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BIOPROTA

BIOMASS 2020: Interim report

BIOPROTA report, produced in association with IAEA MODARIA II working group 6

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This report concerns a study which was conducted by BIOPROTA. The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

A pdf version of this document can be downloaded from www.skb.se.

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Foreword

The International Atomic Energy Agency issued a report in 2003 on reference biospheres for use in the context of safety assessment of solid radioactive waste disposal. The development of that report involved substantial efforts over several years from many organisations to provide a common methodology for addressing the assessment of doses following the release of radionuclides in to the biosphere in the long term, the so-called BIOMASS methodology. Much work has been undertaken and experience gained since 2003, in terms of site characterisation, scientific understanding of processes, system description modelling that accounts for climate change and landscape evolution, as well as project specific application of the 2003 methodology. There have also been changes in international recommendations, standards and guidance on radioactive waste safety and further experience in regulatory review of the adequacy of safety assessments and safety cases. Noting all these developments, members of the BIOPROTA Forum have been working in parallel with IAEA MODARIA II Working Group 6 to review and enhance the BIOMASS Methodology.

The report presented here is an Interim report, setting out progress made so far (March 2018) and the direction of future work, focussing on integration of the biosphere assessment within an overall assessment and safety case; selection of assumptions for exposure groups and populations; transparent presentation of the methodology and clear communication of results; achieving an appropriate balance between complexity and simplicity, and building confidence in the conclusions. A final report is due to be completed by the end of 2019, for publication in 2020.

The SKB is pleased to participate in this programme of work. However, the conclusions and viewpoints presented in this report are those of the authors and do not necessarily coincide with those of SKB.

Solna, 23 March 2018

Tobias Lindborg
Swedish Nuclear Fuel and Waste Management Co.

Preface

BIOPROTA is an international collaboration forum that seeks to address key uncertainties in the assessment of environmental and human health impacts in the long term arising from release of radionuclides and other contaminants as a result of radioactive waste management practices. It is understood that there are radio-ecological and other data and information issues that are common to specific assessments required in many countries. The mutual support within a commonly focused project is intended to make more efficient use of skills and resources, and to provide a transparent and traceable basis for the choices of parameter values, as well as for the wider interpretation of information used in assessments. A list of sponsors of BIOPROTA and other information is available at www.bioprota.org.

The general objectives of BIOPROTA are to make available the best sources of information to justify modelling assumptions made within radiological and related assessments of radioactive waste management. Particular emphasis is placed on key data required for the assessment of long-lived radionuclide migration and accumulation in the biosphere, and the associated radiological impact, following discharge to the environment or release from solid waste disposal facilities. The programme of activities is driven by assessment needs identified from previous and on-going assessment projects. Where common needs are identified within different assessment projects in different countries, a common effort can be applied to finding solutions.

This report is the first report from a BIOPROTA project reviewing and updating the International Atomic Energy Agency (IAEA) BIOMASS methodology. It represents an interim stage in the development of a fully updated methodology, referred to here as BIOMASS 2020.

The BIOMASS methodology provides guidance on the treatment of the biosphere in post-closure safety assessments for solid radioactive waste disposal. A first draft of this report provided input to a BIOPROTA project meeting, which was held in parallel with the second annual technical meeting of Working Group 6 (WG6) of the second phase of the IAEA project on Modelling and Data for Radiological Impact Assessments (MODARIA II). WG6 also has the objective of enhancing the BIOMASS methodology; the BIOPROTA project aims to help facilitate this and provide interim documentation of progress. This report has been updated following the BIOPROTA project and parallel WG6 meeting. It is intended to provide a basis for discussion at future meetings, with a view to supporting the continuing development of the fully updated BIOMASS methodology.

This report therefore represents an Interim Report for discussion amongst the wider participants in both the BIOPROTA and MODARIA II projects. It aims to provide a framework for discussions and to provoke suggestions, drawing on the experience and expertise of those involved. Placeholders are included in the text to indicate topics where discussion and/or expansion of the report may be required. However, the report also provides a suitable basis for those wishing to refer to the latest international work in this area.

This version of the report has been drafted by members of the BIOPROTA Technical Support Team, comprising individuals from Quintessa Ltd., Mike Thorne & Associates Ltd., RadEcol Consulting Ltd., GMS Abingdon Ltd. and Amphos21. The report has been drafted taking into account information presented and discussed at three prior project workshops as well as the 2018 MODARIA II annual Technical Meeting. Reports of each workshop are available from www.bioprota.org. The BIOPROTA project has been supported financially by the following organisations: French National Radioactive Waste Management Agency (ANDRA), Swiss Federal Nuclear Safety Inspectorate (ENSI), Low Level Waste Repository Ltd. (LLWR, UK), National Cooperative for the Disposal of Radioactive Waste (Nagra, Switzerland), Norwegian Radiation Protection Authority (NRPA), Nuclear Waste Management Organisation of Japan (NUMO), Nuclear Waste Management Organization (NWMO, Canada), Posiva (Finland), Radioactive Waste Management Ltd. (RWM, UK), Swedish Nuclear Fuel and Waste Management Company (SKB), Swedish Radiation Safety Authority (SSM).

Version history

Version 1 Draft: First draft interim report, provided as input to the 2017 technical meeting for MODARIA II WG6. Circulated to the WG6 participants 26 October 2017.

Version 1 Draft Final: Draft final interim report. Circulated to the BIOPROTA project sponsors for comment 20 December 2017.

Version 1: Final interim report, taking account of comments received on draft final version. Circulated to BIOPROTA members 6 March 2018.

Contents

1 Introduction

Assessments of post-closure safety form an integral part of the Safety Case for solid radioactive waste disposal and support the associated decision-making process (IAEA 2012). Such assessments help to ensure a sufficient level of protection for humans and the environment and necessarily require consideration of potential adverse impacts arising in the biosphere (see Figure 1-1). Consistency between the different components of the post-closure safety assessment is essential, and procedures to achieve such consistency should be an integral part of the approaches and methodologies that are applied.

1.1 Aims

This report updates previous guidance on undertaking post-closure biosphere assessments on the long timescales of relevance to solid radioactive waste disposal. The report has been produced through a project within the BIOPROTA international collaborative biosphere forum and is intended to provide an input to Working Group 6 (WG6) of the second phase of an International Atomic Energy Agency (IAEA) co-ordinated project on Modelling and Data for Radiological Impact Assessments (MODARIA II).

1.2 Background

International guidance on biosphere modelling for radiological assessment was first developed at an international level within Phase II of the collaborative Biosphere Modelling and Validation Study (BIOMOVS II), which ran from 1991 to 1996 (Davis et al. 1999, van Dorp et al. 1999). The study included a working group on 'Reference Biospheres', the mandate of which was to consider the potential to develop internationally accepted standardised biosphere models for use in long-term safety assessments concerning solid radioactive waste disposal. The working group concluded that standardised models would be difficult to apply in practice, due to the need for biosphere models to reflect the context specific to each assessment. Instead of focusing on 'reference biosphere' models, the working group sought to encourage transparency, consensus and harmonisation in biosphere modelling through the development of a reference methodology, supported by a list of generic biosphere Features, Events and Processes (FEPs). The BIOMOVS II study concluded by recommending that further refinement of the methodology was needed.

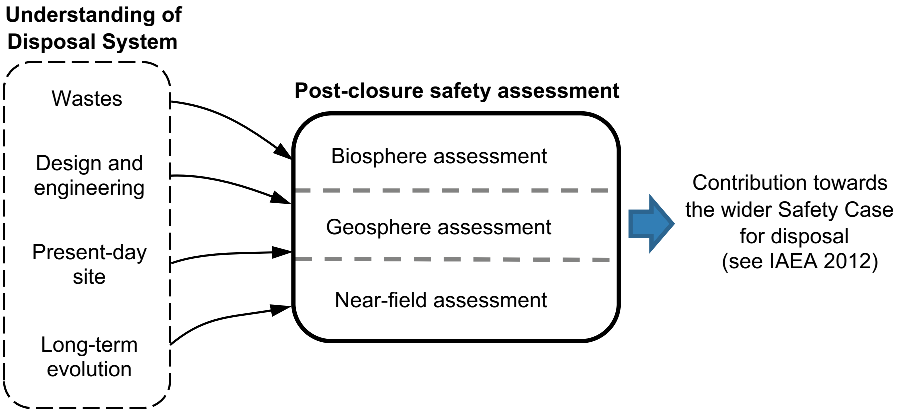

Figure 1-1. *Biosphere assessment within the context of the broader Safety Case.*

Theme 1 of the IAEA Biosphere Modelling and Assessment (BIOMASS) project, which ran from 1996 to 2001, further developed and refined the reference biosphere methodology, drawing on experience of its application and through development of several illustrative examples (IAEA 2003). The 'BIOMASS methodology' included:

- A high-level approach, emphasising the importance of clarity regarding the assessment context as a foundation for identifying the biosphere(s) to be represented and subsequent model development.
- An explanation and description of steps of the methodology that could be undertaken, including detailed tables of biosphere characteristics and classification schemes.
- An updated biosphere FEP list.

Several Example Reference Biospheres (ERBs) were developed. These demonstrated the application of the BIOMASS methodology while also serving the following three purposes.

1. The ERBs (through to the stage of defining the conceptual model, at least) are relevant to a wide range of assessment contexts. It should therefore be possible to use the examples as 'benchmarks' against which other assessment biosphere calculations may be compared.
2. By adopting a series of progressively more detailed examples, it was possible to illustrate the effects of including additional processes of radionuclide transport and pathways of exposure on the results obtained.
3. By taking the examples all the way through to a numerical endpoint, the methodology was fully exercised. Also, the issue of data selection was addressed. However, it was noted that the project underestimated the level of effort that would be required to satisfactorily complete the work of data selection.

Three groups of examples were developed. ERB1 solely considered use of potentially contaminated groundwater for drinking. ERB2 considered irrigation with potentially contaminated groundwater (ERB2A) as well as groundwater discharge to surface (ERB2B) in the absence of long-term environmental change. ERB3 included consideration of environmental change, though there was insufficient time to carry this last example through to numerical modelling. The issue of climate and environmental change was acknowledged as one aspect of the methodology that required further development.

The European Commission (EC) BIOCLIM project, which ran from 2000 to 2003, sought to build on BIOMASS and establish a practical methodology for assessing climate and environmental change (BIOCLIM 2004). BIOCLIM established long-term projections of global climate and explored approaches for downscaling the global projections to regional and site-scales. The project elaborated on the BIOMASS approach to considering environmental change, with specific consideration of climate change. BIOCLIM explored the development of narratives of environmental change and their interpretation as sequences of biosphere states with transitions in-between, including the potential use of tools such as interaction matrices and state transition diagrams.

Following-on from the BIOMASS project, the IAEA ran a programme on Environmental Modelling for Radiation Safety (EMRAS). The first phase of EMRAS, which ran from 2003 to 2007, included a working group on updating data for safety assessments (IAEA 2010), but did not review biosphere assessment methodologies. Working Group 3 of the second phase of EMRAS, which ran from 2009 to 2011, considered reference models for waste disposal. That study focused on environmental change, noting that stylised models, models of sites analogous to future conditions at the site of interest, and explicit modelling of the dynamic evolution of the biosphere may each have a role to play in building confidence in long-term post-closure safety (IAEA 2016a).

Most recently, WG6 of the first phase of the MODARIA project (the successor to the EMRAS project) that ran from 2012 to 2015, updated the BIOCLIM recommendations, particularly in terms of potential patterns of long-term climate change at local, regional and global scales, and sought to develop a common framework for addressing climate change in post-closure safety assessments. The approach developed within WG6 (and described further in Appendix A.4), which involved a substantial programme of detailed modelling using climate-system models of various types, enables narratives of long-term climate change and landscape evolution to be developed as input to safety/performance assessments taking into consideration that climate and landscape change will impact on the total system, not just the biosphere (IAEA 2016b). Indeed, potential changes in climate and alterations of the landscape may need to be considered when developing the overall safety case for a facility, and not solely as factors in a quantitative post-closure safety assessment.

1.3 Scope and objectives of the current project

The BIOMASS methodology has been widely referenced in support of biosphere assessments for geological disposal of radioactive waste (Griffault 2013, Posiva 2013, SKB 2010, SNL 2007, Walke et al. 2013), as well as in support of some assessments for near-surface disposal *[Andra Aube Assessment]*. The high-level methodology has helped to provide consistency in the way in which the biosphere is characterised and assessed in different disposal programmes, and in widely different assessment contexts. Much experience has been gained, particularly as disposal programmes have moved from the proof-of-concept stage to detailed analyses at specific sites. In the context of submissions to construct repositories for spent fuel, the importance of making good use of international consensus and guidance has been acknowledged in legal hearings. Reference to such international consensus and guidance helps to provide assurance that best current practice is being adopted in the safety assessment. The BIOMASS methodology has therefore been an important aspect of establishing the international consensus on how a post-closure safety assessment should be conducted.

In addition to the substantial experience in the application of the BIOMASS methodology, the assessments and other studies have given rise to new knowledge and developments. Significant developments since the BIOMASS methodology was originally developed include

- updated international recommendations and guidance from the IAEA and ICRP,
- experience gained in undertaking biosphere assessments in the intervening time, including integration of the biosphere within the total system assessment and the overall Safety Case, and associated regulatory scrutiny of this information,
- recognition of the broader applicability of the BIOMASS approach, e.g. to near-surface disposal as well as to geological disposal,
- experience in integrating information from site characterisation into biosphere assessments,
- significant developments in approaches and recommendations for explicitly demonstrating environmental protection through biota dose assessments,
- improved understanding of long-term climate changes and landscape developments, and consideration of their representation in long-term assessments (most notably as reflected in the outputs from MODARIA WG6),
- experience in considering potential impacts of non-radiological contaminants that may be released from radioactive waste disposal facilities,
- improved understanding and modelling of specific radionuclides that behave in a different way to other trace contaminants and that are of potential importance in post-closure safety assessments, including C-14, Cl-36, Se-79 and I-129, and
- developments in modelling capabilities and approaches for interpreting contaminant behaviour in the biosphere and across the interface with the geosphere.

WG6 of the MODARIA II project thus aims to review and update the BIOMASS methodology to reflect these developments. This interim report has been prepared through a parallel BIOPROTA project, which is intended to help facilitate the update to the BIOMASS methodology.

As stated in Section 1.1, this interim report documents progress with the above activities and aims to draw out the experience of those participating in the respective BIOPROTA and MODARIA projects so that this may be reflected in the updated BIOMASS methodology, due for completion and publication in 2020.

1.4 Terminology

There is broad recognition of the usefulness of the original “BIOMASS methodology”, as evidenced by the range of assessments that reference it, as noted above. In this report, the enhanced methodology is referred to as the “updated BIOMASS methodology”, so that the “BIOMASS” name is retained, both to retain a direct connection and to acknowledge the original work.

The final MODARIA II technical meeting is due to take place in October/November 2019, whereupon a final report will be delivered by WG6 to the IAEA for publication. It is anticipated that the IAEA report on the updated biomass methodology will be published in 2020. The BIOPROTA project in support of the update is therefore referred to as the "BIOMASS 2020" project.

Safety assessment, including the post-closure phase, is recognised as being a part of an overall Safety Case for disposal of radioactive waste, as described in IAEA (2012). In this report, the term "safety assessment" has been used in preference to "performance assessment" (PA) because the focus is on biosphere assessment, where potential exposures of humans and biota to ionising radiations and to chemical contaminants are the primary performance measures.

The biosphere(s) adopted for safety assessment should not be regarded as simulating the actual conditions that will necessarily be present when a future release to the biosphere occurs. Rather, it is appropriate to consider them as adequately representative of possible outcomes for assessment purposes, ideally spanning the range of impacts of such outcomes on human health and the environment. Biospheres represented in safety assessments therefore comprise[1]:

"*the set of assumptions necessary to provide a consistent basis for calculations of potential adverse impacts on human health and the environment arising from long-term releases of repository-derived contaminants into the biosphere.*"

The biosphere model(s) themselves are the tool(s) that represent these assumptions in a numerical framework that is needed to carry out the calculations. Biosphere modelling is, therefore, the process of calculating the potential adverse impacts by quantitatively evaluating the biosphere model(s).

Discussion in the original BIOMASS methodology focussed on radionuclide releases from solid radioactive waste disposal to the biosphere. In practice, other contaminants can be released from solid radioactive waste disposal facilities, including heavy metals and organic compounds. Such non-radiological contaminants may be present in the waste itself but may also be present in and released from the engineering structures within the disposal facility (e.g. shielding, packaging, piping, wiring, structural reinforcement). Safety assessments may need to consider these non-radiological contaminants as well as radionuclide releases. The updated BIOMASS methodology provides a sound framework for assessing both radiological and non-radiological hazards and so the term "contaminants" is used in this report to encompass both types of substance.

One of the major developments since the original BIOMASS methodology was developed is in international recommendations and approaches regarding explicit demonstration of environmental protection through assessing potential dose rates to non-human biota in addition to assessing potential doses to humans. For simplicity, non-human biota dose assessment is referred to as "biota dose assessment" in this report.

In the broader context of overall post-closure safety assessments, reliance has often been placed on generic or project-specific sets of Features, Events and Processes (FEPs) that require consideration in the assessment. Sets of FEPs are often reported in the form of structured lists, with the amount of detail relating to the individual entries depending upon the context in which the FEP list was created or elaborated. Such FEP lists can help to demonstrate comprehensiveness of the assessment process as well as keeping track of how possibly relevant issues have been addressed within an assessment. Thus, a FEP list may be used either to identify those FEPs that need to be included in a post-closure safety assessment or to audit an existing assessment to ensure that all relevant FEPs have been appropriately considered. FEP lists or sections of FEP lists have been developed specifically relating to the biosphere and these can be used to inform biosphere identification, description and characterisation, which are steps in the BIOMASS methodology (discussed further below). In addition, it can be helpful to distinguish FEPs that are internal to the disposal system from External FEPs (EFEPs) that operate outside the disposal system but influence it. Climate change, earth processes such as volcanism and sea-level rise, as well as extra-terrestrial processes such as meteorite impact, would typically be classed as EFEPs.

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[1] Adapted from IAEA (2003).

As discussed later in this report, the main components of the biosphere, e.g. soils, water bodies, biota, would typically be thought of as features of the system. Processes generally operate to modify those features, or to transport contaminants between them, e.g. groundwater flow or fluvial erosion. Events are more difficult to characterise, but they can be viewed as processes operating on a short timescale that change significantly the arrangement of features of the system or alter substantially the processes that act upon it. Thus, a volcanic eruption would be considered as an event.

1.5 Managing uncertainty in post-closure assessments

Assessment of the safety of radioactive waste disposal facilities on timescales of thousands through to hundreds of thousands of years is subject to profound uncertainties. The management of uncertainty is a fundamental component of post-closure safety assessments. The updated BIOMASS methodology draws on experience to provide guidance on identifying and managing uncertainties; nonetheless, results must be interpreted in the context of the explicit and residual uncertainties with which they are associated and the way in which they have been addressed, both in the biosphere assessment and within the total system Safety Case (e.g. IAEA 2012).

It is helpful to recognise the different types of uncertainties associated with post-closure safety assessments, because different approaches can be used to help to understand their potential importance. The types of uncertainty and associated approaches for managing them are summarised below, to provide a foundation for their subsequent discussion in the context of the updated BIOMASS methodology.

- Uncertainty about the broad future evolution of the system being modelled can be addressed by consideration of a range of different scenarios of possible future conditions (termed *scenario uncertainty*). Examples of uncertainties that are typically addressed through different scenarios include alternative climate sequences, e.g. covering different amounts and temporal patterns of future greenhouse-gas emissions, and alternative landscape evolutions.
- Uncertainty about the way in which contaminant migration, accumulation and potential exposures are most appropriately modelled (termed *model uncertainty*) can be addressed through variant calculations/side calculations with differing modelling approaches. Uncertainty about the interpretation of a scenario and different views on how processes should be represented can be addressed through developing assessment models by more than one researcher (or group) and establishing a consensus model afterwards (e.g. Kirchner et al. 1999). In some circumstances, the establishment of a consensus model may not be appropriate, e.g. where alternative hypotheses as to how a process operates all have some evidential support. In these circumstances, it will be appropriate to carry more than one alternative model through the assessment process, just as it is often appropriate to address more than one scenario, if the alternatives could all be realised[2].
- Uncertainty about the value of parameters (termed *parameter uncertainty*) can be addressed through probabilistic calculations and/or variant deterministic calculations based on alternative combinations of parameter values. Probability distribution functions reflecting site conditions may be preferred to generic distributions, though care should be taken to ensure that they are not unduly constrained by present-day site characteristics.

When addressing uncertainties in probabilistic analyses, risk dilution should be avoided. This arises where peak risks are uncertain in respect of their location in time or space, but the approach to probabilistic analysis adopted uses an averaging procedure that does not take account of this, e.g. by averaging at a fixed location in each realisation rather than averaging over the location of highest risk in each realisation. Risk dilution can be caused, for example, by variability in event timing, spatial effects, parameter correlations, or the assignment of unduly wide parameter value distributions (Dverstorp et al. 2005, Wilmot and Robinson 2005). Unduly broad distributions of parameter values may produce misleading results also in sensitivity analyses, and often it is useful to define the distributions separately for uncertainty analyses and sensitivity analyses.

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[2] In some assessments, ‘what if’ scenarios are used to explore situations that could not occur in practice, but that illustrate some aspect of the safety case. For example, a scenario in which radionuclides are assumed to require a negligible amount of time to traverse the geosphere may be used to illustrate the robustness of the safety case and its reliance on multiple barriers.

The difficulty, not to say impossibility, of validation of models for post-closure safety assessments for radioactive waste disposal has long been recognised (Hill 1989). Natural systems are always open, and our knowledge is always incomplete and approximate, as discussed in the context of earth sciences modelling in Oreskes et al. (1994). Therefore, safety assessment results are not presented as predictions, but as projections of possible futures, as discussed in IAEA (2016a). The transparent recognition of the uncertainties, and the documented approach to addressing them, are important steps in building sufficient confidence in the results of a safety assessment to support decisions. This is, therefore, an important factor to build into the updated BIOMASS methodology. Fundamental to that is sufficient understanding of the nature of the decisions to be made and the associated level of confidence that is needed.

1.6 Updated BIOMASS methodology

There is general consensus that the overall structure of the original BIOMASS methodology has proved sound (BIOPROTA 2016a, b, 2017a). The updated methodology, summarised in the central column of Figure 1-2, is, therefore, consistent with the original. Inputs to the methodology from closely associated sources of concepts, models and data are shown at the sides of the figure. Each stage of the methodology is discussed and described in the following sections of this report. As the report updates the original, some material is reproduced from IAEA (2003).

Comprehensive documentation of the approach that is adopted in a specific assessment is a fundamental element of each stage of the methodology. This facilitates scrutiny of the assessment, e.g. for auditing purposes or by the regulator, helps to ensure transparency, and enables lessons learned in developing the assessment and interpreting its results to be used to revisit assumptions and decisions, either by iteration within the assessment cycle or at some subsequent time when the assessment requires updating. Such information may also be used to refine the assessment, perhaps by identifying particularly important FEPs or sensitive parameters. A systematic methodology thus provides a ‘living’ approach for incorporating new information into biosphere assessments, taking account of experience from using the models and interpreting the results, changing assessment contexts, new scientific understanding and evolving regulatory requirements and overall Safety Cases. Maintenance of comprehensive records of each assessment is of great importance where multiple assessment cycles are undertaken at different stages of repository development (site selection, site characterisation, repository construction, waste emplacement, closure and post-closure site management). Reference to these records should facilitate the maintenance of continuity in the assessment process, while ensuring that the significance of moving to the next stage of development and of incorporating new information and understanding is properly evaluated through a comparison of assessment results.

1.7 Report structure

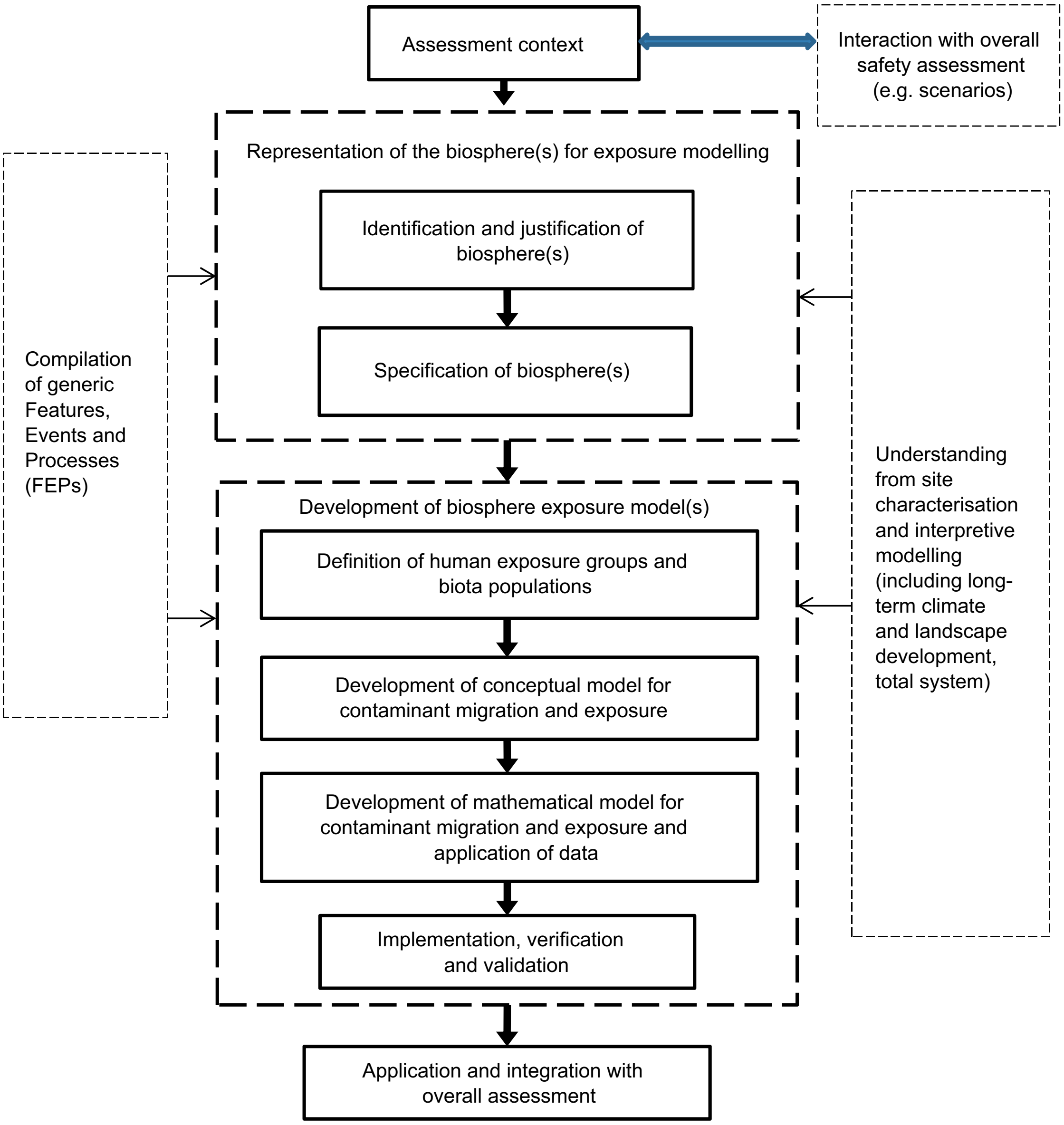
The report structure follows that of the updated BIOMASS methodology illustrated in Figure 1-2.

- Definition of the assessment context is described in Chapter 2.
- Identification and description of the biosphere system(s) to be assessed is described in Chapter 3.
- Development biosphere exposure models is described in Chapter 4.
- Application of the resulting biosphere models and evaluation of results are discussed in Chapter 5.

Conclusions are presented in Chapter 6. References are provided in Chapter 7 and a glossary of technical terms and abbreviations is provided in Chapter 8.

Further details on technical aspects are provided in Appendix A and further information on illustrative examples is provided in Appendix B.

The report will be subject to further development as the BIOPROTA and MODARIA II WG6 projects progress. Placeholders for some specific aspects that will be developed further are *[highlighted with square brackets and italics]* in this interim report.



N.B. Although not explicitly shown, *iteration* will be needed throughout, alongside the management of uncertainties.

Figure 1-2. *Schematic illustration of the updated BIOMASS methodology (central column) with supporting information and interactions (shown at the sides).*

2 Assessment context

The biosphere is complex, but it is not usually necessary to develop a very detailed representation of it for post-closure safety assessments. Such assessments apply to the long-term future, which can be characterised only in terms of possibilities (alternative scenarios) and only in outline for each such possible future, which must itself stand for or represent a multiplicity of alternatives differing in detail from each other. However, very simple models are potentially difficult to defend because they may not explicitly address important features and processes, or they may distort their significance, e.g. by adopting a scale larger than that at which the process characteristically operates.

Demonstrating 'fitness for purpose' of biosphere models entails striking an acceptable balance between the level of detail and the defensibility of the approach that is adopted, considering the context in which it will be used. Finding the balance can be supported by an understanding of why the assessment has been commissioned, what questions it is supposed to answer, and the intended audience or audiences. Historically, these questions were not answered very clearly and, particularly for the biosphere modeller, the answers were not so simple. There was generally no agreement on what type of dose or risk to calculate. This was addressed in the 2003 methodology by making the first step a comprehensive documentation of the biosphere assessment context.

To a large degree, the overall assessment context and the biosphere assessment context are very similar, differing only in the characterisation of an appropriate source term (see below). Both the overall and biosphere assessment contexts answer fundamental questions about the post-closure safety assessment, namely: 'What are you trying to assess?' and 'Why are you trying to assess it?'. In a quantitative assessment, these become 'what are you trying to calculate?' and 'why are you trying to calculate it?' (IAEA 2003).

The common components of the overall and biosphere assessment contexts are:

- The purpose of the assessment, including the regulatory regime within which it is conducted, or which it is intended to inform.
- The endpoints of the assessment.
- The assessment philosophy.
- The repository system and the site context.
- The time frames to be represented.
- The societal assumptions to be made.

These components are significantly driven by the regulatory regime and the nature of the overall Safety Case (IAEA 2012). However, they may also be strongly driven by the interests of a wider range of stakeholders.

Since 2003, one can see a stronger recognition of the following issues:

- Assessments are not just about regulatory endpoints.
- There are chemical risks, e.g. associated with uranium, that may also need to be considered.
- Property and resources such as groundwater may also need to be protected.

The one component that differs between the overall assessment and the biosphere assessment contexts is the component that relates to the source term. In the overall context, the source term relates to the time-dependent inventory of contaminants in the wastes and the repository. In the biosphere context, the source term usually relates to the time-dependent flux of contaminants entering the biosphere. This requires the definition of an interface between the biosphere and the rest of the disposal system at which this flux can be defined.

In general, the assessment context will be defined specifically for each assessment cycle. It may be varied during an assessment or between assessments. Only minor changes would be expected during an assessment, as the context, including stage of repository development, is largely fixed.

However, substantial changes in assessment context may occur from one assessment to the next, e.g. between the beginning and end of detailed site characterisation. Nevertheless, the assessment context at each assessment will be strongly conditioned by the approach to assessment previously adopted, the results obtained, and the reception of those results by stakeholders, including regulatory bodies. In defining the context for the next assessment, it is important to examine critically this historical legacy, to determine lessons learned, but also to challenge previous assumptions that may no longer be appropriate.

In assessment studies undertaken since the original BIOMASS methodology was developed, there has been increased recognition that assessments are not just about demonstrating compliance with regulatory criteria but must satisfy a variety of stakeholder interests. Also, the scope of assessments has broadened to address potential adverse impacts on human health and the environment from both radionuclide and toxic chemical releases. In this broader context, it has also been recognised that over and above direct impacts on humans and other biota, consideration needs to be given to the protection of environmental resources, e.g. through avoidance of pollution of groundwater bodies. Thus, the overall assessment context now needs to be defined more widely than was previously the case.

In the following, the components of the assessment context are discussed in more detail. In general, this discussion applies both to the overall and biosphere assessment contexts.

2.1 The purpose of the assessment

The general purpose of a post-closure safety assessment is to support a decision concerning radioactive waste management. In turn, this will generally involve sufficient understanding of the disposal system to evaluate the potential adverse effects of releases of contaminants on human health and the environment through consideration of a range of situations that may apply in the future. In the context of the biosphere, there is a presumption that contaminants will, at some time, be released into the biosphere and that there is a need to quantitatively assess their potential adverse impacts. In the context of the overall disposal system, it may be sufficient to demonstrate that adverse effects will be negligible by demonstrating that no, or very small, amounts of contaminants would reach the biosphere under any reasonably foreseeable scenario. Thus, biosphere modelling is not always required, but, as most disposal concepts envisage the possibility of releases to the biosphere either in a reference, central or variant scenario, in general a biosphere model will be required to evaluate potential adverse impacts on human health and the environment.

The purpose of conducting an assessment may vary from simple calculations to test initial ideas for disposal concepts, to support for a disposal licence application requiring detailed, site-specific calculations with results compared against regulatory criteria and evaluated by the regulatory authorities. The purpose may also be to satisfy the requirements of various stakeholders, including regulators, scientific specialists in radioactive waste management, the wider scientific community, local residents and the general public.

Assessment purposes include the following (IAEA 2003, 2009):

- development of national radioactive waste management strategy,
- demonstrate compliance with regulatory requirements/regulatory development,
- contribute to public confidence,
- contribute to confidence of policy makers and the scientific community,
- provide a guide to research priorities,
- provide proof of concept (site generic),
- provide guidance in site selection and provide a basis for approval at later stages in repository development, and/or
- facilitate system optimisation.

2.2 Endpoints of the assessment

The endpoints of an assessment will typically be measures of potential adverse impact on humans and the environment. The structure and composition of a biosphere model will tend to reflect the results that it is designed to evaluate. These will depend largely on the criteria (regulatory or otherwise) that are adopted to judge the overall safety of the disposal system. Several endpoints may be necessary in developing a Safety Case for a licensing application. Examples or measures of radiological impact suggested in IAEA (2003) included

- individual risk,
- individual dose,
- collective doses and risks,
- doses (or dose rates) to non-human biota,
- modifications to the radiation environment, i.e. relating to the distribution of repository derived radionuclides in the environment and their concentrations,
- fluxes of radionuclides into or through parts of the biosphere, and/or
- estimates of uncertainty and/or confidence.

More recently, and as noted previously, the scope of assessments has broadened such that potential adverse impacts on both human health and the environment from toxic chemical releases associated with radioactive waste disposal may also merit attention. Furthermore, consideration may need to be given to the protection of environmental resources through, for example, avoidance of pollution of groundwater bodies.

It is generally accepted (ICRP 2007), that the effective dose received by a representative person is an appropriate measure for estimating radiological risks in prospective assessments (planned exposure situations), for which limited information is generally available on the characteristics of the exposed individual[3]. However, even if the radiological endpoints of an assessment, in respect of human health, are expressed in terms of effective dose (or the detriment to health associated with that effective dose), there is considerable flexibility over how those effective doses should be determined. For example, the representative person may be selected as representative of either a small or larger population (a distinction made in the Finnish regulations where different standards are adopted for the most-exposed small population and a larger population located around a contaminated regional lake), and the effective dose may be calculated for each scenario separately or summed over scenarios by assigning each a probability of occurrence. Furthermore, effective doses may be calculated for several groups within a local population characterised by different patterns of behaviour. These groups are often termed Potentially Exposed Groups (PEGs). If PEGs are defined in the assessment context, then the characteristics of the biosphere representation must be compatible with those PEGs, e.g. if the PEG is defined as a self-sufficient household living on the contaminated land, then the biosphere representation must be able to accommodate such agricultural practice. Conversely, if PEGs are not defined in the assessment context, their characteristics can be selected at a later stage of the methodology to be consistent with the biosphere representation developed under, and constrained by, other considerations. Similar considerations apply to the assessment of exposure of populations of biota.

In principle, potential adverse effects on human health could be evaluated for exposed populations, as well as for representative, more highly exposed, individuals. For post-closure safety assessments, assessment of such collective doses is not generally recommended, and no international compliance standards have been set, based on the limitation of collective effective dose. However, the exposure of larger groups of people (i.e. much larger than the most highly exposed group) can be considered as a relevant factor, e.g. in the Finnish regulatory standards (STUK 2001). More recently, ICRP has noted in the context of geological disposal that optimisation of protection is the process to keep the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses as low as reasonably achievable, taking into account economic and societal factors (ICRP 2013).

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[3] Exceptions arise in the case of scenarios giving rise to doses large enough to cause acute radiation effects, e.g. if highly active waste were left on the surface and it was not possible to provide controls over access or limit disturbance far enough into the far future so that such doses cannot occur.

If collective doses are to be assessed as part of the comparison of options or as a part of an optimisation process, it is appropriate to disaggregate the results, so that contributions in different relevant areas, over various relevant future periods should be evaluated, see discussion in ICRP (2006), Disaggregation over different ranges of individual dose rate could also be informative. It may also be that annual *per capita* effective dose (annual collective effective dose divided by the size of the exposed population) is a more useful measure than collective effective dose, as it is likely to be less dependent on assumptions relating to the size of the exposed population and its variability over time.

Measures of potential adverse impact on the environment could be evaluated at individual, population, community, habitat or ecosystem levels. However, the population level is commonly accepted as the appropriate protection target, for evaluating both radiological and non-radiological impacts. This gives rise to considerations of the range of the population of interest, which, in turn, has implications for the spatial extent of the biosphere representations that need to be specified.

2.3 Assessment philosophy

The assessment philosophy (or approach) relates to the choices made in calculating the endpoints of the assessment. These can include restrictions on the pathways of exposure to be considered, use of probabilistic or deterministic methods of calculation, and the choice of realistic or cautious parameter values in deterministic calculations. The selection of specific scenarios or types of scenario requiring assessment might also be considered part of the assessment philosophy.

The assessment philosophy, which is likely to be determined at the level of the Safety Case, or at least in defining the overall approach to post-closure safety assessment, should include consideration as to how uncertainties should be identified, characterised and propagated through the assessment. For initial assessments, it may be sufficient to undertake a limited number of deterministic calculations, essentially to determine whether the proposed disposal system is potentially viable. However, in most assessments it will be necessary to quantify the robustness of the results obtained. This will require the identification, characterisation and propagation through the assessment of those uncertainties with the potential to significantly affect the quantitative results obtained. As discussed elsewhere in this report, these uncertainties arise from the range of scenarios that may be adopted as a basis for assessment, potential choices of alternative conceptual and mathematical models of the system to be represented, and both variability-associated (aleatory) and lack-of-knowledge-related (epistemic) uncertainty in the parameter values that should be used in the mathematical models. The assessment philosophy may include consideration as to whether deterministic methods (local sensitivity analyses), probabilistic methods (e.g. uncertainty analyses, global sensitivity analyses) or a combination should be used to explore these various uncertainties and demonstrate the robustness of the assessment.

In exploring uncertainties, one possibility is to adopt a cautious approach that is thought to overestimate potential adverse impacts on humans and the environment. Caution can be shown in the choice of scenarios, in the models adopted and in the parameter values selected for use with those models. However, it is not always clear whether a specific assumption is cautious once it has been propagated through the assessment process (e.g. an increased distribution coefficient may slow the transport of a contaminant to the environmental medium of interest, but also enhance its retention in that medium – whether these processes together will increase or decrease the concentration of that contaminant in the medium may not be readily determined without explicit calculations). Another consideration is that adopting multiple, modestly cautious assumptions may result in an overall assessment that is extremely cautious. Results from such an assessment, by exaggerating impacts, may distort choices between different sites or repository designs, since it is unlikely to be possible to adopt the same level of caution for each such option.

Alternatively, assessments may be directly based on characterisation of present-day biosphere systems. This approach was adopted in Sweden by SKB (SKB 2010), based on data derived from a comprehensive site characterisation programme. This approach provides confidence that the data can coexist and that correlations and dependencies are taken into account. Thus, it is possible to make a scientifically coherent assessment, underpinned by site data and site understanding, although this can be at the expense of greater complexity. In SKB (2010), the bounding cases were identified by searching for the maximum calculated doses, both in space and time, throughout the landscape. Uncertainties were addressed by exploring various scenarios, alternative models and/or multiple parameter sets, spanning significant uncertainties.

Thus, in practice, safety assessments are likely to require the generation of a wide variety of results, so that highly cautious calculations are not given undue weight, but also to ensure that safety is not threatened by unlikely, but plausible situations that have not been addressed.

2.4 Repository system and site context

As part of the assessment context, the repository system and site context should be outlined, to inform and set some boundary conditions for the biosphere assessment. Examples given in IAEA (2003) included

- depth of repository, host geological medium, waste type, and
- spatial extent, surface topography, current climate, surface lithology and soil types, fauna and flora, local surface water bodies and near-surface aquifers.

To a large degree, the repository system adopted for a specific waste type or set of waste types will be matched to the site context. This may be because a site has been sought that is suitable to a predetermined design or because a design has been developed to match a preselected site. However, it will more generally be the case that a design will both constrain the search for a site and later be adapted to the preferred or selected site. In some countries, very different alternative designs may be carried forward in the site-selection process, with those designs being potentially applicable in distinct geological contexts.

A detailed typology of the different types of facility that could be developed to dispose of a wide range of radioactive waste types (from very low-level waste to high-level wastes and spent nuclear fuel) in a wide range of geological contexts is set out in IAEA (2016b). That typology is not reproduced here, but IAEA (2016b) should be consulted on the various assessment-related considerations that apply depending on the type of facility and geological context that are proposed.

The spatial context of the site may be defined narrowly (e.g. just the area within the designated site boundary) or more widely (e.g. a region that includes a variety of types of land use potentially relevant to the future land-use characteristics at the site). A wider spatial range may also be needed to cover the spatial extent over which relevant human groups or biota populations exploit the landscape. This range may be considerable in cold or arid climate conditions in which primary productivity is low but may also be large for humans in conditions of high productivity, but where a hunter-gatherer lifestyle means that the natural productivity is exploited to only a small degree. For humans, maximal use of local resources obtained from a small area is likely to occur with intensive agricultural use, but, if this is assumed, the sustainability of such use, e.g. in terms of maintenance of soil quality, should be checked (Saetre et al. 2013). A wider spatial range may also be needed if that wider spatial range includes features, e.g. lakes and wetlands, that do not occur in potential contaminant discharge locations at the present day but could occur at potential discharge locations in the future. This has been illustrated in the programmes undertaken by SKB (SKB 2010) and Posiva (Posiva 2013).

The issue of site context is closely tied to the way in which site characterisation is related to biosphere system representation. This is discussed in detail in Box 1. Here, it is sufficient to note that the site context is one of the factors that will determine the extent and nature of site characterisation activities. These activities, in turn, will feedback to give an improved understanding of the site context. However, it should be noted that a site context can be defined prior to site identification and characterisation. This is termed a generic site context and can be specified through desk studies using previously published data, with the context constrained by the type of facility proposed and the areas of a country designated as potentially suitable, e.g. because of geological considerations or because they have volunteered to host a solid radioactive waste disposal facility.

The iterative nature of site characterisation and its relation to post-closure safety assessments of a proposed facility at the site are discussed and illustrated in Box 1.

Box 1: Site characterisation and its relation to post-closure safety assessment

Site characterisation is required for a variety of purposes. It informs facility design, operational impact assessment, environmental impact assessment and post-closure safety assessment. Biosphere characterisation is included as an integral part of site characterisation but is not necessarily explicitly represented as a single-defined activity. Because site characterisation is a multi-disciplinary activity, it may be structured by discipline (geology, hydrology and hydrogeology, hydrogeochemistry, ecology, demographics and land use etc.), with an overall site descriptive model being used to integrate the results obtained into a coherent description. Nevertheless, some site characterisation programmes have found it useful to include surface systems in the overall conceptual model, with those surface systems closely matched in terms of components and spatial extent to the initial state of the biosphere system adopted in the safety assessment. However, even in such cases, the biosphere used for safety assessment purposes is generally a simplification and abstraction of what is known concerning surface systems at the site, particularly in the latter stages of site characterisation, when a great deal of information will have been collected and synthesised concerning the site. This information will be very extensive, not only because it is required to address the various specific purposes outlined above, but because it is fundamental to providing an assurance of site understanding by the site developer. This builds confidence in stakeholder groups and specifically in residents of the site and its immediate area, who are assured that their local knowledge has been considered and that their specific concerns are being addressed through field investigations.

Site characterisation iterates with facility design, environmental impact assessment and operational and post-closure safety assessments. It provides information that is required for those various studies, and results from those studies will suggest new lines of site characterisation or changes of emphasis to existing lines of site characterisation. However, many site characterisation activities are necessarily continuous. In the absence of pauses in data collection, significant care and consideration must be given into structuring feedback, to ensure that design and assessment studies are based on coherent datasets, and that changes to the site characterisation programme are not contraindicated by subsequent observations under that programme.

Site characterisation includes the collection of data that can be used in paleo-environmental reconstruction. Thus, site characterisation addresses not only the current characteristics of the site, but also its past development. This can be very useful in making projections of potential future changes at the site, bearing in mind that anthropogenic climate change may mean that past changes at the site are not a good model for future changes, at least over the next few millennia to tens of millennia. Also, in making projections, it may be useful to characterise an area larger than the site, such that features that are not currently present on the site, but could be present in the future, are appropriately identified and characterised.

2.5 Source term and geosphere-biosphere interface

The geosphere-biosphere interface is not an intrinsic characteristic of the disposal system. Rather, it is imposed as a convenience in modelling, because it facilitates handling of the deeper components of the disposal system separately from the, often more dynamic and changeable, near-surface and surface components. In some disposal assessments, biosphere modelling is integrated with that of the geosphere and near-field. In such cases, the geosphere-biosphere interface is still present within the integrated model and the same degree of care is needed to ensure consistency across all components.

The location and extent of the geosphere-biosphere interface may change with time. Furthermore, assumptions about the interface may differ for different contaminants and may vary according to whether impacts on human health or the environment are being assessed. Considerations relating to the biosphere, in defining and characterising the geosphere-biosphere interface are set out in detail in a BIOPROTA report and an associated journal article (BIOPROTA 2014, Smith et al. 2014). These documents should be consulted for more detailed information. Previously (IAEA 2003), the geosphere-biosphere interface has been defined in terms of a well, a surface-water body such as a river or lake, surface soils, or a combination of these. In general, the most convenient type of geosphere-biosphere interface to adopt will depend on the type of disposal concept, the site context and the approach to system modelling applied in the overall post-closure safety assessment. In some integrated approaches to modelling, it may not even be necessary to define a geosphere-biosphere interface (see for example, SKB 2014).

In the overall assessment context, characterisation of the source term relates mainly to consideration of the physico-chemical form of the waste and the way in which it is conditioned and packaged. In some contexts, there may be no projected releases of contaminants from the wastes themselves until they are contacted by groundwater penetrating the packaging. For spent fuel or high-level waste contained within high-integrity waste packages, e.g. copper canisters, the delay before release from the waste may be hundreds of thousands of years. In contrast, for other types of waste and for non-radioactive materials incorporated in the closed facility, releases to the geosphere may begin almost immediately after repository closure.

Once releases to the geosphere start to occur, release rates will be determined by the availability of contaminants in the wastes[4], the solubility of those contaminants, and their sorption to near-field materials, such as corrosion products. Consideration needs also to be given to potential releases of volatile substances in gaseous form, e.g. C-14 incorporated into methane.

In terms of releases to the biosphere across the geosphere-biosphere interface, the source term may be expressed either as a flux per unit time (e.g. Bq y^{-1}) or a flux per unit area and per unit time (e.g. Bq m^{-2} y^{-1}). Alternatively, the source term may be expressed as a concentration (e.g. Bq m^{-3} in groundwater). There is likely to be a conversion issue arising in this context, e.g. with a flux per unit time being supplied from the geosphere model, but with a concentration required by the biosphere model. It is important that when making such a conversion (in this example by diluting the delivered flux by a groundwater flow rate (m^3 y^{-1})) that the conversion factor used is fully justified and consistent with the assumed fluxes in the geosphere modelling. This will typically require physically-based modelling.

Contaminants may be released to the biosphere in liquid, gaseous or solid form. Contaminants dissolved in groundwater may either discharge at the surface, mixing with recent meteoric water as it does so, or be subject to well abstraction. Colloidal transport and precipitation associated with the groundwater pathway can may also be relevant. Volatile radionuclides and other substances, notably hydrogen, methane and carbon dioxide, may be released in gaseous form. Solid releases can arise through erosion into either a developing contaminant plume or into the disposal facility itself, or through human intrusion into the disposal facility or its immediate environs.

The spatial scale of releases to the biosphere may differ substantially depending upon the type of repository under consideration and its hydrogeological context. For example, releases from an intermediate level waste facility may be broadly distributed over its area, whereas releases from a spent fuel repository may arise from only one or a few damaged disposal canisters. In fractured hard rock environments, either distributed or localised releases from a repository may be captured by, and transported through, a small number of major fractures containing flowing groundwater. In turn, these fractures may be expressed as particular features in the landscapes, e.g. fault-bounded valleys. In contrast, in sedimentary sequences releases may become widely dispersed in a local or regional aquifer prior to being subject to well abstraction or discharging to soils or surface-water bodies such as rivers and lakes. For near-coastal facilities discharges may occur to estuarine, coastal or marine environments, where much more rapid and effective dispersion and dilution may occur than is characteristic of many terrestrial environments.

For releases over limited spatial extents, the main consideration in determining radiological and non-radiological impacts may not be contaminant concentrations in environmental media within the release area, but average concentrations in a wider area, determined by, for example, resource requirements of the potentially exposed groups of humans and/or characteristic exploitation ranges of potentially exposed populations of biota. It is, therefore, important to avoid being unduly constrained to the area in the immediate vicinity of contaminant releases when considering the biosphere.

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[4] For example, actinides incorporated within the matrix of spent nuclear fuel or metals such as chromium that are present as components of corrosion-resistant steels will be of low availability, whereas anions such as Cl-36 and I-129 in ungrouted low level wastes or in the 'gap' inventory of spent fuel are likely to be of high availability.

2.6 Time frames

Broadly speaking, a distinction can be made between the time that elapses before contaminants begin to be released to the biosphere in significant amounts, noting that this may be beyond the limit of the assessment period for some repository systems, and the duration of the period over which such releases occur. For biosphere assessment, an important focus is on the period over which releases occur. However, in the overall assessment context, both the time elapsed before releases start to occur and the duration of those releases are relevant, as the climate and landscape will change over both these periods, with potentially significant effects on releases of contaminants from the engineered near-field and through the geosphere. Knowledge of projected long-term changes in climate and an understanding of the past and present-day characteristics of a site, as determined from site characterisation, can be used to inform the development of definitions of future biosphere systems and the characterisation of those systems for use in post-closure safety assessment.

Although the characteristics of the biosphere appropriate to the near future may be closely constrained (though even on timescales of a few years human actions can impose significant changes, e.g. in land use, see also Section 2.7), at longer times into the future greater uncertainties arise. Also, whereas changes may be gradual for an extended period, there may then occur an event, such as the advance of an ice sheet across the site, that completely resets the characteristics of the biosphere. Overall, the increase in uncertainties with time mean that the quantitative results obtained from assessments based on present-day characteristics become increasingly illustrative and this must be taken into account in their interpretation, bearing in mind the consideration that the intent is not to predict the future, but to provide a reasonable assurance of safety. On very long timescales, simple but robust calculations and, possibly, other complementary arguments (e.g. based on natural analogues) are likely to be preferred over very detailed calculations, where the level of detail cannot be supported because of uncertainties in how the biosphere may develop.

2.7 Societal assumptions

Assessment timescales beyond even a few tens, or at most hundreds, of years introduce profound uncertainty into any quantitative description of human behaviour. This means that the biosphere adopted for assessing system safety, in which human behaviour is an integral part, can only be considered as illustrative i.e. as providing indicators of the potential adverse impact of the repository. When integrated with understanding arising from assessments of the behaviour of the disposal system as a whole, these indicators are then used as input to decisions regarding the acceptability of long-term safety performance.

As there is little technical basis for predicting the nature of future human behaviour, it is necessary to make a variety of assumptions in order to quantify potential adverse impacts on human health and the environment (the latter is included because human activities can have a strong influence on the characteristics, distribution and abundance of different types of biota, which may, in turn, significantly influence the assessed adverse impacts arising from releases of radioactive and other materials on both humans and the environment). Typically, present-day levels of technology are assumed, but this still leaves open the potential to assume a wide variety of patterns of human behaviour, with attention often focused on those patterns of behaviour that are likely to maximise exposure to repository-derived contaminants, e.g. through maximum reasonable use of local resources.

3 Representation of the biosphere

After definition of the assessment context, the next stage of the updated BIOMASS methodology is to identify, justify and describe the biosphere systems to be represented in the post-closure safety assessment. External factors (EFEPs mentioned previously), such as those associated with global changes in climate, earth processes and human activities, are typically used as drivers for reference and alternative evolution scenarios to be addressed in the overall safety assessment. The biospheres identified for assessment need to be consistent with the overall assessment scenarios and associated boundary conditions.

3.1 Identification of the biosphere and characterisation of its development

3.1.1 Selecting the biosphere systems to be described

As noted in Section 1.7, different scenarios for the overall disposal system evolution may require distinct biosphere representations. However, even within one scenario, various alternative approaches may be adopted to the definition of biosphere systems appropriate to assessment (see Section 1.4). It should be kept in mind that, in the current context, the emphasis is on the development of biosphere system definitions suitable for assessing potential adverse effects on human health and the environment due to releases of contaminants from a disposal facility for solid radioactive wastes. At a broader scale, these biosphere representations should be compatible with the changing climate and landscape projected to apply to the region of the disposal facility under the scenario being investigated.

Figure 3-1 shows a decision tree for defining the biosphere systems appropriate to assessment for a specific scenario under a specific regulatory regime. In some assessment contexts, the biosphere system or systems may be prescribed by legislation or guidance (Option 1), e.g. present-day conditions are to be assumed over a quantitative assessment period of 10 000 years. In such a context, all that is required is to describe the pre-defined biosphere system(s). This is not necessarily a trivial exercise. For example, a large amount of site-specific information may need to be collected and analysed to ensure that present-day conditions are described in sufficient detail for assessment purposes.

If the biosphere system is not predefined, then the principal characteristics of the biosphere system(s) must be identified and described. However, the level and nature of the description can only be determined once subsequent decisions have been taken on whether and how biosphere system change is to be addressed. Thus, at this stage, it is sufficient to list the principal characteristics for each biosphere system that will require detailed descriptions at a later stage. These have been identified (IAEA 2003) as:

- Climate and atmospheric composition.
- Geographical location and extent of the biosphere system.
- Topography of the biosphere system.
- Near-surface lithostratigraphy, covering the structure and composition of soils, sediments and weathered material overlying the bedrock.
- Subsurface and surface water bodies, which may include near-surface aquifers and ice caps or ice sheets.
- Terrestrial and aquatic biota present within the biosphere system(s).
- Human communities within the biosphere system, including their behaviour, level of technological development and degree of subsistence.

It is emphasised that these are broad characteristics of the biosphere. They are not defined and do not require description at the level of detail appropriate to development of a conceptual model of either the biosphere system or of the transport of contaminants through that biosphere system and evaluation of the potential adverse impacts of those contaminants on human health and the environment.

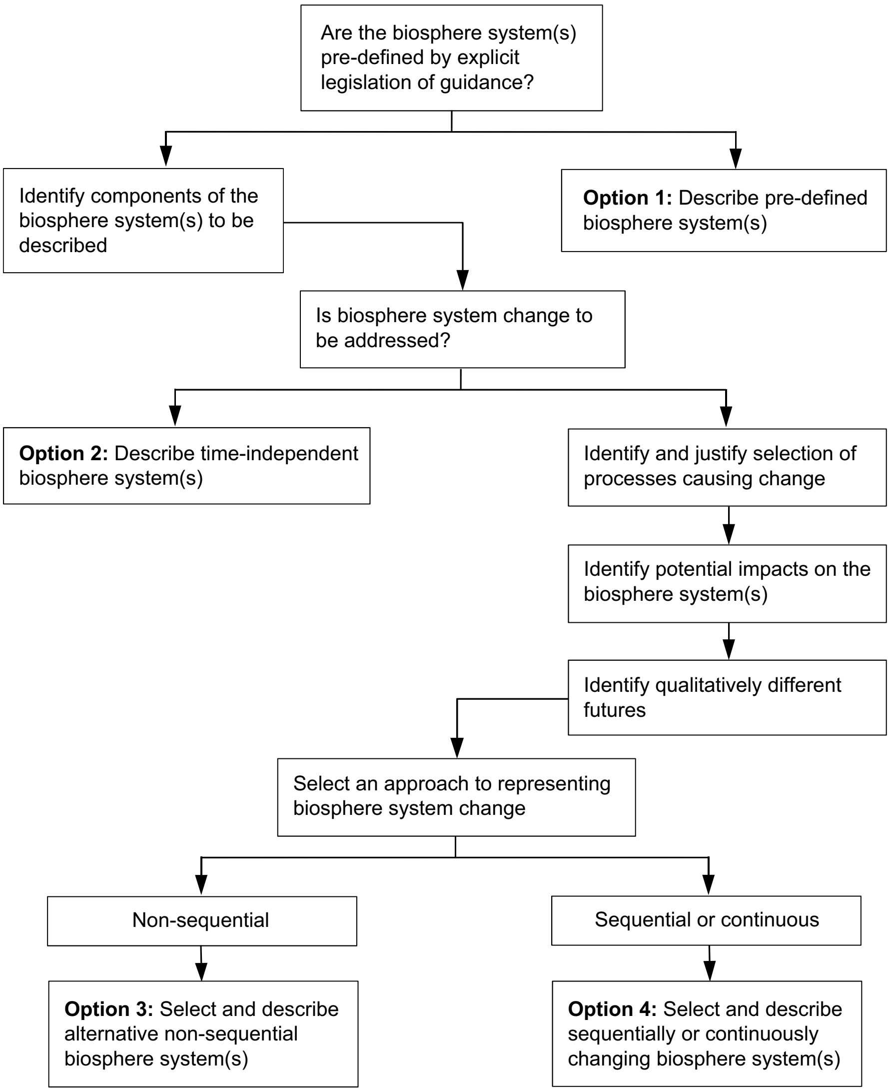


Figure 3-1. *Decision tree for the description of biosphere system(s)*

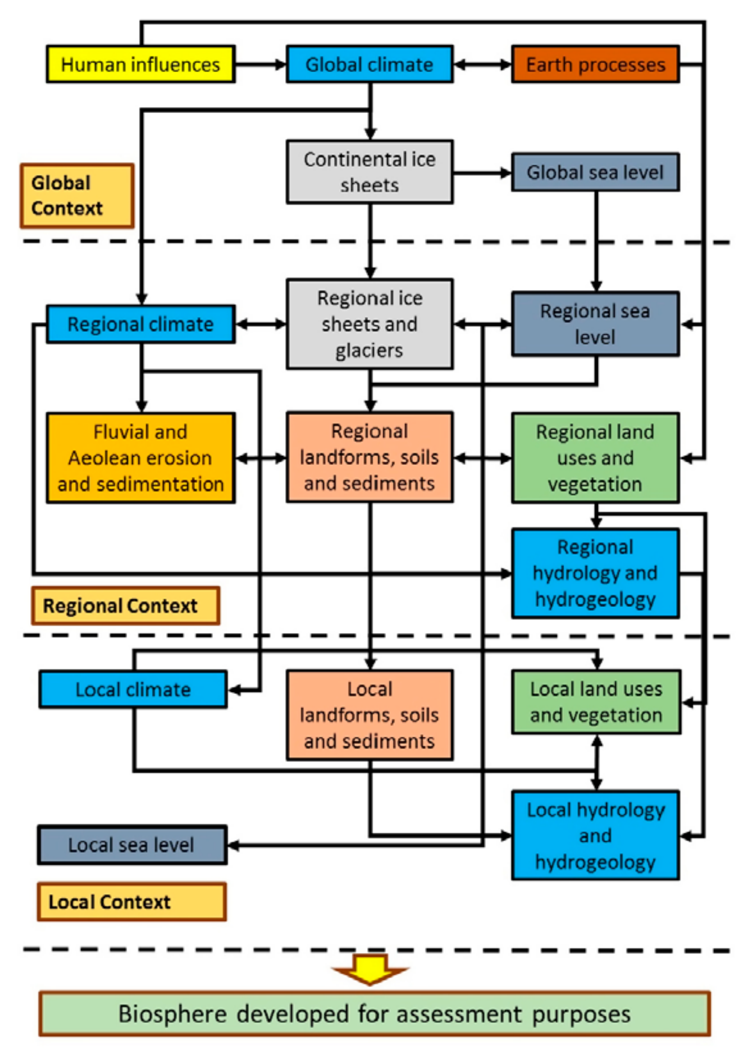
It may be appropriate to use information from site characterisation to describe these principal characteristics of the biosphere at the present day, and to use climate and landscape modelling (undertaken in the overall assessment context) to project how these components may change with time into the future.

If biosphere system change is not to be addressed, then Option 2 applies and all that is required is to describe a time-independent biosphere system or systems. More than one system may be required if, for example, various alternative potential groundwater-discharge or well-abstraction locations are identified. However, if biosphere system change is to be addressed then consideration must be given to the processes causing change and their potential impacts on the biosphere system, with a view to identifying qualitatively different futures that need to be assessed, since more minor changes in biosphere characteristics can typically be addressed through parameter variation within a single conceptual and mathematical model of the biosphere system.

In identifying the causes of change, it is likely to be helpful to distinguish between those that are internal to the biosphere system and those that are external to it. External causes (i.e. EFEPs) may arise as a result of natural processes or human actions and may include, for example changes in land use, climate change (which may be either natural or human induced), and earth processes, e.g. isostatic movements of the crust. All these examples are closely linked, with human activities affecting climate, climate affecting earth processes, e.g. through changes in ice and water loadings on the continents and ocean basins, and earth processes affecting land use through changes in shoreline location. The EFEPs will then affect the internal characteristics of the biosphere in a wide variety of ways. The relationship between EFEPs and internal causes of change is explored further in Box 2.

Box 2: Relationship of EFEPS to internal biosphere system characteristics

The way in which EFEPs cause changes in the biosphere system of relevance to assessments is illustrated in the following figure.



In this figure, EFEPs are identified as operating at a global scale. The main influence is the changing climate. Changes in climate are caused both by natural processes and by human activities. Relevant earth processes include volcanism. Extra-terrestrial processes, such as meteorite impact, are of little importance, mainly because of the very low rate of occurrence of events of significance to repository safety. Changes in climate affect the existence and size of continental ice sheets, which, in turn, change the amount of water in the oceans and hence global sea level. At a regional scale, deformation of the Earth's crust due to changing ice-sheet and water loadings means that regional sea-level changes may differ from global changes. Also, regional changes in climate may differ markedly from overall global changes. Regional changes in climate, and alterations in the position of the shoreline at coastal locations, affect the erosional and depositional regime, vegetation cover and land use, and the characteristics of soils and sediments. Changes in climate and in these other factors affect the regional hydrological and hydrogeological regime (e.g. altering the volumes and flows of surface-water bodies, and the characteristics of groundwater aquifers). Changes that occur at a regional scale set the context in which changes in biosphere characteristics occur at the site of interest and in its immediate vicinity. It is these characteristics that constrain the biosphere systems of interest that must be specified for assessment purposes. More detail on the processes determining climate change at different spatial scales and of the effects of those changes on the landscape are given in IAEA (2016b).

In practice, if climate and landscape modelling studies are undertaken, then a quantitative account should be available of how external processes (primarily climate-related processes, e.g. erosion and sea-level change, and earth system processes, e.g. isostatic uplift and subsidence) will impact the biosphere system over time. However, it may be that insufficient information is available for quantitative climate and landscape modelling. In such circumstances, it may only be possible to construct a generalised narrative of how the biosphere system is expected to change with time.

Also, although the biosphere system will change continuously with time, it may not be necessary to model the process of change in assessments. Rather, a set of calculations for time-independent biosphere systems may be sufficient to determine the range of potential adverse impacts on human health and the environment. This would be the case, for example, if the key contaminants had short residence times in the biosphere system compared with the timescales over which the biosphere system was projected to change significantly. This does not mean that the biosphere system to be modelled would be that of the present day. Substantial biosphere change could occur before the release of contaminants began. The key consideration would then be whether the released contaminants had short residence times in the then existing biosphere compared with its persistence. If releases could occur after different periods of delay, or if there was uncertainty as to what type of biosphere system might be present after a specific period of delay, it might be appropriate to model several different types of biosphere, but without making any judgement as to their order of occurrence or as to their probability of occurrence.

These various considerations suggest two broad approaches by which biosphere system change might be represented in safety assessments. In Option 3, it is determined that the biosphere has only a limited ‘memory’ of the time history of previous discharges of contaminants. Thus, calculations can be made for individual biosphere states separately, with no need to evaluate the durations of those states or the order/probability with which they occur. Where contaminants are envisaged to persist in the biosphere system on timescales comparable with or longer than those over which significant changes in the biosphere system occur, then Option 4 is likely to be applicable. Option 4, treats the biosphere system either as a sequence of time-independent states with transitional periods (which may be of extended duration) between them (as was done in BIOCLIM 2004) or as a continuously changing system. The sequential approach may be useful where generalised narratives of expected patterns of future biosphere system change are available, but there is no fully quantitative model of such change. In this case, the narrative can be used to construct descriptions of the individual states, e.g. based on analogue data from various locations, and the characteristics of transitions can be inferred by interpolation between the before and after end states.

Where a quantitative model of climate and landscape change is available, this can be used to underpin a quantitative model of biosphere system change. Thus, a time-dependent model for contaminant transport and accumulation in the biosphere can be coupled to a time-dependent model for contaminant release from the near field and transport through the geosphere. This approach may be preferred when enough data are available to construct a time-dependent model of the overall disposal system, and where key contaminants are retained in the various components of the system on timescales comparable with, or longer than, the timescales over which those components change substantially.

The sequential and continuous approaches to representing biosphere change are included under a single option to emphasise that mixed or intermediate representations may sometimes be appropriate. Thus, for example, a continuous description of larger-scale changes, e.g. shifts in the position of the shoreline, may be coupled with snapshot descriptions of various aspects of the landscape that arise because of such changes, e.g. the types of lake that may be present.

Whichever of the options is adopted, the aim is to produce narratives of changing biosphere characteristics and how they are to be considered in assessment studies. These narratives (incorporating both text descriptions and diagrams) provide a context in which biosphere descriptions are developed and those descriptions transformed into conceptual and mathematical models. These matters are addressed below.

Box 3: Example of the Influence of Assessment Context on Biosphere Identification and Justification

[Can describe the way that the long-term climate representation in SR-Site and SR-PSU differs due to time scale of potential interest. To be included in a future version of this report.]

3.1.2 Narrative description of biosphere system(s)

In the previous subsection, the characteristics of the biosphere system(s) to be described and modelled for assessment purposes were identified. In the context of biosphere identification, these need to be described in broad narrative terms (more detailed description is the next stage of the methodology, Section 3.2). The narrative description(s) may, for example, be set in a broader context by systematically following from global through regional to the local scale (consistent with Box 2).

Climate and atmospheric composition: Climate could be described in terms of the Køppen-Trewartha scheme (Rudloff 1981) or that scheme could be used to define a set of climate stations with a range of climates that could be characteristic of the biosphere system under consideration. Alternatively, quantitative climate modelling could be used to characterise the range of climatic conditions that could occur for the biosphere system under consideration. The climatic conditions might be characterised for a time-independent state (e.g. described as glacial, periglacial or interglacial), with potential changes in time mapped into uncertainties in the characteristics at any time during the existence of that state, or changes in climate with time during that state might be represented explicitly. The approach adopted would depend on which option for assessment was adopted from the decision tree in Figure 3-1.

Atmospheric composition might be described only in terms of concentrations of greenhouse gases and aerosols, with consideration being given to ensuring that these concentrations were consistent with the climatic conditions associated with the biosphere system. Other potentially relevant characteristics of the atmosphere, e.g. relative humidity and wind field, would be included in the description of climate.

In general, the principal characteristics of climate of relevance would be seasonal temperatures and precipitation, but derived variables, such as soil-moisture content and precipitation minus actual evapotranspiration, might also be described.

Geographical extent and location of the biosphere system(s): These are primarily of relevance in defining the variation in aspects of the biosphere system(s) to be described. For overall assessment purposes, an area substantially larger than the site might need to be adopted, since this would define the boundary conditions relevant to characterising the deep hydrogeology and hydrogeochemistry of the disposal system. For biosphere assessment purposes, a smaller area might be defined, but this area would not necessarily be located immediately above the disposal facility. Instead, it might be at some distance from it and be located over an area or areas where contaminants might discharge into the accessible near-surface environment or form a plume in a water body that could potentially be used for groundwater abstraction.

Topography of the biosphere system(s): This influences factors such as land use, settlement patterns and the nature of the drainage network. It can also affect local climatic conditions (e.g. through the influence of altitude and aspect). At the stage of biosphere identification, it would need to be described only in broad terms. However, once the geographical extent and location of the biosphere have been defined, it is relatively straightforward to develop a quantitative description of the topography, e.g. a Digital Elevation Model (DEM) can be developed for the present-day system and geomorphological models can be used to inform how that DEM should change with time due to aeolian, fluvial and coastal processes. This would be a part of conceptual model development but could feed back into biosphere system characterisation.

Near-surface lithostratigraphy: As with topography, the lithostratigraphy of the biosphere system is likely to be a relatively stable aspect, though potentially altered from its present-day characteristics by erosion and deposition. For a specific site, it can be studied in detail during site characterisation by both invasive (e.g. borehole) and non-invasive (e.g. ground radar and seismic survey) techniques.

Both topography and lithostratigraphy will need to be characterised by reference to the broader context of the overall disposal system, since topographic features may be controlled by underlying geological structures, such as faults, and the composition of soils, sediments and weathered rock will often be closely related to that of the underlying geology (though not, for example, where the superficial deposits have been transported from elsewhere by ice sheets and laid down during the subsequent retreat of the ice).

Subsurface and surface water bodies: Surface-water bodies can be described in general terms, e.g. the overall drainage density likely to be present in the landscape and the potential locations of lakes. Similarly, subsurface water bodies can be described in terms of those strata in which aquifers are likely to be present. These descriptions will rely heavily on the characteristics of the climate, topography and lithostratigraphy. It is likely that site characterisation and geomorphological modelling of how the topography of the site and its vicinity may change over the assessment timescale will result in a need to revisit the descriptions of subsurface and surface water bodies associated with a specific biosphere system. Thus, iteration is particularly important in ensuring that the description of surface and subsurface water bodies is coherent with the developing understanding of site topography and lithostratigraphy under the climate conditions adopted for assessment purposes.

Human communities and terrestrial and aquatic biota: The biota potentially present within the biosphere system(s) will be determined, in part, by the climatic conditions and by the topography of the landscape. However, they will often also be strongly determined by land uses and human community aspects. Thus, it is appropriate to consider these two aspects together. Specifically, the type of human community adopted may be partly determined by the assessment context (e.g. a requirement to make maximum reasonable use of the contaminated land). In turn, this will constrain the types of land use and partially determine the types of biota likely to be present.

Nevertheless, even if the assessment context places constraints on human community, land uses, and biota characteristics, those constraints are unlikely to fully define these characteristics of the biosphere system. Thus, there is the potential to describe a biosphere system with a heterogeneous human community and mix of land uses within which several different Potentially Exposed Groups (PEGs) and Potentially Exposed Populations (PEPs) may be defined for assessment purposes. The selection of PEGs and PEPs is addressed later in this report.

3.2 Biosphere description

Narratives of the biosphere system(s) that need to be represented in the post-closure safety assessment need to be developed into descriptions sufficient to provide a foundation for building conceptual and mathematical models. These descriptions, which provide accounts of the broad characteristics of the biosphere systems of interest and of why those characteristics are relevant, may be of time-independent states, the transitions between those states, or of a time-dependent biosphere system. In a generic study of a region, it is likely to be possible to describe the broad climate conditions existing at the present day, the typical topographic contrasts and the variations in lithostratigraphy. It is also likely to be possible to make broad projections of these characteristics into the future, at least until grossly disruptive external events occur, e.g. the advance and retreat of ice sheets or glaciers over the region. Once attention is focused on one or a few sites, it is anticipated that desk studies will be complemented by a site characterisation programme and that, as this programme proceeds, information from field and laboratory studies relating to the site or sites will come to dominate the information available to characterise that site or sites.

As noted previously, biosphere system(s) identified and characterised for assessment purposes are not to be regarded as predictions, they represent internally self-consistent projections of a range of plausible situations that are used to assess the range of potential adverse impacts that could occur due to releases of contaminants from a closed disposal facility. The range of systems that are identified and characterised should therefore be sufficient to satisfy the assessment purpose.

Site characterisation provides an important input into biosphere system descriptions appropriate to safety assessment, informing on present-day and past characteristics of the site and/or future analogues. The characteristics of the site at the present-day may be assessed as being subject to only limited modification over the next few millennia, whereas palaeo-environmental and/or site-analogue data may be used to infer likely characteristics at the site during projected future periods. Therefore, it is important that site characterisation data should be structured in such a way as to facilitate the use of those data in developing biosphere system descriptions appropriate to safety assessment.

In terms of developing biosphere system descriptions appropriate to safety assessment, various tools may be used, but an important consideration is that the tools adopted should facilitate the conversion of each system description into a conceptual and then a mathematical model of the system. Thus, both interaction matrices and influence diagrams are likely to be useful in the subsequent interpretation of a biosphere description expressed in narrative terms. The nature and roles of such tools are discussed in later sections of this report.

This stage of the BIOMASS methodology delivers full descriptions of the biosphere system(s) and their evolution that need to be represented in the post-closure safety assessment. Such descriptions may be supported by outputs from quantitative supportive modelling, including, for example, projections of climate characteristics, landscape development modelling, near-surface hydrogeology and surface hydrology modelling. Translating this understanding into conceptual models of contaminant migration and potential exposure within the context of these descriptions and thence into a quantitative mathematical model is the topic of Chapter 4.

4 Biosphere modelling

After identifying, justifying and describing the biosphere systems for assessment, the next stage of the updated BIOMASS methodology is to develop associated quantitative models of contaminant migration and potential exposure. The biosphere models need to be developed in a way that is both practical and transparent. Model development therefore follows a systematic approach that allows assumptions and simplifications to be recorded and justified in a traceable manner. The starting point for simulating contaminant transport, accumulation and exposure is the description of the biosphere (provided above) in which exposures are assumed to take place, coupled with a description of contaminant release into or within that system.

The development and justification of a biosphere assessment model will almost never be a linear process; an iterative approach to refining the model, as well as enhancements to the corresponding biosphere description, will typically be needed to ensure that a practicable and justifiable model is achieved. Nevertheless, the following basic steps can be identified, building-on from the biosphere system description.

1. Identify and characterise the human PEGs and PEPs of biota that need to be explicitly addressed in the assessment based on the description of the source term to the biosphere (described in the assessment context) and the human and biota communities (defined in the biosphere description).
2. Identify those principal biosphere components that are to be distinguished as separate features (i.e. distinct potentially contaminated environmental media) in the representation of contaminant transport and potential exposure of the identified PEGs and PEPs.
3. Devise a conceptual model of contaminant transport between these media, while taking into account the assumed spatial configuration and intrinsic dynamics of the biosphere features, and of how the contaminated media give rise to potential exposures of the PEGs and PEPs.
4. Define the mathematical model, taking account of the availability of data.
5. Collate and justify the data required by the mathematical model, drawing on the system description and taking account of the approach defined in the assessment context with regards to treatment of parameter uncertainties.
6. Implement, verify and validate[5] the model and undertake the calculations.

An overall conceptual model for the biosphere may be developed that encompasses potential contaminant behaviour and exposure within all the scenarios to be considered within an assessment. Alternatively, several specific conceptual models may be developed for each scenario, or for sub-sets of the scenarios to be considered. The choice will reflect the degree of consistency in the timing, location and form of contaminant releases to the biosphere, and the variety of assessment endpoints that need to be addressed. For example, radionuclide releases in post-glacial conditions may require a different conceptual model to releases in interglacial conditions, radionuclide releases in the gas phase may need to be treated differently from releases in groundwater, releases of radioisotopes of elements that are involved in major biogeochemical cycles (e.g. C-14) may require specific models and impacts on PEPs may be assessed using a different model from that used to assess impacts on PEGs. However, where different transport and exposure pathways can be handled within a single conceptual model, this may be preferred, both for consistency and in presenting the results of the assessment.

Each of the steps towards model development is discussed in turn in the sub-sections below.

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[5] It is typically impracticable to validate biosphere assessment models over the timescales relevant to post-closure safety assessment, nonetheless, it may be possible to validate components of the models and thereby build confidence in the whole (Hill, 1989).

4.1 Defining human exposure groups and biota populations

The assessment context provides a description of the contaminant source terms to the biosphere and the biosphere description provides information about the potentially evolving environment into or within which those contaminants are released, together with a definition of human communities and biota within that environment. From these inputs, with reference back to guidance on the definition of endpoints included within the assessment context (see Section 2.2), the next step of the updated BIOMASS methodology is to define the sub-set of PEGs and PEPs that need to be quantitatively evaluated through biosphere modelling.

Several factors merit consideration when defining PEGs and PEPs for explicit representation in the biosphere modelling; these are discussed below. There is inevitably a degree of iteration between developing conceptual models for contaminant behaviour (the next step in the methodology) and defining the human and biota exposure groups and populations. The former provides understanding of potentially contaminated environmental media, whereas the latter provides constraints with regards to the locations and associated areas of interest. Assessments typically aim to ensure that potential exposures are not underestimated, which focuses attention on the areas of potential contaminant accumulation, coupled with behaviours that may maximise associated exposures.

The assessment context may include guidance on the size and behaviours of PEGs and PEPs, which may, in turn, be derived from regulatory guidance.

In general terms and in relation to radiological exposures of humans, the emphasis is on the most exposed individual, but for assessment purposes this is generally interpreted as a representative person from a more highly exposed group in the population (ICRP 2007). Typically, the emphasis is on the exposure of adults, as an adequate representation of long-term (lifetime) exposure, but doses to other age groups are often also assessed for comparative purposes. In any case, annual effective dose is the main quantity that is calculated. Where it is required to assess annual or lifetime risks, annual or lifetime effective doses are multiplied by a standard factor of risk per unit of effective dose, i.e. the linear no-threshold dose-response model is implicitly assumed. Collective effective dose is not generally considered to be a useful measure of system performance and is not usually calculated, but *per capita* doses or to larger populations located on or near the assumed contaminated environment are sometimes calculated.

For biota, absorbed dose rates from external plus internal exposure are usually calculated, sometimes with high-linear energy transfer (LET) components given a larger weighting than low-LET components. These dose rates are typically compared with screening dose rates below which significant adverse effects on populations are not expected to occur. It remains unclear how dose rates above these screening levels should be interpreted in terms of potential adverse effects on populations.

For non-radioactive contaminants, comparisons are generally made with standards and criteria for limiting concentrations in environmental media. These include drinking-water criteria recommended by the World Health Organisation (WHO) and Environmental Quality Standards (EQS) developed by various national regulators.

In broad terms, exposures of humans and other biota from radionuclides released to the biosphere can be distinguished into external and internal exposures. External exposures arise due to irradiation from the contaminated environmental media and are determined by the geometry of those media, the sizes and shapes of the exposed organisms, and their location relative to the contaminated media. Internal exposures arise primarily from ingestion or inhalation of radionuclides, but uptake across body surfaces or from wounds can be of significance in some contexts. Ingestion involves a variety of pathways, but broadly comprises foods, waters and non-food materials, e.g. soil or sediment attached to foods. For non-radioactive contaminants, external exposure is not usually a consideration and internal exposure pathways are similar to those applicable to radionuclides. External contact could be an issue for those substances for which allergic reactions are a possibility, e.g. contact dermatitis.

Selection of both the communities to be adopted for assessment purposes and the PEGs within them need to consider stakeholder interests. Therefore, it may be important to explicitly include community characteristics and patterns of behaviour that are either typical or distinctive at the present day. In particular, there may be concern that specific exposure pathways considered distinctive of the community at the present day are included in the assessment even if potential adverse impacts are found to be relatively low. However, a focus on the present-day community must not result in exclusion from consideration of potential future communities within which exposures might be larger than in the present-day community.

Prior to undertaking the assessment modelling, it may be unclear which parts of the biosphere will give rise to the highest potential exposures. If it is considered unreasonable to assume that a single PEG or PEP may be maximally exposed via the range of potential pathways that are to be assessed, then more than one group and/or population may be defined.

It is important to keep in mind that it is not possible to predict societal or human behavioural characteristics over the multi-millennial timescales typically of relevance in post-closure safety assessment of solid radioactive waste disposal. Thus, PEGs should be defined in broad terms (e.g. intake rates of broad classes of foodstuffs, rather than individual foods), to avoid any implication that details of future behaviour can be predicted.

In general, PEG characteristics have tended to be treated deterministically, using point values for occupancies of contaminated areas, consumption of food, water and other materials, and respiratory characteristics. This approach tends to be adopted in recognition that the exposures being calculated are indicative and are for a representative individual, rather than being measures of the distributions of exposures in a real local population. Where probabilistic modelling is adopted, broad food categories should be used, as the variability in consumption rates can be large for individual foods, but the primary consideration is the uncertainty in radionuclide intake considered across the diet as a whole.

Consideration will also need to be given as to whether the focus is to be on typical or more extreme patterns of behaviour within the community. The adoption of more extreme patterns of behaviour coupled with a requirement that those patterns of behaviour are focused on the more highly exposed components of the environment, could be regarded as unduly cautious.

[Guidance to be included on the definition of PEPs, potentially with some short introductory text and the box below. Bearing in mind that the ecosystems will have been described in Chapter 3, so this is about selecting PEPs/RAPs etc for explicit assessment]

Box 4: Selection principles for potentially exposed populations (PEPs)

[To be inserted here. To include consideration of landscape scenarios that may be of interest for assessment of PEPs in comparison to humans. To highlight the BIOPROTA SPACE report.]

4.2 Identification of conceptual model COMPONENTS

Environmental media to be represented as separate conceptual model components should be distinguished not only based on their contribution to potential contaminant impacts (e.g. resources exploited by humans and biota), but also in terms of the role they would play in contaminant migration and accumulation. These conceptual model components and their properties are largely analogous to features within the biosphere system from the perspective of FEP analysis.

The principal characteristics identified earlier are discussed below from the perspective of contaminant behaviour and potential exposures. Note that these principal characteristics and associated aspects of them are defined much more broadly than the environmental media that would be included in a conceptual model for a specific biosphere system.

- **Climate and atmosphere:** The near-surface atmosphere within the modelled region is a component of the biosphere, the properties of which are defined by the local climatic conditions. Contaminants can reach the atmosphere in particulate, aerosol and/or gaseous form and give rise to potential exposures. Contaminants reaching the atmosphere may be relatively quickly dispersed outside the biosphere system of interest.

- **Location, geographical extent and topography of the biosphere system:** The geographical extent and topography of the biosphere system will determine the spatial extent of the media to be represented in the conceptual model. It will also determine whether any explicit sub-division of biosphere components (e.g. soils, sediments and water bodies) may be needed to reflect their configuration. For example, different locations/regions/ecosystems may need to be distinguished in the conceptual model for contaminant migration and potential exposure.
- **Near-surface lithostratigraphy:** This is distinguished into a sub-surface component (e.g. below a rooting/bioturbation depth) and surface soils and sediments.
    - *Sub-surface lithostratigraphy:* This may comprise weathered and/or till material overlying a bedrock that falls outside the region considered in any geosphere modelling. This component helps to define the configuration and properties of the hydrogeological system and may host near-surface aquifers (it is therefore linked with water bodies, see below).
    - *Soils/Sediments:* Soils and sediments are intrinsic principal components of terrestrial and aquatic ecosystems and it is, therefore, appropriate to identify physically distinct regions within the conceptual model, linked to each ecosystem that is identified as being present within the biosphere. Depending on assumptions concerning the nature of the geosphere-biosphere interface and on how principal components of the biosphere system are spatially configured, further sub-division may be required to distinguish regions of the same soil or sediment type that play distinctly different roles in contaminant transport and accumulation within the biosphere. For example, if the interface for release to the biosphere is an irrigation well, it may be appropriate simply to consider a single "irrigated soil" medium. Alternatively, for contamination resulting from natural discharge of groundwater, there may be several different soil/sediment types (differing e.g. by their hydraulic and/or sorption properties) and regions of interest.
- **Water bodies:** As with near-surface lithostratigraphy above, this is distinguished into surface and sub-surface components.
    - *Sub-surface water bodies:* Sub-surface water bodies identified as belonging to the biosphere system can be considered conceptually as part of the geological strata within which they exist (see above). Alternatively, when developing a conceptual model, it may be helpful to consider soil/sediment solids as distinct from soil/sediment water, i.e. to have two conceptually distinct environmental media occupying the same spatial domain. This would be the case, for example, if there was a need to represent explicitly exchange processes between soil solids and soil water.
    - *Surface water bodies:* Each surface water body (natural or artificial) that is identified as belonging to the domain of the biosphere system of interest can play a distinct role in the distribution of contaminants and may support a separate ecosystem or sub-ecosystem. Depending on how potential transport and exposure pathways are affected by the assumed spatial and temporal characteristics of surface water bodies, as well as their configuration within the biosphere system, it may be helpful to distinguish different water bodies as separate conceptual model objects. For example, it may be convenient, or necessary to distinguish streams/rivers, lakes, estuaries and marine water, and/or distinguish between deep and shallow lake waters.
- **Biota:** Given the different ways in which plants and animals exist in the biosphere (i.e. principally sessile *versus* principally mobile), it is typically convenient to consider them separately.
    - *Flora:* Taken to encompass plants, fungi, algae, lichen etc. and will include cultivated plants as well as wild plants as well as both terrestrial and aquatic plants. Flora may be an endpoint in themselves (e.g. in biota dose assessment) and/or may contribute to other endpoints (e.g. doses to humans). Flora will also be involved in contaminant migration and distribution in the biosphere, e.g. by taking contaminants up and then changing their mobility by incorporation into organic matter. Flora, therefore, merit explicit consideration as a component of the conceptual model, and may merit further subdivision into parts of plants, as necessary or convenient.
    - *Fauna:* Including both terrestrial and aquatic animals. Fauna will encompass domesticated livestock as well as wildlife. As with flora, fauna may be an endpoint in themselves (e.g. in biota dose assessment) and/or may contribute to other endpoints (e.g. doses to humans). Fauna will also be involved in contaminant migration and distribution in the biosphere, e.g. drinking contaminated water and distributing the contamination across their habitat. Fauna therefore merit explicit consideration as a conceptual model component.

- **Human communities:** The fundamental role played by human communities as a principal component of the biosphere is an important part of the system description. Assumptions relating to the contribution of people to potential contaminant migration and accumulation pathways will be implicitly incorporated in the descriptions of the characteristics, configuration and dynamics of other biosphere system principal components. Nevertheless, it is typically helpful to explicitly include human communities with the conceptual model, both to support identification of exposure pathways (if human doses are an endpoint), as well as to recognise that they can provide a vector for contaminant migration (e.g. via consumption of produce and disposal of waste).

If the spatial scale adopted in the assessment is sufficient to provide sufficient resources for PEGs and PEPs, it may be convenient to sub-divide the overall conceptual model, for example, at the catchment/sub-catchment and/or ecosystem level. Conceptual models may then be more practicably defined for each sub-unit, with interactions between those sub-units then being addressed separately. This is a choice for the assessment team, bearing in mind the objective of being no more complicated than can be justified for the long timescales being considered. Even if the sub-unit distinction is not propagated into the subsequent mathematical models, conceptualising contaminant transport and exposure on a sub-unit basis may aid communication by addressing the problem at a scale that is commensurate with the supporting science and ecosystem understanding and/or at a scale that is more tangible to stakeholders.

It is emphasised that, as with principal characteristics, the biosphere assessment team can determine those aspects that they choose to explicitly represent as components in developing a conceptual model. The above is intended as a guide. Iteration may lead to refinement of the conceptual model, with either greater resolution, or amalgamation of aspects that can be considered together.

In addition to the main components to be considered within the biosphere system, there are two further aspects that are important for consideration in developing the conceptual model, which should also be explicitly considered as components of the conceptual model.

- **Source term(s) to the biosphere:** Although not part of the biosphere itself, the contaminant source terms are an important consideration in the development of the conceptual model of contaminant behaviour and exposure. The nature of the releases to or within the biosphere will determine the form of contamination, e.g. aqueous phase in well water or discharging groundwater, gaseous phase in releases of contaminated gas to the biosphere and/or solid phase in eroding material or contaminated material (including waste) arising from human intrusion. The spatial distribution of the source term(s) will determine which biosphere media are initially affected and the form of contamination will determine the processes that will affect contaminant behaviour in the biosphere. It is therefore typically convenient to explicitly represent the source term(s) as a conceptual model component.
- **Contaminant ‘sinks’:** The spatial extent of the biosphere system will be based on the objectives and constraints defined in the assessment context. Typically, biosphere assessments are limited to considering the region within which potential exposures will be greatest, which, in turn, will typically be near to the points or areas of discharge into the biosphere. The conceptual model will need to explicitly consider mechanisms for contaminants to be lost from the biosphere system to be represented, e.g. via the flow of air, surface water and groundwater out of the system, or through degradation or radioactive decay. Failure to recognise these losses would result in an artificial build-up of contamination within the model.

4.3 Conceptual model of migration and exposure

Having identified the main distinct biosphere features to be represented, a conceptualised description of the dynamics of contaminant transport through the biosphere is then developed based on an analysis of the biosphere system description. Such conceptualised descriptions are typically aided by tools such as process-influence diagrams and/or interaction matrices, which help to systematically consider (i) the potential processes operating between the features to be represented and (ii) associated exposure pathways. It can be helpful to consider both aspects in sequence.

- Process-influence diagrams: The conceptual model components (features) identified above can be represented as boxes in a flow diagram. Annotated arrows between the boxes can be used to illustrate potential movement of contaminants via specific processes that operate between the boxes. Similarly, arrows can be used to highlight exposure pathways to be considered.
- Interaction matrices: The conceptual model components (features) identified above are represented as lead diagonal elements (LDEs) in a matrix (see Box 5). Processes that operate to move contaminants between the features are explicitly listed in the associated off-diagonal elements (ODEs), operating in a clockwise direction. Similarly, potential exposure pathways can be explicitly listed in the ODEs.

The conceptual model of the biosphere may show explicitly, but without the use of equations, how fluxes across the geosphere-biosphere interface can be evaluated in terms of potential adverse impacts on human health and the environment. Thus, the main aspects that should be included are the characteristics of the input fluxes, their transport through and concentrations in the various environmental media comprising the biosphere system, and the implications of those concentrations, e.g. in terms of annual effective doses to humans or absorbed dose rates for biota in case of radionuclides (for non-radioactive contaminants, exposures, intakes or concentrations in tissues or organs will replace these dose-type quantities). Thus, in interaction matrix terms, the fluxes across the geosphere-biosphere interface could be taken as the first element on the LDEs. The next set of LDEs could then be the environmental media through which transport occurs and within which concentrations are estimated. A third set of LDEs could then be the biota and humans, which may both act to transfer contaminants but also act as receptors. The final LDE should be included to represent sinks, allowing contaminants to be lost from the region of interest.

Box 5: Conceptual model developed for RWM's terrestrial biosphere model

[To be addressed in following work programme. Generic context, so relatively simple biosphere model.]

From Walke et al. (2013)

4.3.1 Conceptual model for contaminant migration and accumulation

The conceptual representation of the biosphere system is developed by identifying all processes (and events) that are associated with contaminant transport between those environmental media that have been selected to be represented as separate conceptual model components. Contaminant transport pathways will depend on the assumed spatial configuration and connectivity of the biosphere system components, as reflected in the system description.

During development of the conceptual model, it is important to bear in mind that more than one process or event can act between two conceptual model components. Also, the features represented as distinct media/conceptual model components may have processes that operate intrinsically within them, for example the processes of sorption that determine partitioning between solid and liquid phases within the soil/sediment. Such internal processes are important in determining the transfer of contaminants around the biosphere and need to be captured in the conceptual model, either explicitly within the diagrams or, potentially, within descriptions for each conceptual model component.

There is potential to further disaggregate the conceptual model components to ensure that processes intrinsic to some of the features are made explicit (e.g. by representing soil solids and soil solution as distinct conceptual model components). Should components be disaggregated in developing the conceptual model of contaminant migration and exposure, then the list of conceptual model components defined above would need to be updated accordingly. This provides an example of the iteration that will be needed in developing conceptual models.

The conceptual model should be structured such that it is readily translated into a mathematical model (Section 4.4), with associated supporting data (Section 4.4.5). The longer the timescale of an assessment, the more illustrative the results become. Acknowledging the significant uncertainties associated with long-term assessments should help to constrain the level of detail included within a conceptual model (Section 1.7).

An important component of developing the conceptual model of contaminant migration is to explicitly record judgements regarding the relative significance of processes, especially if they are excluded from the model based on such judgements. Such decisions can be supported by qualitative and/or quantitative arguments. Examples of quantitative evidence include side calculations, previous assessment iterations and/or reference to other evidence in the literature. Qualitative arguments may include natural analogues or expert judgement.

4.3.2 Conceptual model for exposure

To complete the conceptual model, human and biota exposure pathways need to be identified and associated with each of the environmental media represented in the conceptual model for contaminant transport. Assumptions relating to the exploitation of biosphere resources by the human community and the presence of biota populations of interest will have been defined within the biosphere system description. These can be related to the components within the conceptual model, either by annotating the diagrams developed above or separately. If exposed organisms (humans and biota) are included within the conceptual model (e.g. as principal diagonal elements of an interaction matrix), then the representation and annotation of exposure pathways linking environmental media to exposed organisms will occur naturally.

There are also explicit methods for exposure pathway analysis developed in recent years, developed in a broader contaminant context than radioactive waste; e.g. ATSDR (2005). Modes of exposure for chemicals and radioactivity might best be considered coherently, and this issue has been considered within a BIORPOTA project (BIOPROTA 2017b).

Exposure modes for both humans and biota include ingestion of contaminated material (water, food and inadvertent ingestion of soils, sediment and water), inhalation (gases, aerosols/particles), dermal absorption and uptake through wounds. In the case of radionuclides, organisms can also receive a dose from external irradiation (from soils/sediments, from water, including immersion, and from air). As with other system characteristics, the systematic selection of exposure pathways as part of the overall conceptual model for radiological assessment is undertaken by including, where appropriate, modelling judgements regarding the relative significance of specific pathways.

4.3.3 Review of the conceptual model

The approach of building a conceptual model on the foundation of a description of the biosphere system being represented and within the context of the overall assessment aims to help ensure that the resulting model is fit-for-purpose. The model itself may have been developed from a generic or project-specific FEP list (a bottom-up approach as discussed above), or it may have been developed from the system description based on expert judgement (a top-down approach). In either case, once developed, the conceptual model should be reviewed to help build confidence that the potentially important FEPs have been adequately addressed.

Where a top-down approach has been employed, then there is potential for the conceptual model to be checked against a generic or a project-specific FEP list. For each of the conceptual models that have been developed (recognising that different conceptual models may have been developed for different scenarios), the relevance of FEPs can be reviewed. For each FEP that is deemed relevant to the conceptual model in question, its inclusion/representation can be checked. Such a review should be transparently documented, including arguments as to why FEPs are considered irrelevant and explanations of where any relevant FEPs are captured in the conceptual model.

There is potential for such checking to highlight FEPs that may have been overlooked and it may uncover configurations or interactions that have not been considered. Such findings are very helpful, as they enhance the rigour of the assessment. The conceptual model should be updated in response to any such findings and the implications of any changes considered.

In addition to auditing against a FEP list, the conceptual model should also be reviewed and refined. One consideration in refining the conceptual model is that, subject to the overall requirement that it should satisfy the purposes determined by the assessment context, the model should generally also be as simple as can be justified (Section 1.7). Additional complexity that does not lead to a meaningfully improved estimate of the required assessment end points should be screened out.

An example of such refinement may be that there is no need to explicitly represent diffusion in a groundwater pathway dominated by advection. Diffusion in groundwater may therefore be explicitly identified in the conceptual model but may be justifiably excluded from the mathematical model on the basis of its limited significance. Such arguments may be supported by quantitative evidence (e.g. side calculations), reference to previous assessment iterations where the case is demonstrated and/or reference to other assessments or analogues. It is important to record the screening process and the justification used to ensure transparency of the model development process and to help ensure that the target audience or audiences for the assessment can follow the associated logic.

The review/refinement process may include individuals not directly involved in development of the model. There is also potential for stakeholders to be involved in reviewing conceptual models and the scenarios/system descriptions from which they have been derived. Such reviews will help to build confidence that important issues have not been overlooked and will also help to ensure a degree of understanding and buy-in to the biosphere assessment process.

4.4 Mathematical model development

The conceptual model developed using the procedure described above represents a specific list of FEPs that require representation in a quantitative assessment model. Consideration will need to be given to the modelling approach. Because of the distinct media, spatial configuration and connectivity and timescales typically considered in biosphere models, a compartment modelling approach is typically adopted, though finite-element and (integrated) finite-difference approaches may also be considered. However, these are typically more relevant to detailed process models that may be used to underpin the assessment modelling approach.

A compartment modelling approach provides considerable flexibility in scale and resolution, allowing a model to be developed that has sufficient complexity to adequately represent the key components and processes that need to be considered. There is a need to include a sufficient degree of complexity that the results obtained are not biased (e.g. by excessive homogenisation when a small number of compartments is used), but not to make the model more complex than is required by the assessment context (e.g. some homogenisation can be justified by considering the exposure routes, such as harvesting, food processing for humans and home ranges for biota). Each *feature* of the conceptual model is represented with one or more compartments and the *events* and *processes* relevant to the migration of contaminants around the biosphere represented as transfers between the compartments. Contamination may already exist in the compartments at the start of a calculation or may be introduced into the model from elsewhere. Losses from the biosphere can be directed to a 'sink' compartment, which can collect contaminants that migrate outside the region of interest, thereby satisfying balance. General considerations in translating a conceptual model to a mathematical model with the associated propagation of uncertainties are discussed in Appendix A.1 and A.2.

In addition to describing equations for specific transfer and exposure processes, it is important for the underlying basis of any mathematical model to be clearly stated. If a compartment modelling approach is to be used, then the mathematical basis for that model should also be presented, with the number and characteristics of the individual compartments suitably justified. For example, the evolving amount of a contaminant N in compartment i (N_i, moles) can be represented mathematically with the following first-order linear differential equation, if the transfers can be represented as linear functions based on the donor compartments:

$$\frac{dN_i}{dt} = \sum_{j \neq i} \lambda_{ji} N_j + \lambda_M M_i + S_i(t) - \sum_{j \neq i} \lambda_{ij} N_i - \lambda_N N_i \qquad \text{(Eq. 4-1)}$$

where:

i and j are compartments and j is effectively taken to represent compartments other than i ($j \neq i$),

N and M are the amounts (moles) of contaminants N and M in a compartment (M is the parent of N in a decay/degradation chain),

λ_{ji} is the transfer rate representing the loss of contaminant N from compartment j to i (y^{-1}),

λ_N and λ_M are the decay/degradation rates for contaminants N and M, respectively (y^{-1}),

$S_i(t)$ is a time dependent source of contaminant N (moles y^{-1}), such as entering the biosphere from the geosphere, and

λ_{ij} is the transfer rate representing the loss of contaminant N from compartment i to j (y^{-1}).

The first three terms of Equation 4-1 represent process that can add amounts of contaminant N to compartment i; the last two terms represent processes that result in a loss of contaminant N from compartment i.

Equation 4-1 allows time-dependent amounts of contaminants in each compartment to be determined. There are some components of the conceptual model for which the degree of contamination can be considered to be in equilibrium with other components. This arises where transfer processes between those components and other components are typically rapid relative to processes that move contaminants around the biosphere system as a whole and where the uptake of a contaminant can be taken to not significantly diminish the amount in the associated compartment (this may either be because the amount that is transferred is small or may be conservatively neglected). Typical examples include soil-to-plant uptake, direct contamination of plants via irrigation water, and contamination of PEGs and PEPs via ingestion and inhalation.

Equilibrium assumptions determine the number of compartments that need to be explicitly represented and the type of mathematical equations to be used. It is therefore helpful to screen the conceptual model to distinguish those components that can be considered in equilibrium with their environment from those for which explicit representation with compartments is needed (e.g. for soils, sediments, near-surface strata and surface water). It is important that the rationale for equilibrium assumptions is documented based on the biosphere system description, so that the justification for the modelling approach is clearly communicated.

There is an extensive history of biosphere studies from where inspiration can be drawn for mathematically representing processes included in a conceptual model. It is beyond the scope of this guidance to recommend one approach above another. The biosphere assessment team should clearly explain the approach and equations being used to represent the biosphere and justify the level of complexity. Some modelling topics and issues of relevance to biosphere assessment are discussed in the sub-sections below.

During development of the mathematical model, a list of parameters relevant to the calculation will be identified. Each of these, and its specific meaning within the context of the model, should be documented to provide a clear basis for collating the associated data. In practice, the mathematical representation of many processes tends not to be explicit but is instead based on an empirical model of effects observed at the system level. For example, the uptake of radionuclides by plants and other biota is often represented in terms of a concentration ratio, as noted above. An empirical model of this type can represent the combined action of several FEPs (e.g. root uptake and translocation) identified separately within the interaction matrix. Where this is the case, care needs to be taken to avoid double-counting the effects of certain processes or, conversely, the inadvertent exclusion of potentially relevant FEPs.

The mathematical model can be audited against the conceptual model to help build confidence that the specification is complete. The conceptual model will provide a list of FEPs that need to be considered and the relationships between them (possibly expressed in an interaction matrix), which can be used as a check-list for the components of the mathematical model.

The sub-sections below provide guidance on some issues that typically need to be considered for biosphere assessments. These include

- the use of biosphere dose conversion factors (Section 4.4.1),
- the level of detail/complexity that is appropriate to assessments, which is discussed here, although it is equally applicable to other aspects of the assessment, most notably the conceptual model development (Section 4.4.2),
- the importance of discretisation for compartment models (Section 4.4.3),
- the representation of short-lived radioactive progeny in biosphere assessments (Section 4.4.4), and
- modelling of contaminants with special/distinct behaviours in the biosphere, which is again an issue that bridges conceptual and mathematical modelling (Section 4.4.5).

Supporting models or models of sub-systems, may be used to justify simplifications in the overall biosphere model, as discussed, for example, in Appendix B with respect to the 'Smart Kd' concept.

4.4.1 Biosphere dose conversion factors and integrated assessments

It may be appropriate to assess potential adverse impacts of contaminant releases to the biosphere by modelling a constant flux of contaminants to the biosphere and solving the mathematical model to equilibrium to give flux-to-annual-effective-dose factors for humans, flux-to-dose-rate factors for biota, or flux-to-concentration factors for non-radioactive materials. This may be the case if the biosphere is being modelled independently of other components of an assessment and if consideration of the timescales of biosphere change and radionuclide releases mean that it is being represented as specific biosphere states of unspecified duration. These conversion factors can then be used to scale time-dependent fluxes to the biosphere computed using other components of the overall system model. This is a conservative approach for contaminants that take a long time to reach equilibrium in the biosphere compared with the period of peak release from the geosphere.

Conversely, if the biosphere is being represented in an integrated manner with other components of the total system and/or if the system description identifies a need to explicitly represent biosphere change, then the mathematical model should not generally be solved to equilibrium. Rather, calculations with the biosphere model should use time-dependent fluxes obtained using other components of the overall system model. Nevertheless, even in these cases, there will be uses for calculations based on constant input fluxes to the biosphere, e.g. to examine equilibration times in different components of the biosphere to determine, in retrospect, whether a time-dependent biosphere model was required or whether a time-independent, biosphere state model would have been sufficient. Thus, it may be necessary to go a step beyond the final aim in biosphere modelling to demonstrate that a simpler approach is justified and leads to similar results.

Box 6: Integration of the biosphere in the total assessment

[Future work will include reference to examples of use of biosphere dose conversion factors. Include SR-Site which used LDFs for an evolving system and shows that, for their specific context, the equilibrium factors remain valid no matter when the release begins to occur.

Refer to examples of integrated assessments, including DGR, POSIVA 2012, SR-PSU.]

4.4.2 The level of detail/complexity in biosphere assessments

Given the uncertainties associated with the biosphere on timescales relevant to post-closure safety assessment, the associated models should aim to be no more complex than is necessary. This raises the question as to what level of complexity is appropriate. There is no simple answer to this question. The BIOMASS methodology places strong emphasis on defining the context for each assessment, which then helps to guide and help justify assumptions that are inevitable when modelling contaminant migration and exposure in the biosphere on long time scales. For assessments that build on previous studies, the results and experience gained in identifying key contaminants, processes and pathways can help to refine the level of detail and complexity in subsequent iterations. This should not be an exercise in ever-increasing complexity – previous assessments can provide justification for simplifying the representation of specific processes and/or pathways where they have been shown to be unimportant. Such evidence should be explicitly quoted when justifying the modelling approach being adopted. Biosphere assessments need to justify the degree of complexity in modelling approaches as well as simplifying and conservative assumptions.

Although assessment models for the biosphere should aim for simplicity, they may be supported by much more complex, process-based models. This is particularly the case where site-characterisation information requires interpretation. A complex model may then be used to fully account for the detailed spatial, temporal and multi-parametric information available. However, an important consideration is then the need to simplify this model for application in an assessment context. This may be done by developing a simplified abstraction of the complex model that is suitable for incorporation in the biosphere assessment model. Alternatively, the complex model may be used to compute effective parameter values for use in the assessment model. The latter approach is illustrated in Appendix B.3, where it is shown how a coupled geochemical and contaminant transport model can be used to compute effective distribution coefficients (K_d values) that could be used directly in an assessment model.

There is potential to build confidence in the way in which the biosphere is represented in post-closure safety assessments through comparison of alternative modelling approaches. For example, Posiva have used simple biosphere models to cross-check the results of their 2012 assessments (Posiva 2013). Independent modelling may also be conducted in support of regulatory review of biosphere assessments, as has been the case for SSM's review of the SR-Site assessment in Sweden (Walke et al. 2015).

4.4.3 Discretisation

A key issue for compartment models is the degree of discretisation that is used to reflect each component of the conceptual model that is to be explicitly represented with compartments. Contaminants within a compartment are effectively universally and uniformly available throughout the region of the model represented by that compartment. For transfer processes, this 'numerical dispersion' can result in faster migration and dispersion, and thus also in lower concentrations than would be expected in practice. Numerical dispersion in compartment models can be managed by discretising the model appropriately (e.g. by representing an advective groundwater pathway with five compartments instead of a single compartment). Such discretisation can provide a more appropriate representation of the time-dependent migration and breakthrough of a contaminant. The time dependency is important regarding the residence time for contaminants in each part of the system, and hence the potential for decay/degradation and ingrowth for radionuclides and other contaminants, especially where progeny may be more toxic than their parents. It is particularly important for biosphere systems that are evolving over time; the benefit of taking care to characterise the time scale of changes is lost if the time scales for contaminant migration and accumulation are not treated with the same degree of attention. Further guidance on discretisation of compartment models is available elsewhere (e.g. Kirchner 1998, Xu et al. 2007).

Consideration of spatial scale is an important factor when discretising biosphere models, including spatial scales of the distinct features/media to be represented (such as different surface water features and different soil types) as well as the spatial scales for evaluating the endpoints (human and biota exposure habits). If only part of the home range for humans and/or biota may be contaminated, then there is no need to explicitly model the uncontaminated regions, so long as occupancy factors and fractional intakes of contaminated materials are suitably specified. Also, if the human and biota habits mean that exposure will be averaged over certain spatial scales (e.g. harvesting crops across an entire field), then there is no need to impose a greater degree of discretisation of those areas, so long as average properties can adequately represent the potential for contaminant migration and accumulation. When considering biota exposures, it is important to recognise that it is the spatial scale over which the biota populations range that is of interest, not the range of individual organisms. The spatial scales of the biota populations of interest should be defined when the PEPs are identified (see Section 4.1).

4.4.4 Short-lived radioactive progeny

Another aspect typical of biosphere models for solid radioactive waste disposal is the potential to assume that some radionuclides are present in secular equilibrium with their parents. Some radioisotopes have half-lives that are very short in comparison with the transfer processes that move contaminants around in biosphere systems. In such cases, they can be considered to be effectively present in secular equilibrium with their parent (i.e. at the same activity concentration) and their transport need not be explicitly modelled. Where this simplification is adopted, it is important that the contribution of any progeny assumed to be present in secular equilibrium be taken into account when assessing calculated endpoints, such as effective doses. The contribution of the short-lived progeny should be explicitly added to that of their parent radionuclide. The Ra-226 decay chain provides a case in point, as discussed in Box 7.

Box 7: Example of secular equilibrium treatment of short-lived radionuclides

[Provide an example for Ra-226 and its progeny. This also provides an opportunity to discuss modelling of Rn-222.]

4.4.5 Modelling contaminants with distinct behaviours in the biosphere

The same biosphere processes will be relevant to many of the trace contaminants that may be released into the biosphere in the long-term as a result of solid radioactive waste disposals. This allows the same mathematical models to be applied, albeit with differing parameterisations reflecting the different physico-chemical properties of each contaminant. However, some contaminants exhibit specific behaviour in the biosphere that require special consideration. In developing conceptual and mathematical models for contaminants in the biosphere, consideration should be given to the suitability of models for the full range of contaminants that are specified in the source-term to the biosphere and/or that may arise within the biosphere as a result of contaminant releases. Examples of contaminants for which special considerations arise are given below. It is emphasised that this list is not comprehensive, though it does serves to emphasise the sorts of characteristics that may need to be given special consideration.

- H-3: Hydrogen is of fundamental importance to biological life; H-3 can therefore be present in significant quantities throughout the biosphere in various chemical forms (including tritiated water and organically bound forms), each of which can be subject to different environmental behaviour.
- C-14: Carbon is a fundamental component of organic compounds and biological life; it is present in significant quantities through the biosphere in differing chemical forms (including gaseous forms, CO_2 and CH_4, organic and inorganic substances), each of which can be subject to different environmental behaviour. The behaviour of C-14 and its representation in assessment models have been the subject of a series of BIOPROTA reports (BIOPROTA 2005a, 2013, Limer et al. 2009a, 2011, 2017, Smith and Smith 2014). This work has resulted in an improved understanding of C-14 behaviour within media relevant to radiation dose assessment over relevant temporal and spatial scales, reducing previously identified, significant uncertainties. Application of 'specific activity' models should be justified with a sufficient understanding of these scale issues for the system(s) under consideration.
- Cl-36: Chlorine can be present in the environment as chloride or in organic forms. Chloride is readily available for root uptake but is only poorly retained in soils. In contrast, organic forms of chlorine can be well-retained in soils but are not very available for plant uptake. In addition, some compounds of chlorine are subject to volatilisation from soil-plant systems. In mammals, chloride is subject to homeostatic control, with retention in the body varying inversely with stable chloride intake. The behaviour of Cl-36 and its representation in assessment models has been considered in BIOPROTA (2006) and Limer et al. (2008, 2009b).
- Se-79: Selenium is an essential trace element for animals but is also a biochemical analogue for sulphur. It is present in the environment in multiple oxidation states, with oxidised forms being much more mobile than reduced forms. It is also susceptible to volatilisation from soils. The behaviour of Se-79 and its representation in assessment models has been considered in a series of BIOPROTA reports (Smith 2008, Smith et al. 2009, 2012).
- I-129: Both iodide and iodate may be present in surface waters, and iodine is also readily incorporated in organic matter and can become immobilised in organic sediments. Volatile forms include both iodine vapour and methyl iodide. Iodine is an essential trace element in mammals, being strongly preferentially taken up in the thyroid. It is subject to both short-term and long-term homeostatic control. The former involves blocking of receptor sites in the thyroid, whereas the latter involves changes in the size of the thyroid.

4.5 Application of data

The mathematical model will provide a list of parameters that will need to be assigned point values or distributions in the biosphere assessment. Mathematical models will need to be developed with a view to the availability of data with which to support them; there is, therefore, a non-trivial degree of iteration between these two steps in the methodology.

The collation of internally consistent data sets, including definition of uncertainty bounds or distributions and correlations, is an important component of biosphere assessment. The derivation of assessment-specific parameters from a wider data base of biosphere information is a general challenge in environmental modelling. In long-term biosphere assessments, the difficulties are compounded by the need to represent both the existing biosphere system (where this is known and remains relevant) and potential systems that may be present in the future.

The system description will provide data that will be needed to support the mathematical model, particularly in relation to the configuration of the biosphere, its physical characteristics, the dynamics of masses of water, air and solids, as well as the way that it may evolve into the future (if biosphere change needs to be explicitly represented). Where data are drawn from the system description, it is important that this is clearly explained and justified, including any interpretation that may be needed to match the format of the mathematical model.

The assessment context will define the approach being adopted to manage parameter uncertainty, including the potential for propagating uncertainties by explicitly representing feasible distributions of values for individual parameters (parameter distribution functions, PDFs) via probabilistic modelling. Another means is to formulate alternative datasets for deterministic calculation cases exploring uncertainties. The choice between a probabilistic and a deterministic approach will determine the sort of information that will need to be gathered when collating data. In some assessments, a mix of deterministic and probabilistic calculations may be undertaken. Whatever approach is used, it should be kept in mind that the aim of uncertainty and sensitivity analyses is to enable stakeholders to appreciate the degree of robustness of the results of the assessment and to identify topics worthy of further investigation to reduce or clarify the uncertainties.

[Refer to appendix/annex with further guidance on use of probabilistic approaches]

Biosphere models for radioactive waste disposal typically require extensive databases due to the range of contaminants and potential exposure pathways that are addressed. Some parameters will depend on site characteristics (e.g. configuration of the biosphere, properties of environmental media). Other parameters will not depend on the specifics of a site (e.g. effective dose coefficients for humans and dose conversion coefficients for biota). Some parameters will need both site-specific and generic data to be assimilated (e.g. distribution coefficients and concentration ratios). Where data are not prescribed, the assessment team will need to justify the values and distributions that are used in the assessment. Effort should be focused on those data that are important to the outcomes of the assessment. A possible approach to identifying those parameters that are important to the outcomes of the assessment is illustrated in Smith et al. (2010). A protocol can also help guide and explain the approach to data selection for biosphere assessment, as illustrated in Figure 4-1.

Data management should be considered from the beginning of any safety assessment, especially due to the influence it can have on model developments and because it can be resource intensive. Its treatment should be explicit and properly documented, trying to avoid confusion and potential loss of information. Data chosen to represent the biosphere in the safety assessment needs to be clearly documented and justified. Assessments should also include sufficient quality control and assurance to help build confidence that the correct data have been transcribed from source (this is a part of verification).

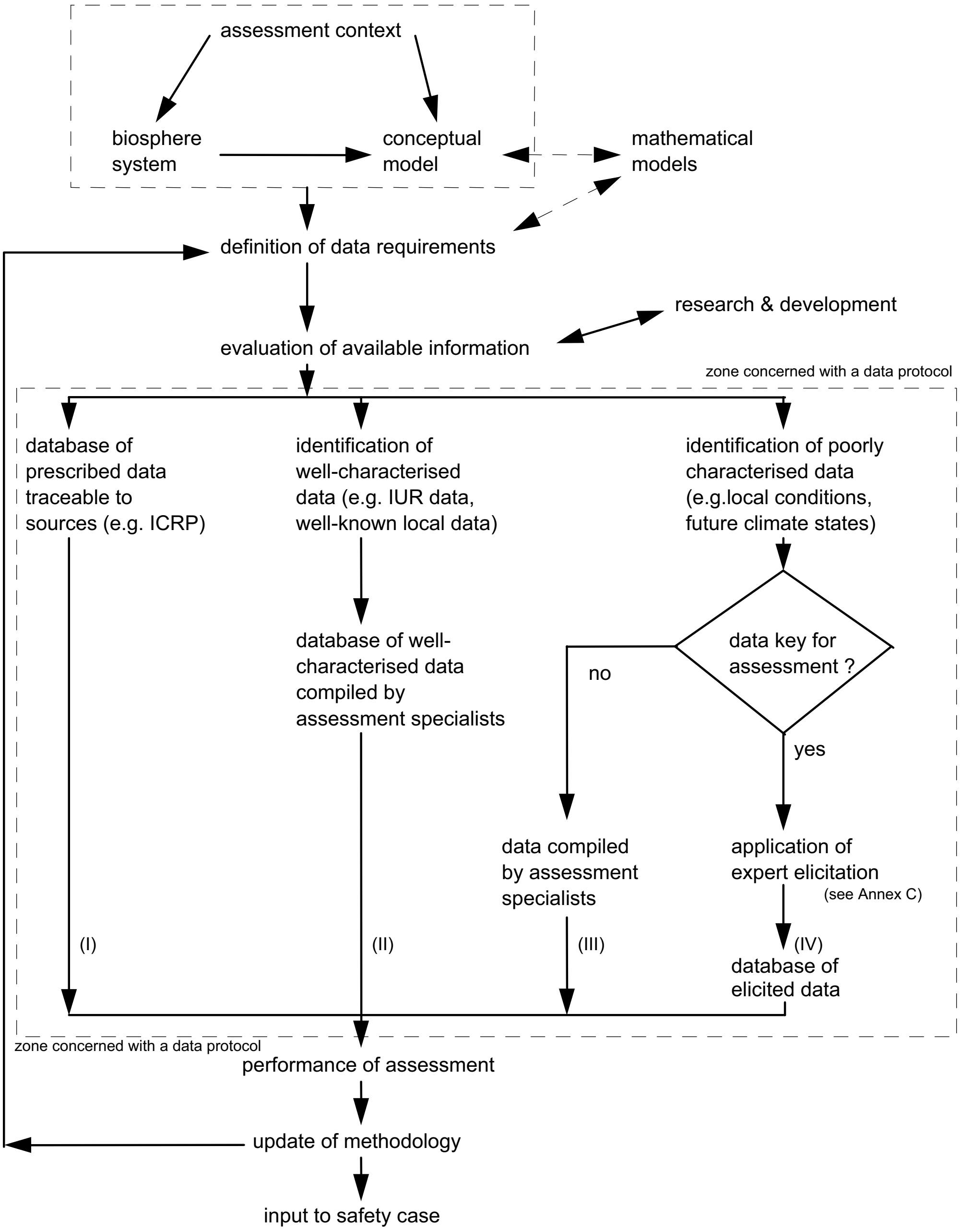

Figure 4-1. *Relationship between data types, data availability and data requirements [From original BIOMASS, to be discussed and updated]*

4.6 Implementation, verification and validation

In implementing a mathematical model for biosphere assessment, consideration will need to be given to the solution method to be chosen. Very simple models may only require a spreadsheet calculation. However, once the complexity of a model extends beyond a few key features and in contexts for which the time-dependent history of contaminant concentrations is required, then a numerical modelling tool will be needed. Several numerical modelling tools for modelling contaminant behaviour and exposure are available. Typical tools for assessment of radioactive waste disposal include AMBER[6], Ecolego[7] and GoldSim[8]. Alternatively, more generic software can be applied, such as MATLAB® and Simulink®[9] (see, for example, SKB 2011). Important considerations in choosing a software tool include

- availability, ease of use, level of support, robust numerical solvers, assurance of software quality/verification, awareness of units and checking for consistency, suitability to automation,
- transparency of models implemented in the tools, both to help in implementing models suited to the assessment context and to help facilitate quality assurance and review,
- probabilistic and deterministic modelling capabilities (depending on the approach being adopted), and
- capability to communicate the implementation and support for outputting results.

Those responsible for implementing biosphere assessments should review the capabilities of the tools that are available and select the most appropriate for the given context.

IAEA (2007) defines model validation as the process of determining whether a model is an adequate representation of the real system being modelled, by comparing the predictions of the model with observations of the real system. Model verification is the process of determining whether a computational model correctly implements the specified conceptual model or mathematical model. Hill (1989) noted that radiological assessment models with the lowest potential for quantitative validation appear to mainly those used in assessments of the long-term impact of geological disposal of solid radioactive wastes. However, the scope for partial validation is potentially important, e.g. with respect to specific processes and radionuclides, combined with consideration of analogues (BIOPROTA 2005b).

Safety assessments will typically involve consideration of several different scenarios, as well as variant calculations exploring the sensitivity of the results to alternative assumptions. This can result in many calculation cases within which much of the structure of the models and many of the data remain the same. Consideration should be given to implementing multiple calculation cases within a single model file, with specific calculations being controlled via ‘option switches’. This makes it easier to manage the data consistently between calculation cases and is also more efficient in comparison with having to maintain multiple calculation files. For large numbers of calculations, models can typically be run in an automated manner using script languages.

The same model implemented in different numerical tools should give the same result. Nonetheless, there is an element of uncertainty in the numerical calculations that may, for example, be explored by implementation in different codes and/or using side calculations to help build confidence in the quantitative results. For example, implementation of models in different calculation tools is sometimes undertaken in support of regulatory reviews (Xu et al. 2013).

As with earlier steps in the methodology, maintaining an audit trail for the model that is implemented is important for maintaining transparency and building confidence and understanding in the results. The implementation should match the specification of the model. Where modifications to the mathematical model are made to facilitate efficient implementation, the model specification should be updated to reflect such changes. Furthermore, the overall implementation of the model structure, equations and data should be audited against the specification (verification). The process used for such quality assurance checks should be documented as part of the assessment because it is an important contributor to building confidence in the assessment as a whole.

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[6] quintessa.org/amber

[7] ecolego.facilia.se

[8] goldsim.com

[9] mathworks.com/products/simulink.html

The timescale for which biosphere assessment models are deployed and the level of understanding of some of the processes included mean that strict validation of the models against observations is not feasible. Nevertheless, a limited degree of validation of some parts of a model against observations may be possible. Where this is the case, such validation is an important aspect of building confidence in the model. For example, the hydrological component of a biosphere model could be validated at the present day by comparing observed flows of surface waters against model projections for rainfall events of different intensities and durations. Here, the argument is that if individual flow events can be estimated adequately, then the long-term time-averaged flow regime can also be estimated adequately.

In addition to the verification and validation procedures mentioned above, there is a need for scrutiny of the assessment results to determine whether they are generally plausible and can be explained by reference to the characteristics of the model used. It is often found that whereas it is difficult to forecast the results to be obtained from a complex model, when such results have been obtained a deductive approach can be used to determine why they arose.

5 Model application and evaluation of results

Once a model has been implemented and quality assured, it can be applied to the range of scenarios and calculation cases to be addressed in the assessment. Any choices made in undertaking the calculations should be documented and justified. This includes, for example, the choice of numerical solver used (where applicable and where multiple options are offered) and the resolution in solve steps (if they are not intelligently selected by the computational tool itself).

Calculation files and details of any post-processing should be retained as part of a quality assurance system. The calculations and the results should be independently checked to help ensure that reported results accurately reflect the specification for each case.

For probabilistic assessments, the assessment context should provide guidance on the output that is relevant for comparison against any stated criteria. This may, for example, be the 'expectation value', or average calculated result. Alternatively, comparison may conservatively be made against other metrics, e.g. the 95th percent confidence in the mean, or 95th percentile of results. It is important for any comparisons to be made on a reasonable basis, to help ensure that results are not overly pessimistic, especially as they approach the criteria that may have been defined. Guidance on balancing realistic and conservative assumptions and on the metrics to be used for comparison against criteria should be included in discussion of the 'assessment philosophy' component of the assessment context (see Section 2.3).

Assessment results at later times are increasingly indicative, given the increasing uncertainties. If the timescale of relevance to an assessment encompasses both shorter (tens to hundreds of years) and longer (thousands, to tens of thousands of years and longer) periods, then consideration should be given to explicitly distinguishing results in different periods of time. This can help to emphasise that results presented on long timescales can only be taken to be illustrative of potential impacts, rather than being inadvertently interpreted as predictions.

Consideration should also be given to the format of graphed outputs. Logarithmic scales need to be used with care because they can appear to over-state very small results. It is often helpful to place numerical results in context, e.g. by explicitly including background concentrations, fluxes and doses on charts. There is also merit in identifying a magnitude of result that is considered negligible, to avoid too much weight being given to very small numerical results.

The spatial scale of calculated results will be of interest, to distinguish, for example, small results over a small area from small results over an extensive area. It can therefore also be helpful to visualise model results in a spatial context.

6 Conclusions

The BIOMASS methodology has been shown to provide useful guidance in helping to ensure consistency in the way in which the biosphere is represented in post-closure safety assessments for solid radioactive waste disposal facilities. This Interim Report records progress with international work to review and enhance the methodology to reflect experience gained and developments made in the period since 2001, when technical work on the original BIOMASS methodology was completed.

There are many areas of important experience gained since 2001 covering:

- site characterisation;
- understanding of key processes that influence the headline assessment results, and hence areas for focussed consideration;
- approaches to addressing environmental change;
- treatment of the geosphere-biosphere interface; and
- regulatory developments and regulatory review, and hence, sufficiency of a safety assessment.

The continuing international work, within BIOPROTA and IAEA MODARIA II WG6, is planned to further consolidate the progress reported here, with additional and special focus on: integration of the biosphere assessment within an overall assessment and safety case; selection of assumptions for exposure groups and populations; transparent presentation of the methodology and clear communication of results; achieving an appropriate balance between complexity and simplicity, and building confidence in the conclusions.

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8 Glossary and abbreviations

Glossary of technical terms

[To be added in future iterations]

Abbreviations

BIOCLIM	Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal (EURATOM 5th framework programme)
BIOMASS	Biosphere Modelling and Assessment (IAEA co-ordinated research programme)
BIOMOVS	Biosphere Model Validation Study
DEM	Digital Elevation Model
EC	European Commission
EFEPs	External Features, Events and Processes
EIA	Environmental Impact Assessment
EMRAS	Environmental Modelling for Radiation Safety
EQS	Environmental Quality Standard
ERB	Example Reference Biosphere
FEPs	Features, Events and Processes
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
K_d	Solid:liquid distribution coefficient (also termed sorption coefficient)
LDE	Lead Diagonal Element
LET	Linear Energy Transfer
MODARIA	Modelling and Data for Radiological Impact Assessments
ODE	Off-diagonal element
PA	Performance Assessment
PDF	Parameter Distribution Function
PEG	Potentially Exposed Group
PEP	Potentially Exposed Population
WG6	Working Group 6
WHO	World Health Organisation

Appendix A

Further detail on technical aspects

A.1 The development of conceptual and mathematical models of the biosphere and the propagation of uncertainties

Introduction

At the highest level, uncertainties arise in post-closure safety assessment in terms of the scenarios to be modelled and the FEPs to be considered. These uncertainties can be addressed by comparing the results obtained from making calculations for different scenarios and by considering alternative models of all or part of the disposal system. However, once a scenario and associated set of FEPs have been adopted as a basis for calculation, it is appropriate to address the uncertainties that are associated with modelling that situation. If an interaction matrix is used in formulating the conceptual model appropriate to a specific scenario and set of FEPs, the issue can be formulated as the uncertainties that arise from translating that conceptual model into a mathematical model, and in assigning point values or distributions to the parameters that are associated with the equations characterising that mathematical model.

Relating the elements of an interaction matrix to mathematical equations

In an interaction matrix, the elements on the principal diagonal can be associated with properties (e.g. temperature, density, chemical composition), with the off-diagonal elements typically representing processes that relate properties and changes in the properties of one principal diagonal element to properties and changes in the properties of another principal diagonal element. Let $\boldsymbol{\phi}^0{}_i$ be the properties of principal diagonal element i and $\boldsymbol{\phi}^n{}_i$ be the nth derivative of those properties with respect to time (t), i.e. $\boldsymbol{\phi}^n{}_i = d^n\boldsymbol{\phi}^0{}_i/dt^n$. Note that $\boldsymbol{\phi}$ is a vector $(\phi_1, \phi_2, \ldots \phi_k)$ relating to k properties. Translation of the relationships between principal diagonal elements from conceptual to mathematical form then comprises defining functions $\mathbf{f}_{ij}$ where:

$$\boldsymbol{\phi}^n{}_j\ (n = 0, n_{max}) = \mathbf{f}_{ij}\{\phi^n{}_i\ (n = 0, n_{max})\} \qquad \text{(Eq. A-1)}$$

Here n_{max} is the highest-order time derivative that needs to be addressed. Typically, this will be no higher than two (for diffusive processes). Note that this relates only two principal elements. In practice, the values of $\boldsymbol{\phi}^n{}_j$ will be determined by the characteristics of all the other principal diagonal elements and will also determine their characteristics. Here it is sufficient to limit consideration to individual pairwise interactions, but it should be remembered that the individual pairwise interactions contribute to an overall matrix of interactions that must be satisfied simultaneously.

Alternative views may be taken on the general functional form of $\mathbf{f}_{ij}$. However, even when appropriate functional forms have been selected for all off-diagonal elements, issues arise in approximating those functional forms in circumstances where numerical methods must be used to solve the resulting system of equations under specified (and possibly time-dependent) boundary conditions. This will be the usual situation where there are dependencies on $\boldsymbol{\phi}^n{}_i$ for $n > 0$ and systems of ordinary differential equations must be solved. Such solutions will require spatial and temporal discretisation of the model domain and solution of the discretised equations by, for example, finite difference or finite element approaches. This process of discretisation can be thought of as an expansion of the interaction matrix, with each principal diagonal element being expanded into its discretised components. Thus, for example, the principal diagonal element 'soil' would be replaced by multiple elements, with each one representing an individual soil layer in a 1D model or a single layer within a model element of limited areal extent in a 3D model. The equations characterising this expanded system are of the same general form as equation A1, but a different nomenclature is used to indicate that the expanded, discretised form is implied:

$$\boldsymbol{\Phi}^n{}_j\ (n = 0, n_{max}) = \mathbf{g}_{ij}\{\boldsymbol{\Phi}^n{}_i\ (n = 0, n_{max})\} \qquad \text{(Eq. A-2)}$$

If an alternative approach to conceptual model representation is used, a similar procedure of translation to a mathematical model can be adopted. With an influence diagram, properties can be associated with the nodes and functions relating those properties can be associated with the influences connecting those nodes.

Parameterising the mathematical equations

The mathematical model represented by a set of equations each of the form of equation A2 may represent either a time-independent or time-dependent system, depending upon whether the time derivatives are used in defining $\mathbf{g}_{ij}$. Furthermore, the properties included in $\mathbf{\Phi}$ (i.e. $\Phi_1 \ldots \Phi_k$) may include radionuclide amounts, masses, temperatures etc., so these equations can represent both changes in the physical system and the movement of radionuclides within it.

The functions $\mathbf{g}_{ij}\{\mathbf{\Phi}^n_i\ (n = 0, n_{max})\}$ over all i and j will be characterised by a set of parameters $\boldsymbol{\eta}$ ($\eta_1 \ldots \eta_N$), where not all of these parameters will be relevant to a specific $\mathbf{g}_{ij}$ (i.e. for a particular pair of i and j). Each of these parameters may take either a point value or be sampled from a distribution. Furthermore, where parameters are sampled from distributions, the sampling of individual parameters may either be uncorrelated or correlated. For example, if two parameters are positively correlated, sampling one from the upper part of its range may impose the requirement that the other is sampled from the upper part of its range.

Whether parameters are assigned point values or are sampled from distributions will depend on the assessment context. Some assessment contexts will require results to be calculated as expectation values, implying that input parameter uncertainties must be propagated through the model to give the appropriate distributions of output parameter uncertainties. Other assessment contexts will require specific assumptions to be made in selecting input parameter values. In such assessments, point values can be assigned, though there will often also be requirements to undertake sensitivity analyses in which these parameter values are altered, either individually or in combination.

Although sampling from distributions of parameter values is often adopted in representing the near field and geosphere associated with solid radioactive waste disposal facilities, there is more debate as to whether such sampling is appropriate in relation to the biosphere. This arises because the biosphere tends to be much more subject to change, including human-induced change, than the deeper parts of the disposal system. Thus, it has been argued that the process of defining a potential biosphere system appropriate to the far future corresponds to the imposition of a plausible ‘measuring instrument’ that permits conversion of radionuclide fluxes to radiation doses or dose rates that can be compared with compliance criteria. If such a measuring instrument is required to be precisely defined, then there is a strong argument for specifying it deterministically. However, if it is argued that the biosphere assessment needs to explore the implications of the range of biosphere characteristics that could arise in the far future, or if it is considered that current epistemological (lack of knowledge) uncertainties in measurable biosphere characteristics (e.g. distribution coefficients in soils) should be propagated through the assessment, then a probabilistic approach is likely to be required (or at least a deterministic approach supplemented by extensive sensitivity analyses).

A.2 The propagation of uncertainties

The propagation of uncertainties in a safety assessment must be considered at every stage of the assessment process. Broadly speaking, this can be addressed through the following hierarchical approach.

a) Qualitatively different descriptions the disposal system (or the biosphere associated with the disposal system) at various times in the future, or as functions of time, can be addressed through the adoption of several alternative scenarios that can be propagated through the assessment. Each such description (of either a time-independent biosphere state or a time-dependent biosphere system) can be associated with a conceptual model of the system.

b) Conceptual models are associated with uncertainties concerning the principal components that should be adopted and the key processes relating those principal components. Such uncertainties can be addressed by defining alternative conceptual models and propagating these through the assessment to give alternative mathematical models.

c) The translation of a conceptual model into a mathematical model is associated with two types of uncertainty. The first is the mathematical form of the equations that are used to represent a process named in the conceptual model. In some cases, the choice of equation is straightforward, but in other cases there may be substantial scientific uncertainty, e.g. whether a continuum or fracture-flow model is required. This type of uncertainty can be addressed by propagating the alternatives through the assessment. The second type of uncertainty concerns the degree of spatial and temporal discretisation that is required. This can often be addressed through the application of grid-refinement techniques.

d) Mathematical models include input parameters. These will typically be subject to uncertainty. Whether such uncertainty is propagated through the assessment will depend substantially on the assessment context. However, if this uncertainty is propagated, this can be by explicit sampling of the input parameter value distributions to give resultant output parameter value distributions, or by deterministic calculations complemented by extensive sensitivity analyses.

A.3 Overall consideration of uncertainty

[To be produced early in 2018. Potential to move Section A.2 text here.]

A.4 Consideration of long-term climate and landscape change in the MODARIA project

Between 2012 and 2015, the International Atomic Energy Agency coordinated an international project addressing climate change and landscape development in post-closure safety assessments of solid radioactive waste disposal as part of the overall MODARIA project (IAEA 2016b). The work was supported by results of parallel on-going research that has been published in a variety of reports and peer reviewed journal articles. An overview of the work has recently been accepted for publication (Lindborg et al. 2018).

The main activities undertaken in the project were: identification of the key processes that drive environmental change (mainly those associated with climate and climate change), and description of how a relevant future may develop on a global scale; development of a methodology for characterising environmental change that is valid on a global scale, showing how modelled global changes in climate can be downscaled to provide information that may be needed for characterising environmental change in site-specific assessments, and illustrating different aspects of the methodology in a number of case studies that show the evolution of site characteristics and the implications for the dose assessment models.

The methodological approach that was developed within the MODARIA project, together with the technical developments in long-term climate modelling made in support of that project, complemented by developments of representations of landscape development in ongoing national programmes, jointly facilitate the consideration of climate change and landscape development within post-closure safety assessment that can be applied to a wide range of site and repository types, and at different stages of the development of a disposal option, ranging from generic, initial studies to detailed site-specific assessments. The methodology has been set out as a road map, as described in Lindborg et al. (2017). This provides a practical framework and common basis for future assessment work that is consistent with international recommendations and guidance, as well as the latest technical developments.

Global climate results at a 200 km scale have been generated in the MODARIA project for a wide range of carbon dioxide emissions scenarios, ranging from no anthropogenic emissions to a prolonged business-as-usual scenario, using a newly developed emulator underpinned by an ensemble of Atmosphere-Ocean General Circulation Model (AOGCM) runs. These global results could be used in any safety assessment programme worldwide in which the focus was on radiological impacts during the current interglacial episode. Ongoing studies sponsored by SKB and Posiva have the potential to extend this applicability to multiple glacial-interglacial cycles. However, even in the context of applying the results to the current interglacial episode, it would be desirable to explore uncertainties in these results by comparing them with emulators conditioned on the results from alternative AOGCMs. Also, whereas results at a resolution of 200 km may be sufficient for many assessment purposes, there may be circumstances in which downscaling of these results will be appropriate. Since such downscaling depends strongly on the local geographical context, the MODARIA project was not able to present results that are applicable anywhere world-wide. However, it was demonstrated how physical-statistical downscaling, the preferred method, can be applied to AOGCM results for the UK. A similar approach could be applied to results from the emulator at any location of interest to provide long time series of downscaled climatic information.

Once climate evolution data are available at appropriate spatial and temporal resolution, they can be used to drive landscape-development models along with other relevant data, notably crustal uplift rates which are relevant both to shoreline regression and to river incision.

Again, landscape development is strongly dependent upon local geography, so the MODARIA project was limited to discussions of the relevant issues and presented as an approach that, in turn, is supported with illustrative examples for warm, arid and temperate conditions, periglacial conditions and glacial conditions as well as transitions between them. These illustrate the approach adopted to construction of narratives for environmental change, based on the assumptions used in climate modelling and downscaling. Different aspects of the narratives can be developed and used differently within a single assessment, but it is important that they draw on the same foundation.

The next part of the MODARIA methodology concerns the use of these narratives in radiation dose assessments. The approach adopted draws on experience of the application of biosphere assessment approaches, as well as on-going project specific assessments. It is highlighted that the narratives can be used in various ways to support the assumptions for dose assessment models. The choice of simplifying assumptions can be an important consideration, along with how to address uncertainties in the context of present-day conditions and the treatment of future climatic and landscape conditions.

The case studies that have been reviewed and evaluated demonstrate the value of a step-by-step approach in building confidence in dose modelling results, show the potential value of the use of analogues, and illustrate the role of stakeholder engagement in building trust. Description of the landscape at the present day and how it may evolve in the future is an aspect of the post-closure assessment process that is particularly accessible to, and understandable by, various stakeholder groups. Descriptions of future biosphere characteristics and human behaviour can appear speculative and subject to challenge. There is, therefore, a need to carefully distinguish those aspects of the assessment that are based on quantitative analyses (e.g. derived from climate and landscape models), from those that are based on regulatory requirements or other judgements and decisions. It is recognised that, in practice, the distinction is not clear cut and that some aspects will be determined by judgemental interpretations of quantitative modelling results. In this context, uncertainty analyses play an important role in investigating the alternative scenarios that arise from different points of view on assessment issues and determining the robustness of safety arguments across these alternative points of view. Engagement with stakeholders is essential both to explain the basis of quantitative aspects of the assessment and to support development of consensus on those aspects where judgement has the predominant role. An important example is the selection of assumption(s) for anthropogenic CO_2 releases that depend upon a combination of technical, economic and political factors.

Noting these issues, it is highlighted that the results produced through the application of the methodology are only intended as projections of possible futures based on a set of assumptions, i.e. reference futures. Therefore, it is emphasised that assessments must not be considered as predictions of the future. Rather they should be considered as illustrative projections that encompass plausible future situations to an extent that is sufficient to provide confidence in the safety of a disposal facility. Notwithstanding the uncertainties that exist, it has been shown, through research reviewed and undertaken in the MODARIA project, that quantitative long-term climate modelling is sufficiently developed and robust to define an envelope of reference futures for use in safety assessments of radioactive waste repositories, as supported by understanding of paleoclimatic conditions. The climate models that can be used for this purpose have limited spatial resolution and in some cases downscaling is necessary. Physical statistical methods exist to do this, but local statistical data are needed to apply them. Qualitative downscaling can also be used.

Quantitative modelling of landscape evolution and the linkage with climate modelling has been significantly developed in recent years but not for all potentially relevant climates and landscapes. Further work in this area is needed and special attention may have to be given to more detailed understanding of the first few thousand years after disposal. This goes beyond the typical focus of the IPCC (see Stocker et al. 2013) but is especially relevant to near-surface disposals and the long-term management of radioactively contaminated legacy sites.

Although the focus of the studies undertaken in MODARIA was radiation dose assessment following releases to the biosphere, the methodology and results obtained should be valuable in a wider post-disposal safety assessment context, e.g. addressing the effects of climate change and landscape development upon releases to the biosphere (see BIOPROTA (2014) for a discussion of approaches to representing the interface between the geosphere and the biosphere). They may also be of interest to those with an interest in assessment of the post-disposal impact of chemically hazardous materials in radioactive waste repositories, and in the general issue of the disposal of hazardous wastes.

A.5 Consideration of long-term sea level changes

As discussed in Section 13.2 of Stocker et al. (2013), the present-day global sea level was reached about 6 ka Before Present (BP). Subsequently, the variation in level has been only about 1 m, with a trend towards increasing sea levels that began worldwide early in the 20th century (Gehrels and Woodworth 2013). In terms of forward projections, the IPCC (Section 13.5 of Stocker et al. 2013) considers that sea-level rise during the 21st century is likely to be between 0.28 to 0.61 m for the RCP2.6 scenario and between 0.52 and 0.98 m for the RCP8.5 scenario. However, projections of rises of up to 2.4 m have been reported in the literature (Stocker et al. 2013, p 1186).

More recently, Jevrejeva et al. (2012) have constructed a probability density function of global sea level at 2100 AD and have estimated that sea-level rises of more than 1.8 m are less than 5% probable. They also gave an upper estimate of 1.9 m obtained by summing the highest estimates of individual sea-level rise components simulated by process-based models with the RCP8.5 scenario. They noted that the upper part of the probability distribution of sea-level rise projections is hard to quantify because of the uncertainties that currently exist in projections from ice-sheet dynamical models.

Relative sea-level rise projections for Europe at 2100 AD are given in Grinsted et al. (2015). These take account of global sea-level rise, alterations in the geoid, expressed through the dynamic ocean response and isostatic adjustments.

Stocker et al. (2013, Table 13.8) also provide longer-term projections of Global Mean Sea Level (GMSL) rise for low, medium and high emissions scenarios (spanning the range from RCP2.6 to RCP8.5). These projections are summarised in the following table.

Scenario	**Year of Projection (AD)**				
	2100	**2200**	**2300**	**2400**	**2500**
Low	0.26 to 0.53 m	0.35 to 0.72 m	0.41 to 0.85 m	0.46 to 0.94 m	0.50 to 1.02 m
Medium	0.19 to 0.66 m	0.26 to 1.09 m	0.27 to 1.51 m	0.21 to 1.90 m	0.18 to 2.32 m
High	0.21 to 0.83 m	0.58 to 2.03 m	0.92 to 3.59 m	1.20 to 5.17 m	1.51 to 6.63 m

On multi-millennial timescales, Stocker et al. (2013) provide estimates of changes in GMSL as a function of the overall global increase in temperature. Contributions arise from thermal expansion of the oceans, melting of mountain glaciers, loss of part of the Greenland ice sheet and changes in the Antarctic ice sheets. The major uncertainty relates to the Greenland ice sheet, which is almost completely lost following a global temperature increase of 2 °C or more and contributes about 6 m of sea-level rise. Overall, the global sea-level rise ranges up to about 10 m in the first 2 ka and up to about 15 m at equilibrium. Stocker et al. (2013) note that GMSL during previous interglacials (MIS 5e and MIS 11) have been up to about 10 m above that at the present day.

Since Stocker et al. (2013) further work has been undertaken in relation to the potential sea-level contribution from the Antarctic ice sheets. For example, DeConto and Pollard (2016) have used a model that includes hydrofracturing of buttressing ice shelves and structural collapse of marine-terminating ice cliffs to estimate that at 2500 AD the global mean sea-level rise for the RCP8.5 scenario would be 12.3 m, to which should be added a further 1.3 m due to warming feedbacks arising from the retreating ice sheet. In this model, the projected sea-level rise at 2100 AD is more than 1.0 m.

If consumption of unconventional fossil fuels such as clathrates is considered, sea-level increases substantially more than this could occur. For example, Winkelmann et al. (2015) have shown through model simulations that with cumulative fossil fuel emissions of 10 000 PgC, Antarctica is projected to become almost ice free with an average contribution to sea-level rise of more than 3 m per century over the next millennium. In this model, an increased sub-ice-sheet melt rate forces grounding-line retreat into an area where the ice is grounded below sea level on inward-sloping bedrock resulting in progressive instability. The authors propose that the West Antarctic ice sheet becomes unstable by this mechanism after cumulative carbon emissions reach 600 to 800 PgC. A similar instability of the larger, East Antarctic ice sheet arises for a release of more than about 2500 PgC.

In the longer-term, when the effects of anthropogenic greenhouse-gas emissions have declined substantially, glacial-interglacial cycling is expected to resume. During glacial episodes, continental ice sheets similar in size to those of the Last Glacial Maximum (LGM, MIS 2) would probably develop, leading to a fall in GMSL of about 120 m relative to the present day. However, because of the long-term persistence of a fraction of carbon dioxide releases in the atmosphere, it is likely that glacial-interglacial cycling will not resume for a minimum of some tens of thousands of years and possibly not for 100 ka or more (IAEA 2016b). If glacial-interglacial cycling does resume and exhibits a pattern like that observed over the last 400 ka, then cycles of about 100 ka are projected to occur, with an oscillatory cooling trend and a corresponding trend in sea level, i.e. generally falling, but with shorter-term increases during periods of global warming.

Appendix B

Further detail on examples

[This is where more detail on examples that illustrate specific aspects of the methodology will be included. Suggestions are explicitly invited.]

B.1 Drawing understanding from a cold climate analogue

[SKB to develop text describing characterisation of cold climate analogue and its use in support of biosphere assessment]

B.2 Biospheres for different climate conditions

[BIOPROTA TST to summarise biosphere modelling under different climate conditions that was undertaken within EMRAS II, WG3 and its potential relevance to the updated BIOMASS methodology]

B.3 Modelling radionuclide transport in near-surface systems by using the "Smart Kd" approach

[Potential summary of Smart Kd approach to be added on agreement with SKB]