon the geology.

4.7.4 Terrestrial and Marine Impact Scenarios Not Recommended for Further Detailed Consideration

Additionally, a number of other scenarios were discussed, but not recommended for further explicit detailed consideration in the project. These scenarios are summarized in Box 10. Scenarios for terrestrial and marine systems are presented together as significant commonalities were observed in the relevant scenario lists.

Box 10: Impact Scenarios for Terrestrial and Marine Systems Not Recommended for Further Detailed Consideration

Displacement of saline formation water due to storage activities (marine environments)	This scenario can be taken into account by considering variants of the scenarios describing '***Localised 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. It was noted that in some cases saline formation water might be produced deliberately during injection operations (as opposed to being released accidentally). Such water would need to be disposed of, potentially leading to impacts. It was noted that there is a need to establish whether it is within the scope of RISCS to consider these impacts. It was noted that water produced from hydrocarbon reservoirs during the exploitation of hydrocarbon resources is often variously re-injected and discharged. Therefore, there is already considerable understanding of the impacts.
Potential for impacts through inadvertent human intrusion (marine environments)	Although the main focus of RISCS concerns consideration of impacts that might be associated with unplanned leakage, it was noted that 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, it was noted that '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.
Potential for impacts through inadvertent human intrusion (terrestrial environments)	Similar arguments apply to terrestrial environments. It is not within the remit of RISCS to consider 'deliberate' intrusions into terrestrial storage systems as 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 already identified.
Sudden releases of free CO_2 due to the 'turn-over' of CO_2-charged seawater (rather like the turn-over that occurred at 'Lake Nyos' in Cameroon, but occurring in a submarine environment rather than a lake) (marine environments)	This scenario was not considered likely. Marine water will mostly be moving across the seabed, thereby preventing sufficient accumulation of CO_2-charged water to cause a 'Lake Nyos'-type release. However, it was noted that there are certain environments where such CO_2-charged water accumulations might occur. For example, within certain fiords, there are deep-water basins within which water circulation is restricted. Therefore, this kind of release scenario cannot be completely excluded. A conclusion was that the group considered this scenario to be worthy of mention and discussion, but to be of sufficiently low likelihood that it should not be analysed explicitly.
Releases related to earthquake / seismic activity (marine environments)	It was recognized that 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 '***Localised 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)	As discussed in Section 4.3 and for the marine environment equivalent above, the importance of tectonic activity was noted, and the potential influence of seismic effects from an impacts perspective considered. Participants considered the influence of tectonic activity in terms of characterisation of the nature and relative likelihood of occurrence of processes such as fault/fracture widening, and is thus addressed by '***Localised release to soil as a result of wells / faults / fractures, leading to high concentrations of CO_2 in near surface', 'Localised release to soils as a result of wells / faults / fractures, leading to long-term low concentrations of CO_2 in near surface', Localised release to freshwater lakes via fractures / faults', 'Diffuse releases to surface and near-surface systems',*** and ***'Localised release to aquifers that may be exploited as drinking or irrigation water resources'*** scenarios.
Induced seismicity caused by CO_2 injection (marine and	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

terrestrial environments)	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 as discussed above. For these reasons, it was agreed that induced seismicity should be mentioned and discussed qualitatively, but not evaluated by means of a specially-developed scenario.
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, it was considered by the discussion group that 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. The discussion group considered that 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; a separate scenario to cover this process is not needed.
Leakage from pipeline ruptures (marine)	There was some doubt about whether this scenario lies within the scope of RISCS. However, it was considered that, from the point of view of impacts, a submarine pipeline rupture would be similar to the 'Localized direct release of free CO_2 to the water column above the sea bed via a point source' scenario (i.e. leaking borehole scenario).

It was also noted that the scenarios in Box 9 will need to be mapped to scenarios that are likely to be of concern to particular groups of stakeholders.

The main processes that affect the impacts considered in each scenario will depend upon the characteristics of the site under consideration. Each kind of site will have a unique combination of the following factors/phenomena affecting dispersion of CO_2:

- salinity (a solubility control);
- temperature (a solubility control);
- water depth (pressure);
- seasonality;
- currents / tides; and
- temperature stratifications;
- benthic / pelagic coupling (reflecting water depth);
- biodiversity (which is much less in low-salinity environment than in fully marine environments); and
- the balance of the main groups of biota, each of which have differing sensitivity to variations in:

- pH
- CO_2
- temperature
- and non-CO_2 chemical stresses (pollutants etc).

5 Issues and Uncertainties

Box 11 presents a list of issues and uncertainties identified as potential priorities for further consideration during participant discussion at the workshop, and as a result of subsequent feedback and analysis.

This list is not considered to be comprehensive; rather it records specific, potentially important aspects of the workshop discussions and analyses that may be relevant to future work streams. An audit of the issues and uncertainties identified against planned RISCS programme activities has been undertaken, and an initial indication of where each issue may best be addressed is provided.

It is suggested that the list could usefully be maintained and developed as the RISCS programme progresses to record new issues, and to track progress as work undertaken helps to characterise uncertainties.

Box 11: Issues and Uncertainties

Issue or Uncertainty	Notes
Context/Scope Related Issues	
Terminology - general	It was emphasised at the workshop that it is important to reach consensus on terminology as quickly as possible, and then to utilise the relevant definitions consistently. The outcomes of discussions on 'technical' terms relevant to WP1 are recorded in Box 1. There will need to be a 'terminology freeze' which records and freezes RISCS decisions on terminology within the first few months of the project. This also applies to definitions that are relevant to other workpackages, or more generally to CCS, but which are not included in the Box 1 list. *Relevant RISCS WP: WP1 to co-ordinate discussion on terms relevant to scenarios, and to suggest a 'frozen' set of definitions by Month 9. Other workpackages to similarly consider how to gain consensus on definitions, in particular WP5. Ultimately, the RISCS project managers may need to make a decision upon any terminology issues for which consensus is not reached.*
Terminology – use of specific terms	The terminology discussion highlighted that the terms/definitions used need to be optimised in order to support RISCS work. For example, terms like geosphere / biosphere are widely used in CCS and other areas, but are not particularly helpful here. The terminology used in RISCS should be optimised to relate to concepts that are directly relevant to the programme. *Relevant RISCS WP: As above*
Value judgements on receptor types	As noted in Section 4.5.1, a wide range of receptor classes could be envisaged to be relevant to RISCS (different plant species, different animal species, resource types etc), and only a subset of these receptor types can be the subject of RISCS research. It could be useful for the RISCS project to agree a clear statement on which receptors shall be prioritised and why. Any 'value judgements' involved could be tested with regulators or other bodies). There are parallels here with the USEPA's VEF approach: which receptors are the most vulnerable / most important to address? *Relevant RISCS WP: Possibly best to address this within WP5.*

Issue or Uncertainty	Notes
Unintended displacement of saline water bodies without CO_2 leakage	Pressurisation of the storage complex could lead to unintended displacement of fluids with the potential for subsequent interactions between saline waters and sensitive domains (e.g. aquifers, or surface effects following interactions with well-bores), even if a CO_2 leak does not occur. It was suggested that while such impacts are out of the scope of RISCS as presently defined, it may be worthwhile reviewing whether this potentially important impacts-related issue should be considered further. *Relevant RISCS WP: WP6 – BGS Project Management team accepted action to make a decision on the approach to be taken.*
Pipeline leaks	Workshop discussions focussed on the possibility of impacts following leakage of CO_2 from storage systems, rather than leaks that might arise from operational issues, as operational issues were generally treated as out of scope. However, point-source leaks from wells etc may be very similar to the types of leaks that could occur from pipelines. It was suggested that while such leaks are primarily out of the scope of RISCS, it may be worth acknowledging the similarities in relevant discussions. *Relevant RISCS WP: WP6 – BGS Project Management team accepted action to make a decision on the approach to be taken.*
Timescales	It was agreed that it is important to bear in mind the influence of different timescales on leak scenarios and their mitigation. The 'monitoring' phase, for example, allows the possibility for mitigating actions to be factored in to estimation of impacts. Also, the data obtained during the monitoring phase will help the site-specific characterisation of the likelihood / magnitude of impacts during that phase, and in particular should help build confidence that impacts will be of low likelihood / consequence post-monitoring (see the updated timescale-related term definitions in Box 1). *Relevant RISCS WP: All*
Reference Environment Related Issues	
Reference environments, and their use to prioritise work	A range of reference environment classes are reported in Box 3. Note that 'extreme' (arid/cold) environments are not represented. The rationale here is that it is unlikely that a European storage project would be implemented in locations with these extreme conditions. Participants expressed the view that this principle should be carried forward for other work; the reference environments are necessarily generic, but research for RISCS should focus on system types within those broad environment classes that could reasonably be expected to be exploited for CO_2 storage, rather than applying an overly simplified broad-brush approach to prioritisation. *Relevant RISCS WP: All*
Site-specific issues	The main variations between reference environments relate to differences in climate, water temperature and depth, etc. However, many issues can only be characterised on a site-specific basis. Therefore, if it is considered important that relevant studies (e.g. those associated with aquifer resource quality degradation, or studies considering impacts to plants that are highly dependent on soil types) progress beyond very high-level generic research. There may be a need to define and analyse a range of representative sites to illustrate issues that may be important to consider in any future site-specific assessment. *Relevant RISCS WP: WP2, 3, 4*
Leakage Mechanism/Pattern Related Issues	
Localised (point-source) vs. diffuse releases	The terrestrial environment group suggested that localised releases are much more likely than diffuse releases (should any leakage occur); the marine environment group qualified their assessment by stating that the present evidence suggests that localised releases are more likely, but that diffuse releases could still be more important than has typically been recognised to date, in particular for marine environments. The general principle was established that impact scenarios and associated calculations should consider localised releases

Issue or Uncertainty	Notes
	first, and then consider if anything would change if a diffuse release could instead occur. To firm up statements on the relative likelihood of localised vs. diffuse releases, and to explore different potential release mechanisms to confirm statements on relative likelihood, it may be useful to produce a specific (short) paper on this topic. *Relevant RISCS WP: WP1, in particular through planned SINTEF contributions, supported by WP2 and 3 work.*
Receptor Related Issues	
General uncertainties associated with estimating impacts	A consistent message from all discussions on receptors and impacts to them was that the sensitivities / thresholds associated with the potential for CO_2 impacts to receptors are generally uncertain (hence, the need for the RISCS programme in the first place). A few specific uncertainties were noted (see below). However, in general each WP will need to consider how to identify and prioritise the key issues for investigation. This may be best informed by cross-project judgements on which receptor classes to prioritise (see the 'value judgements on receptor types' entry above). *Relevant RISCS WP: WP2, 3 and 4.*
General uncertainties associated with estimating impacts – balance of positive and negative impacts to determine the overall impact on an ecosystem	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 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. *Relevant RISCS WP: WP2, 3 and 4.*
Specific uncertainties noted – impacts to plants	Currently, only a few terrestrial plant types (e.g. 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 types. This underlines the importance of WP3. Similar issues apply to sub-surface microbiota, and more broadly to the marine system, also. It was noted that a key issue in modelling effects on terrestrial plants to determine whether it is the canopy or root concentrations that matter in different situations. *Relevant RISCS WP: WP2, 3 and 4.*
Specific uncertainties noted – effect of CO_2 on biodiversity in the marine environment	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. 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. *Relevant RISCS WP: WP2, 3 and 4.*
Specific uncertainties noted – whether or not marine ecosystems with low biodiversity are more vulnerable to CO_2 than more diverse ecosystems	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. *Relevant RISCS WP: WP2, 3 and 4.*
Specific uncertainties noted – impacts of CO_2 in combination with other stresses in the	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. The discussions also highlighted that additives to stored CO_2 may be allowed by

Issue or Uncertainty	Notes
marine environment	regulators if the additives are a necessary part of the operations (e.g. to prevent corrosion). However, it is not permissible to add constituents to the CO_2 stream in order to store them with the CO_2. It was noted that the focus of RISCS experiments will be to understand the effects of CO_2 rather than additives / associated impurities, but the effects of other stresses (e.g. pollutants) that may be present irrespective of whether CO_2 is stored, also need to be taken into account. *Relevant RISCS WP: WP2, 3 and 4.*
Specific uncertainties noted – effect of elevated CO_2 on calcifying organisms	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 cannot 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. *Relevant RISCS WP: WP2, 3 and 4.*
'Secondary' impacts to humans	In discussions on impacts to humans (as outlined in Box 4) it was agreed that WP1 should focus on 'technical' analysis of impacts due to physical effects, e.g. asphyxiation / blood acidification. It was recognised, however, that the most important impact on human populations could relate to lack of knowledge of CCS, and fear of potential impacts (and thus impact on house prices, etc). This would perhaps be best addressed by suitable stakeholder engagement during siting studies and associated planning (and making sure storage systems are sited away from major human population centres etc). In addition, the availability of accessible and authoritative information on impacts would also help mitigate fears. These issues reinforce the need for the Guide to be produced by WP5, and should be recognised in the WP5 work in general. *Relevant RISCS WP: WP5*
Scenario Related Issues	
Comparison with base case / normal evolution 'no leak' scenario	An important point recognised by workshop participants, but not discussed in depth in the plenary sessions, was that 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. These and other processes that are relevant 'framing' arguments that are relevant to exploring the potential site-specific impacts of leakage would benefit from consideration in relevant workpackages, and communication in context through WP5. *Relevant RISCS WP: All*
Communication of scenario likelihoods and consequences	The importance of reporting scenario likelihoods and consequences in context was emphasised at various points. The likelihood of leakage occurring from a storage site is a site-specific issue, but given the primary need for an operator to demonstrate confidence in containment, the risk of leakage will (should) always be very low. Given 'impact' scenarios defined are fundamentally unlikely to

Issue or Uncertainty	Notes
	occur, the discussion on relative likelihoods / consequences of different types of impact scenarios serve to further explore and characterise issues given this basic context. *Relevant RISCS WP: All, but in particular WP1 and WP5.*

6 Next Steps

The following next steps are proposed for work to be undertaken under WP1.

- ▲ It is intended that the information reported in this document will be used to directly inform work to be undertaken through WP4.
- ▲ Consideration will be given to whether any updates should be made to the Quintessa on-line FEP database. The outputs will also provide input to SINTEF's proposed WP1 work on characterising leakage scenarios.
- ▲ The agreed outcomes of the scenario analysis will then be utilised to support presentations at appropriate conferences and other dissemination activities designed to gain feedback from the wider CCS community, including the production of a report on this topic for external distribution beyond the RISCS community.

More broadly, it is anticipated that the work reported in this document, and in particular the scenarios outlined in Boxes 8 and 9 and the issues and uncertainties identified in Box 11 will be utilised across the RISCS programme to aid workpackage-specific planning.

Specifically, it is suggested that it may be beneficial for the list of issues and uncertainties currently contained in Box 7 to be maintained and updated as work progresses. This may be best undertaken under WP5.

References

Det Norske Veritas (DNV), 2009. CO2QUALSTORE: Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO_2. DNV Report 2009-1425, Revision 5.

European Parliament and Council of the European Union (EC), 2009. Directive 2009/31/EC of the EC of 23 April 2009 on the Geological Storage of Carbon Dioxide.

IPCC, 2005. IPCC Special Report: Carbon Dioxide Capture and Storage. Summary for Policy Makers and Technical Summary. Cambridge University Press, New York.

OSPAR, 2007. OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations. OSPAR Convention for the Protection of the Marine Environment of the North-east Atlantic, reference number 2007-12.

Quintessa, 2010. Online FEP Database.
http://www.quintessa.org/co2fepdb/PHP/frames.php

RISCS, 2009. Description of Work. Annex 1 of the Seventh Framework Programme Grant Agreement for RISCS, Grant Agreement number 240837.

United States Environmental Protection Agency (USEPA), 2008. Vulnerability Evaluation Framework for Geologic Sequestration of Carbon Dioxide. U.S. Environmental Protection Agency Report, EPA430-R-08-009.

Appendix A: Agenda

Day 1: Tuesday 4th May 2010

The main objective for Tuesday's session was to discuss and agree fundamental issues relevant to the RISCS project, and thereafter to discuss specific contextual and terminology issues relevant to, and the detailed process for, the impact scenarios analysis.

1230 hrs: *Arrivals, lunch.*

1330: Welcome, introductions (BGS / OGS).

1345: Brief workshop overview (i.e. discussion of Agenda). Overview of proposed aims and objectives (Q).

1400: Discussion on what is meant by 'impacts': Introducing the process for integrating multidisciplinary perspectives (SV)

1415: What is meant by 'impacts': focusing together concepts and issues expressed in the questionnaire (led by SV)

1530: *Coffee.*

1545: Discussion of contextual issues particularly relevant to 'scenarios' process. Agree formal definitions of key terminology issues, aims and objectives required for the process (all, led by Q, supported by SV).

1740: Agree Agenda for next two days (all, led by Q).

1745: *Close.*

Day 2: Wednesday 5th May 2010

The second day focussed on the man scenario analysis.

0830 hrs: *Arrivals, coffee*

0845: Agenda and process for the day (Q, with contributions from all).

0855: Derive and agree reference environments (all, led by Q).

1015: *Coffee*

Participants split into separate 'marine' and 'terrestrial' groups.

1030: Systematic consideration of potential leakage mechanisms/scenarios considering types of subsurface processes that could lead to impacts to receptors (all, facilitated by Q). *Elicit very high level 'FEP group' representations relevant to potential leakage mechanisms that could apply across marine / terrestrial types of environment. Agree a range of statements describing a representative range of leakage scenario types. To include subsurface processes in general, rather than focussing on releases from the storage complex only.*

1145: Identification of features and processes associated with receptors and the media they interact with, mapped against reference environments.

1215: Lunch

1315: Continue identification of features and processes associated with receptors and the media they interact with (all, facilitated by Q).

1345: Review pre-prepared EFEP list to identify 'external' scenario generating FEPs (all, led by Q).

1415: Identify central ('normal') evolution impact scenario descriptions for the reference environments (all, led by Q).

1515: Coffee

1545: Identify other important ('alternative') evolution impact scenario descriptions for the reference environments (all, led by Q).

1700: Review outcomes including identification of the important issues to consider in evaluating scenarios, including the treatment of uncertainty (all, led by Q).

1730: Summary and close.

Day 3: Thursday 6th May 2010

The third day will present and agree scenario descriptions, test for consistency, and agree outcomes and next steps. *Participants will reassemble as one group for Day 3.*

0830 hrs: Arrivals, coffee

0845: Review outcomes from both groups. Agree final list of impact scenarios, issues and uncertainties (all, led by Q).

1000: *Coffee*

1015: Group discussion on process outcomes, next steps etc (all, led by Q).

The remainder of Day 3 will then focus on gaining views relevant to communication issues, informed (in part) by the 'scenarios' discussions.

1100: Discussion on 'Guide' contents as informed by process. Elicit a list of principles relevant to approach to guide development (all, led by JP/SV).

1215: *Lunch*

1300: Presentation and discussion on communication guidelines for interacting with the media

1330: Group discussion on a common approach to communication strategies.

1415: Agree next steps.

1430: Summary and thanks (BGS/Q/SV).

Appendix B: List of Participants

WP1 Workshop participants:

Dave Jones, Jonathan Pearce, Julia West (BGS)

Nils-Otto Kitterød (Bioforsk)

Fontini Ziogou, Vassiliki Gemeni, Nikolaos Koukouzas (CERTH)

Matthew Baggaley, Tim Hill (EON)

Ameena Camps (IAEAGHG)

Guido Crispi, Massimo Pacciaroni, Sergio Persoglia (OGS)

Steve Widdicombe, Jeremy Blackford (PML)

Salvatore Lombardi, Samuela Vercelli (Sapienza University of Rome)

Edwin Foekema (IMARES)

Alv-Arne Grimstad (SINTEF)

Michael Steven (University of Nottingham)

Sara McGowan (Vattenfall)

Camilla Svendsenskrung, Marius Gjerset (ZERO)

Facilitation team:

Alan Paulley, Richard Metcalfe, Philip Maul, Michael Egan, Laura Limer (Quintessa)

Appendix C: FEP Audit

The Table summarises the workshop discussions mapped against the generic FEP list available online at:

http://www.quintessa.org/co2fepdb/PHP/frames.php

Note that this table serves as an audit to ensure that no potentially important topics were omitted from the workshop discussions, or not discussed in enough detail. It does not directly show whether / how each FEP is treated by the impact scenarios defined but the references provided indicate where in the main report text relevant information may be found.

Next to each FEP that was discussed **explicitly** at the workshop, an '**E**' is entered in the second column of Table C1. In these cases, there is corresponding explanatory text in the main report. Where a FEP was not discussed explicitly at the workshop, but the explicit discussions of other FEPs adequately covered its implications for impacts, then the FEP is deemed to have been covered **implicitly** and an '**I**' is entered in the second column. In these cases, there is no corresponding text in the main report. Where the FEP is entirely out of the scope of the RISCS programme, '**N/A**' is entered in this column. Where **additional detail** is required to address a FEP, '**AD**' is entered, and the additional notes record an appropriate discussion.

Table C1: Audit of Workshop Outcomes against the Generic FEP Database

'Generic' FEP	How Addressed	Additional notes
0 Assessment Basis		
0.1 Purpose of the assessment	**E**	See Sections 2 and 3.
0.2 Endpoints of interest	**E**	See Sections 2 and 3.
0.3 Spatial domain of interest	**E**	See Sections 2 and 3.
0.4 Timescales of interest	**E**	See Sections 2 and 3.
0.5 Storage assumptions	**E**	See Sections 2 and 3.
0.6 Future human action assumptions	**E**	See Sections 2, 3 and Sections 4.4 and 4.5. In the case of the terrestrial scenarios, future human actions are only considered in terms of variations to land / resource uses that have an influence on the domains that contain CO_2 or that can be considered to be receptors. In the marine scenarios, the effects of future human actions can be encompassed by variants of the proposed leakage

		scenarios in Box 8.
0.7 Legal and regulatory framework	**E**	See Sections 2 and 3.
0.8 Model and data issues	**E**	See Sections 2 and 5. For many of the impact scenarios considered, site-specific data will be key. Additionally, it is a key justification for the RISCS programme that presently there are important knowledge and data gaps and thus uncertainties associated with the response of receptors to CO_2 (e.g. plants other than those studied to date).
1 External Factors		
1.1 Geological factors		
1.1.1 Neotectonics	**I**	The term 'neotectonics' was not considered explicitly, but all major the aspects of 'neotectonics' were discussed explicitly - see Sections 4 and 5, also FEPs 1.1.2, 1.1.3, 3.27 below. Tectonics, volcanic activity, seismicity, uplift etc are relevant in terms of the potential to open up fractures/faults that could provide conduits for leaks (see below also). These processes are also important because they can alter significantly the nature of the environment impacted by CO_2 leakage and the ecosystems therein. For example, small degrees of uplift around the Baltic could change a marine environment into a terrestrial one.
1.1.2 Volcanic and magmatic activity	**E**	As for 1.1.1.
1.1.3 Seismicity	**E**	As for 1.1.1.
1.1.4 Hydrothermal activity	**I**	Discussions by the group considering marine impacts considered hydrothermal activity together with volcanic and magmatic activity (FEP 1.1.2). Hydrothermal activity is relevant to establishing containment (outside the scope of RISCS) and describing the 'normal evolution' scenario (See Section 5). Were hydrothermal activity to occur in an area, it could stress ecosystems independently of CO_2 leakage and thereby influence the way in which CO_2 impacts the ecosystem. These kinds of impacts were considered implicitly by discussing the impacts of pollutants and other contaminants and impurities besides CO_2 (Sections 4.5 and 5). Some impacts were also considered by the group concerned with marine impacts when discussing thermal shock due to CO_2 leakage.
1.1.5 Hydrological and hydrogeological response to geological changes	**I**	Relevant to describing all 'normal' and 'alternative' evolution scenarios; otherwise not of direct interest to this study (See Section 5).
1.1.6 Large scale erosion	**E**	The aspects of large-scale erosion that impact upon containment are outside the scope of RISCS. However, large-scale erosion could cause temporal variations in environments and hence receptors, both onshore and offshore. For example, large scale erosion could result in the removal of marine sediments and their

		associated ecosystems (Section 4.5.2).
1.1.7 Bolide impact	**N/A**	Outside the scope of RISCS (primarily relevant to containment).
1.2 Climatic factors		
1.2.1 Global climate change	**E**	Climatic factors are relevant to considering variations in impact scenarios across different reference environments; see Sections 4.3, 4.5 and .
1.2.2 Regional and local climate change	**E**	As for 1.2.1.
1.2.3 Sea level change	**E**	As for 1.2.1.
1.2.4 Periglacial effects	**E**	As for 1.2.1. *Note: this FEP was discussed only by the participants considering terrestrial impacts and not by the group considering marine impacts, or in plenary session.*
1.2.5 Glacial and ice sheet effects	**E**	As for 1.2.1.
1.2.6 Warm climate effects	**E**	As for 1.2.1. *Note: this FEP was discussed only by the participants considering terrestrial impacts and not by the group considering marine impacts, or in plenary session.*
1.2.7 Hydrological and hydrogeological response to climate change	**E**	As for 1.2.1. *Note: this FEP was discussed only by the participants considering terrestrial impacts and not by the group considering marine impacts, or in plenary session.*
1.2.8 Responses to climate change	**E**	As for 1.2.1. *Note: this FEP was discussed only by the participants considering terrestrial impacts and not by the group considering marine impacts, or in plenary session.*
1.3 Future human actions		
1.3.1 Human influences on climate	**E**	As for 1.2.1. *Note: this FEP was discussed only by the participants considering terrestrial impacts and not by the group considering marine impacts, or in plenary session.*
1.3.2 Motivation and knowledge issues	**N/A**	Out of the scope of RISCS (relates to post-operational management and the potential for institutional control, as opposed to consideration of potential impacts to ecological receptors)
1.3.3 Social and institutional developments	**N/A**	Out of the scope of RISCS (relates to post-operational management and the potential for institutional control, as opposed to consideration of potential impacts to ecological receptors)
1.3.4 Technological developments	**N/A**	Out of the scope of RISCS (relates to post-operational management and the potential for institutional control, as opposed to consideration of potential impacts to ecological receptors)
1.3.5 Drilling activities	**N/A**	Out of the scope of RISCS (relates to the potential for human

		intrusion, as opposed to consideration of potential impacts to ecological receptors)
1.3.6 Mining and other underground activities	**N/A**	Out of the scope of RISCS (relates to the potential for human intrusion, as opposed to consideration of potential impacts to ecological receptors)
1.3.7 Human activities in the surface environment	**E**	Impacts associated with the 'generic urban' environment require an appreciation of surface and near-surface urban structures; other terrestrial reference environments reflect human land uses such as agriculture (see Sections 4.3, 4.5 and □). Participants considering marine impacts discussed only pipeline leakage; in this case 'surface environment' was taken to mean the seabed (see Section 4.7.3).
1.3.8 Water management	**E**	The impact scenarios identified consider the use of water resources for drinking water and irrigation (see Sections 4.5 and □).
1.3.9 CO_2 presence influencing future operations	**N/A**	Out of the scope of RISCS (relates to post-operational management and the potential for institutional control, as opposed to consideration of potential impacts to ecological receptors)
1.3.10 Explosions and crashes	**N/A**	Out of the scope of RISCS (operational rather than environmental impact issue).
2 CO_2 Storage		
2.1 Pre-closure		
2.1.1 Storage concept	**N/A**	Outside the scope of RISCS (primarily relevant to containment).
2.1.2 CO_2 quantities, injection rate	**N/A**	Outside the scope of RISCS (primarily relevant to containment).
2.1.3 CO_2 composition	**I**	Relevant to assessing impacts as impurities might have a particular impact on receptors (see Sections 4 and 5).
2.1.4 Microbiological contamination	**I**	As for 2.1.3.
2.1.5 Schedule and planning	**E**	As discussed in Section 3.3, the different timescales within which impacts might occur are relevant; for example, impacts during the monitoring period can be detected, allowing the potential for mitigation (see Sections 3.3, 4.4.1, 4.7.2, 4.7.3 and 5).
2.1.6 Pre-closure administrative control	**I**	Covered by 2.1.5.
2.1.7 Pre-closure monitoring of storage	**I**	Covered by 2.1.5.
2.1.8 Quality control	**I**	Relevant to composition, risk of unknown faults/fractures etc.

2.1.9 Accidents and unplanned events	**E**	Operational accidents are out of scope; unplanned events such as fault widening as a result of operations are addressed by the scenarios presented in Section .
2.1.10 Overpressuring	**I**	Covered by 2.1.9.
2.2 Post-closure		
2.2.1 Post-closure administrative control	**I**	Covered by 2.1.5.
2.2.2 Post-closure monitoring of storage	**I**	Covered by 2.1.5.
2.2.3 Records and markers	**N/A**	Relevant to human intrusion / containment rather than impacts to the environment as a result of leakage.
2.2.4 Reversibility	**N/A**	Not relevant to RISCS.
2.2.5 Remedial actions	**I**	Covered by 2.1.5.
3 CO_2 Properties, Interactions & Transport		
3.1 CO_2 properties		
3.1.1 Physical properties of CO_2	**E**	Relevant to consideration of the potential nature of any leaks, as considered in the discussion of leakage mechanisms / patterns described in Section 4.4 and the development or otherwise of dense CO_2-charged water plumes, as described in Sections 4.4.2 and 4.7.3.
3.1.2 CO_2 phase behaviour	**E**	As for 3.1.1.
3.1.3 CO_2 solubility and aqueous speciation	**E**	As for 3.1.1, but in addition directly relevant to consideration of potential impacts to water resources such as aquifers and freshwater lakes, and to the degree to which calcifying organisms are impacted (Sections 4.4.2, 4.5.2 and 5).
3.2 CO_2 interactions		
3.2.1 Effects of pressurisation of reservoir on cap rock	**I**	Not directly in the scope of RISCS, but relevant to the discussion of leakage mechanisms / patterns described in Section 4.4.
3.2.2 Effects of pressurisation on reservoir fluids	**E**	Similar to 3.2.1, but explicitly considered in the nature and form of leaks from point sources.
3.2.3 Interaction with hydrocarbons	**I**	Considered by the participants who discussed marine impacts in the context of organic impurities within the leaking stream of CO_2 or CO_2-charged water (Section 4.4.2).
3.2.4 Displacement of saline formation fluids	**E, AD**	The participants considering marine impacts discussed the displacement of saline formation waters and the possible impacts on marine ecosystems should such waters leak into sediments / rocks immediately beneath the seabed (Section 4.4.2). However, it was concluded that probably impacts from this kind of leakage would be small.

		Displacement of saline formation fluids *into* aquifers associated with water resources etc is a potential impact mechanism that requires to be noted. This was not directly discussed by participants in the workshop. However it is highly unlikely that any leak could lead to an effect on a sufficient scale to lead to a significant impact of this type.
3.2.5 Mechanical processes and conditions	**I**	Relevant to consideration of fault widening and other mechanical effects that could increase the potential for point source leaks.
3.2.6 Induced seismicity	**E**	Explicitly recognised in terms of the potential for fault widening etc, as discussed in Sections 4.4and □.
3.2.7 Subsidence or uplift	**I**	Relevant to statements on the 'normal evolution' conceptual model and tangentially relevant to consideration of fault widening etc.
3.2.8 Thermal effects on the injection point	**N/A**	An operational issue outside the scope of RISCS.
3.2.9 Water chemistry	**E**	As for 3.1.3.
3.2.10 Interaction of CO_2 with chemical barriers	**I**	Relevant to consideration of the potential forms of different leakage patterns, but otherwise outside the scope of RISCS.
3.2.11 Sorption and desorption of CO_2	**I**	Relevant to consideration of the potential forms of different leakage patterns.
3.2.12 Heavy metal release	**E**	As for 3.1.3
3.2.13 Mineral phase		
3.2.13.1 Mineral dissolution and precipitation	**E**	As for 3.1.3.
3.2.13.2 Ion exchange	**I**	As for 3.1.3.
3.2.13.3 Desiccation of clay	**N/A**	Not directly relevant to the scope of RISCS.
3.2.14 Gas chemistry	**I**	Only relevant in terms of the discussions expressed under 3.1.3.
3.2.15 Gas stripping	**I**	As for 3.2.14
3.2.16 Gas hydrates	**I**	As for 3.2.14
3.2.17 Biogeochemistry	**E**	Particularly relevant to consideration of potential impacts to aquatic organisms, resources such as aquifers and freshwater lakes, localised sensitive populations and earth system cycles (Sections 4.4.2, 4.5.1 and 4.5.2).
3.2.18 Microbial processes	**E**	Particularly relevant to consideration of potential impacts to aquatic organisms, resources such as aquifers and freshwater lakes, localised sensitive populations and earth system cycles Impacts to microbes also of relevance directly. (Sections 4.4.2, 4.5.1, 4.5.2 and 4.7).

3.2.19 Biomass uptake of CO_2	**E**	Relevant in terms of the process and its implications for wider biogeochemistry, and also for impacts to organisms that are part of the biomass.
3.3 CO2 transport		
3.3.1 Advection of free CO_2		
3.3.1.1 Fault valving	**E**	Explicitly considered through point-source release scenarios, see e.g. Sections 4.4 and □.
3.3.2 Buoyancy-driven flow	**E**	Considered implicitly by the participants who discussed terrestrial impacts through general discussions on leak mechanisms / discussions. Considered explicitly by the participants who discussed marine impacts in connection with dissolution of leaking CO_2 in water and the circumstances under which free CO_2 or CO_2-charged water would exit from the seabed (Sections 4.4.2 and 4.7.3).
3.3.3 Displacement of formation fluids	**E**	Considered through general discussions on leak mechanisms / discussions, but explicitly noted in the text (Section 4.4.2).
3.3.4 Dissolution in formation fluids	**E**	Considered implicitly by the participants who discussed terrestrial impacts through general discussions on leak mechanisms / discussions. Considered explicitly by the participants who discussed marine impacts in connection with dissolution of leaking CO_2 in water and the circumstances under which free CO_2 or CO_2-charged water would exit from the seabed (Sections 4.4.2 and 4.7.3).
3.3.5 Water mediated transport	**E**	Considered implicitly by the participants who discussed terrestrial impacts through general discussions on leak mechanisms / discussions. Considered explicitly by the participants who discussed marine impacts in connection with dissolution of leaking CO_2 in water and the circumstances under which free CO_2 or CO_2-charged water would exit from the seabed (Sections 4.4.2 and 4.7.3).
3.3.6 CO_2 release processes		
3.3.6.1 Limnic eruption	**E**	The potential for releases to lakes is described in Section 4.7.2. The possibility for such releases to occur from seawater is considered in Section 4.7.3.
3.3.7 Co-migration of other gases	**E**	Explicitly considered in terms of the potential for impacts due to impurities in the stored gas (Sections 4.4.2, 4.5.2 and 5).
4 Geosphere		
4.1 Geology		
4.1.1 Geographical location	**I**	Site-specific, but some aspects of geography that apply across a climate zone are recognised in the Reference Environment descriptions (Section 4.3).

4.1.2 Natural resources	**I**	As for 4.1.1. Particularly relevant to exploring receptors of interest. Also covered implicitly when discussing human intrusion in the marine environment (Section 4.7.3).
4.1.3 Reservoir type	**N/A**	Out of scope. RISCS is focussed on impacts if a leak should occur, not a detailed exploration of the containment complex.
4.1.4 Reservoir geometry	**N/A**	Out of scope. RISCS is focussed on impacts if a leak should occur, not a detailed exploration of the containment complex.
4.1.5 Reservoir exploitation	**N/A**	Out of scope. RISCS is focussed on impacts if a leak should occur, not a detailed exploration of the containment complex.
4.1.6 Cap rock or sealing formation	**I**	The implications of caprock on different leakage mechanisms / patterns are relevant to RISCS (Section 4.4).
4.1.7 Additional seals	**I**	The implications of secondary caprocks on different leakage mechanisms / patterns are relevant to RISCS (Section 4.4).
4.1.8 Lithology		
4.1.8.1 Lithification/diagenesis	**I**	All properties of the lithology are subsumed within discussions of different potential leakage mechanisms / patterns.
4.1.8.2 Pore architecture	**I**	All properties of the lithology are subsumed within discussions of different potential leakage mechanisms / patterns.
4.1.9 Unconformities	**I**	All properties of the lithology are subsumed within discussions of different potential leakage mechanisms / patterns.
4.1.10 Heterogeneities	**I**	All properties of the lithology are subsumed within discussions of different potential leakage mechanisms / patterns.
4.1.11 Fractures and faults	**E**	Faults and fractures are explicitly recognised throughout the analysis as providing potentially important pathways that could lead to point-source releases if leakage does occur (Sections 4.4 and 4.7).
4.1.12 Undetected features	**I**	Subsumed within discussions of different potential leakage mechanisms / patterns, noting that if any undetected features could provide a conduit to a fault/fracture and that this could increase the likelihood of such releases.
4.1.13 Vertical geothermal gradient	**I**	All properties of the lithology are subsumed within discussions of different potential leakage mechanisms / patterns.
4.1.14 Formation pressure	**I**	All properties of the lithology are subsumed within discussions of different potential leakage mechanisms / patterns.
4.1.15 Stress and mechanical properties	**I**	All properties of the lithology are subsumed within discussions of different potential leakage mechanisms / patterns.
4.1.16 Petrophysical properties	**I**	All properties of the lithology are subsumed within discussions of different potential leakage mechanisms / patterns.

4.2 Fluids		
4.2.1 Fluid properties	**E**	A subset of fluid properties is particularly relevant to describing receptors such as aquifers. These properties were discussed by the participants who considered marine impacts when considering dissolution of CO_2 in water (Sections 4.4.2 and 4.7.3).
4.2.2 Hydrogeology	**I**	Essentially covered by broader discussions on receptor characteristics and leakage mechanisms / patterns.
4.2.3 Hydrocarbons	**N/A**	Impacts to hydrocarbon resources, and processes associated with interactions with hydrocarbon features, are beyond the scope of RISCS.
5 Boreholes		
5.1 Drilling and completion		
5.1.1 Formation damage	**I**	Relevant to considering the likelihood of diffuse rather than point-source releases.
5.1.2 Well lining and completion	**I**	Recognised throughout discussions of point-source/localised leakage mechanisms and associated scenarios.
5.1.3 Workover	**I**	As for 5.1.2.
5.1.4 Monitoring wells	**I**	As for 5.1.2.
5.1.5 Well records	**I**	As for 5.1.2. Helps inform upon the likelihood of monitoring / swift response in the case of any leakage.
5.2 Borehole seals and abandonment		
5.2.1 Closure and sealing of boreholes	**E**	As for 5.1.2.
5.2.2 Seal failure	**E**	As for 5.1.2.
5.2.3 Blowouts	**E**	As for 5.1.2.
5.2.4 Orphan wells	**I**	As for 5.1.2.
5.2.5 Soil creep around boreholes	**I**	As for 5.1.1 and 5.1.2.
6 Near-Surface Environment		
6.1 Terrestrial environment		
6.1.1 Topography and morphology	**I**	Site-specific and thus subsumed within the general description of reference environments (Section 4.7.2).
6.1.2 Soils and sediments	**I**	Site-specific and thus subsumed within the general description of reference environments (Section 4.7.2).
6.1.3 Erosion and deposition	**I**	Site-specific and thus subsumed within the general description of

		reference environments (Section 4.7.2).
6.1.4 Atmosphere and meteorology	**E**	Central to the definition of certain reference environments, but details are site-specific (Section 4.7.2).
6.1.5 Hydrological regime and water balance	**I**	Site-specific and thus subsumed within the general description of reference environments (Section 4.7.2).
6.1.6 Near-surface aquifers and surface water bodies	**E**	Explicitly recognised within descriptions of receptors and impact scenarios, although details are site-specific (Section 4.7.2).
6.1.7 Terrestrial flora and fauna	**E**	Explicitly recognised within descriptions of receptors and impact scenarios, although details are site-specific (Section 4.7.2).
6.1.8 Terrestrial ecological systems	**E**	Explicitly recognised within descriptions of receptors and impact scenarios, although details are site-specific (Section 4.7.2).
6.2 Marine environment		
6.2.1 Coastal features	**I**	Implicitly recognised within descriptions of receptors and impact scenarios, although details are site-specific (Section 4.7.3). Coastal features were considered only indirectly, when discussing inputs of water from land to the oceans, variations in water depth, variations in ocean circulation and variations in sediment type.
6.2.2 Local oceanography	**E**	Explicitly recognised within descriptions of receptors and impact scenarios, although details are site-specific (Section 4.7.3).
6.2.3 Marine sediments	**E**	Explicitly recognised within descriptions of receptors and impact scenarios, although details are site-specific (Section 4.7.3).
6.2.4 Marine flora and fauna	**E**	Explicitly recognised within descriptions of receptors and impact scenarios, although details are site-specific (Section 4.7.3).
6.2.5 Marine ecological systems	**E**	Explicitly recognised within descriptions of receptors and impact scenarios, although details are site-specific (Section 4.7.3).
6.3 Human behaviour		
6.3.1 Human characteristics	**E**	Explicitly recognised within descriptions of terrestrial receptors and impact scenarios, although details are site-specific (Section 4.7.2)
6.3.2 Diet and food processing	**E**	Explicitly recognised within descriptions of terrestrial receptors and impact scenarios, although details are site-specific (Section 4.7.2).
6.3.3 Lifestyles	**E**	Explicitly recognised within descriptions of terrestrial receptors and impact scenarios, although details are site-specific (Section 4.7.2).
6.3.4 Land and water use	**E**	Explicitly recognised within descriptions of terrestrial receptors and impact scenarios, although details are site-specific (Section 4.7.2).

6.3.5 Community characteristics	**E**	Explicitly recognised within descriptions of terrestrial receptors and impact scenarios, although details are site-specific (Section 4.7.2).
6.3.6 Buildings	**E**	Explicitly recognised within descriptions of terrestrial receptors and impact scenarios, although details are site-specific (Section 4.7.2).
7 Impacts		
7.1 System performance		
7.1.1 Loss of containment	**E**	Fundamental to the leakage / impact scenarios described.
7.2 Impacts on the physical environment	**I**	Implicit to the leakage / impact scenarios described.
7.2.1 Contamination of groundwater	**E**	Directly recognised in the 'aquifer' impact scenarios discussed (Section 4.7.2).
7.2.2 Impacts on soils and sediments	**E**	Directly recognised in the terrestrial point-release impact scenarios described (Section 4.7.2) and in all the marine impact scenarios described (Section 4.7.3)
7.2.3 Release to the atmosphere	**I**	Described implicitly in various terrestrial scenarios, but note that RISCS focuses on ecosystem impacts, rather than broader impacts to the environment after release to the atmosphere and climate change, etc. The marine impact scenarios concern only emissions of CO_2 and / or CO_2-charged water to the seawater column.
7.2.4 Impacts on exploitation of natural resources	**E**	Directly recognised in the terrestrial point-release impact scenarios described and when discussing human intrusion scenarios in marine environments (Section 4.7.3).
7.2.5 Modified hydrology and hydrogeology	**E**	Noted in the description of relevant release patterns/ mechanisms (Section 4.4).
7.2.6 Modified geochemistry	**E**	Directly recognises in terms of impacts to aquifers and soils, sediments and the marine environment, and secondary impacts on other receptors (Sections 4.3, 4.4, 4.5 and 4.7).
7.2.7 Modified seismicity	**E**	Discussed as a contribution to the characterisation of the relative likelihood of occurrence of point-source leakage as a result of fault widening or well damage. Also by discussions of induced seismicity (Sections 4.4.1, 4.7.2, and 4.7.3). See also FEP 3.2.6.
7.2.8 Modified surface topography		
7.2.8.1 Sinkhole formation	**I**	Noted in discussion but not identified as a likely leakage scenario.
7.3 Impacts on flora and fauna		
7.3.1 Asphyxiation effects	**E**	Directly recognised in the terrestrial impact scenarios described (Section 4.7.2).
7.3.2 Effect of CO_2 on plants	**E**	Directly recognised in the terrestrial and marine impact scenarios

and algae		described (Section 4.7).
7.3.3 Ecotoxicology of contaminants	**E**	Directly recognised in the terrestrial and marine impact scenarios described (Section 4.7).
7.3.4 Ecological effects	**E**	Directly recognised in the terrestrial and marine impact scenarios described (Section 4.7)
7.3.5 Modification of microbiological systems	**E**	Directly recognised in the terrestrial and marine impact scenarios described (Section 4.7).
7.4 Impacts on humans		
7.4.1 Health effects of CO_2	**E**	Directly recognised in the urban impact scenario described (Section 4.7.2).
7.4.2 Toxicity of contaminants	**E**	Directly recognised in the urban impact scenario described (Section 4.7.2).
7.4.3 Impacts from physical disruption	**E**	Directly recognised in the urban impact scenario described (Section 4.7.2).
7.4.4 Impacts from ecological modification	**E**	Directly recognised in the urban impact scenario described (Section 4.7.2).