BIOPROTA

Key Issues in Biosphere Aspects of Assessment of the Long-term Impact of Contaminant Releases Associated with Radioactive Waste Management

Update and Review of the IAEA BIOMASS-6 Reference Biospheres Methodology

Report of the first programme workshop

Karen Smith (Ed)

Version 2.0, 18 August 2016

PREFACE

BIOPROTA is an international collaboration forum which 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 to be 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 describes the presentations and discussions during a workshop held as part of an on-going project organised within the BIOPROTA Forum to review and enhance the IAEA BIOMASS-6 Reference Biospheres methodology. The workshop was hosted by FANC in Brussels, Belgium from 20-22 April 2016. The aim of the workshop was to present an initial review and compilation of experience gained since 2003, to hear from a wide range of organisations about their on-going interests in this area and to identify the focus of activities for methodological improvements to be developed in the next stages of the project.

Version History

Version 1.0: Draft workshop report based on participant contributions and reviewed by Graham Smith (GMS Abingdon) prior to distribution on 5 July 2016.

Version 2.0: Final workshop report prepared by Karen Smith (RadEcol Consulting Ltd), taking account of comments received on the version 1.0 report. Distributed 18 August 2016.

CONTENTS

PREFACE II

CONTENTS III

1. INTRODUCTION 4

1.1 AIMS AND OBJECTIVES 5
1.2 WORKSHOP PARTICIPATION 5
1.3 REPORT STRUCTURE 5

2. INITIAL REVIEW AND COMPILATION OF EXPERIENCE SINCE 2001 6

2.1 OVERVIEW OF THE BIOMASS-6 METHODOLOGY 6
2.2 CLIMATE AND ENVIRONMENTAL CHANGE 11
2.3 MODELLING PROCESSES AT THE GEOSPHERE-BIOSPHERE INTERFACE 15
2.4 SOIL-PLANT SYSTEM MODELLING 19
2.5 SPECIAL MODELS FOR SPECIAL RADIONUCLIDES 21
2.6 ADDRESSING CHEMICAL HAZARDS IN RADIOACTIVE WASTES 23
2.7 ADDRESSING PROTECTION OF THE ENVIRONMENT 24
2.8 DEVELOPMENTS IN INTERNATIONAL RECOMMENDATIONS AND GUIDANCE 26
2.9 CONFIDENCE BUILDING. 27
2.10 SITE INVESTIGATION AND CHARACTERISATION 30

3. EXPERIENCE IN THE APPLICATION OF THE BIOMASS-6 METHODOLOGY TO SAFETY ASSESSMENTS........33

3.1 REVIEW OF BIOSPHERE ASSESSMENTS 33
3.2 APPLYING BIOMASS METHODOLOGY TO POSIVA'S BIOSPHERE ASSESSMENT 40
3.3 APPLICATION OF BIOMASS METHODOLOGY BY ANDRA FOR SITES IN OPERATION AND PROJECTS' SAFETY ASSESSMENTS. 43
3.4 SKB REPORT R-14-02 ON FEP HANDLING AND EXPOSURE PATHWAY ANALYSIS 47
3.5 ADDRESSING CHEMICAL HAZARDS IN RADIOACTIVE WASTE: **MS**PAF METHODOLOGY 51
3.6 STATISTICAL LANDSCAPE EVOLUTION MODELLING AS INPUT TO SENSITIVITY ANALYSIS OF STYLISED RADIONUCLIDE TRANSPORT AND DOSE MODELLING 53

4. DISCUSSION ON FORWARD WORK PROGRAMME AND LINKS TO THE IAEA MODARIA II PROGRAMME.56

4.1 BIOSPHERE MODELLING FOR LONG-TERM SAFETY ASSESSMENTS OF HIGH LEVEL WASTE DISPOSAL FACILITIES: PROPOSAL FOR A WORKING GROUP WITH THE IAEA MODEL TEST AND COMPARISON PROGRAMME, MODARIA II 56
4.2 DISCUSSION ON THE COLLABORATION BETWEEN AND INTEGRATION OF THE MODARIA II AND THE BIOPROTA WORK PROGRAMMES 58
4.3 FORWARD PLAN 58

APPENDIX A. MEETING PARTICIPANTS 59

1. INTRODUCTION

The International Atomic Energy Agency (IAEA) BIOMASS-6 report on reference biospheres for solid radioactive waste disposal was published in 2003[a], following an extensive international collaborative work programme running from 1996 until 2001. The report sets out a structured approach for the assessment of impacts of radionuclide releases to the biosphere from radioactive waste disposal facilities. It also includes examples of the application of the methodology, called Example Reference Biospheres (ERBs) and associated results expressed in terms of radiation dose rates to humans for unit release rates of a sub-set of relevant radionuclides (Nb-94, Tc-99, I-129 and Np-237). With the focus of such assessments being on long-term future biosphere conditions, the methodology was intended to support the development of biosphere models as a measuring instrument, providing assessment results for comparison with protection objectives rather than a prediction of future conditions and exposures. The BIOMASS work built on initial development of a reference biospheres methodology in the BIOMOVS II collaborative study[b].

The reference biospheres methodology has been used to support a wide range radioactive waste disposal assessments. Understanding gained through these assessments and other inputs has given rise to new knowledge and developments. For example, there have been significant developments in relation to how climate is addressed in long-term assessments and in approaches to allow radiation effects on the environment to be explicitly evaluated. There have also been technical developments in models for radionuclide migration and accumulation in different parts of the environment and improved models for assessing doses from the resultant radionuclide concentrations in relevant environmental media, including radionuclide-specific models for C-14, Cl-36 and Se-79, as reported substantially at www.bioprota.org. There have also been significant updates since 2003 in international recommendations on standards for, and methods for assessment of, post-disposal radiological impacts, from the IAEA, the International Commission on Radiological Protection (ICRP) and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA OECD).

Noting all of the above, it was considered timely[c] for the reference biospheres methodology to be internationally reviewed and enhanced to take account of this new knowledge and experience. As such, a project has been initiated, supported by a Technical Support Team (TST) comprising Quintessa, GMS Abingdon, RadEcol Consulting, Mike Thorne and Associates and Amphos[21]. A workshop, hosted by FANC in Brussels, Belgium, from 20th to 22nd April 2016 provided a first opportunity to present and discuss experience and suggestions for methodological improvements. This report provides a summary

---

[a] International Atomic Energy Agency (2003). “Reference Biospheres” for Solid Radioactive Waste Disposal: Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme, IAEA-BIOMASS-6, IAEA, Vienna.

[b] BIOMOVS II (1996). Development of a Reference Biospheres Methodology for Radioactive Waste Disposal. Biospheric Model Validation Study, Phase II Technical Report No. 6, published by the Swedish Radiation Protection Institute, Stockholm, Sweden.

[c] BIOPROTA (2015). Continuing Issues in Biosphere Assessments for Radioactive Waste Management. Report of a workshop held 28 - 29 May 2015, in Madrid, hosted by CIEMAT.

of the presentations and discussions at the workshop and will provide the basis for task implementation through the next stages of the project.

1.1 AIMS AND OBJECTIVES

The overall aim of the project is to retain the same basic methodological steps set out in the BIOMASS-6 methodology, i.e. not to change the overall approach, but to bring it up to date based on new scientific information, experience in assessments and model developments, revised international recommendations and regulatory practice.

The objectives of the workshop were:

- to present an initial review and compilation of experience gained since 2003;
- to hear from a wide range of organisations about their on-going interests in this area; and
- to identify key areas where update activities should be focussed, based on experience gained, knowledge of principal interest areas and scientific developments since 2001.

1.2 WORKSHOP PARTICIPATION

The workshop, hosted by FANC in Brussels, was attended by 32 participants from 11 countries, representing a range of operators, regulators, researchers and technical support organisations. Participants are listed in Appendix A.

1.3 REPORT STRUCTURE

Section 2 of this report summarises the presentations made by the Technical Support Team (TST) summarising an initial review and compilation of experience. Section 3 then summarises presentations from workshop participants on the application of the BIOMASS methodology within biosphere assessments. Overall discussion and a proposed way forward, including linkage to the IAEA MODARIA II programme is then provided in Section 4.

2. INITIAL REVIEW AND COMPILATION OF EXPERIENCE SINCE 2001

The workshop opened with an introductory presentation on the BIOMASS-6 Reference Biospheres methodology. Presentations from the project TST on initial review and compilation of experience were then provided.

2.1 OVERVIEW OF THE BIOMASS-6 METHODOLOGY

Graham Smith presented.

The BIOMASS-6 Reference Biospheres methodology was initially developed to identify common arguments and issues in long-term biosphere assessments for radioactive waste facilities in order to avoid unnecessary differences in arbitrary assumptions that could challenge an assessment's credibility and to address fundamental protection issues, whilst acknowledging scope for local differences. There are a number of practical issues associated with determining the long-term nature of the biosphere. For example, both natural and human-induced changes can occur that can lead to changes in the future environment as well as behaviour of people and biota living in that changed environment. Furthermore, requirements and regulatory and stakeholder interests can change over time as scientific and social contexts develop, so as to require an iterative and interactive approach to biosphere assessments as they develop.

Long-term biosphere assessments are not intended to be predictions; rather, the outputs of assessments are intended to provide illustrations of what could happen and are intended as points of reference for the safety of radioactive waste disposal. The BIOMASS-6 project therefore aimed to identify a common ground on how to justify assumptions for long-term dose assessments and to develop a simple step-by-step assessment process that would be both linear and transparent. The resultant steps are presented in Figure 2-1.

Whilst the process can be presented in a simple manner, it is actually a complex matter to organise information at each step of the methodology, as illustrated in Figure 2-2.

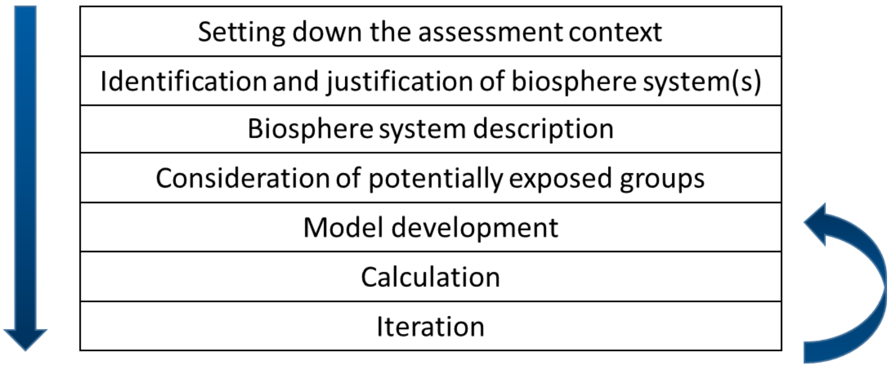

Figure 2-1. The BIOMASS-6 step wise methodology for long-term biosphere assessments.

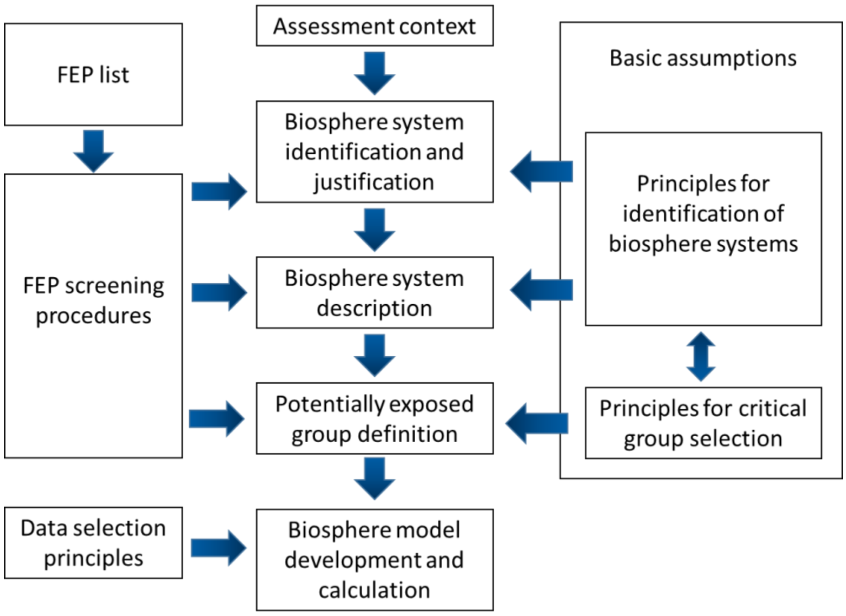

Figure 2-2. Schematic illustration of the BIOMASS methodology, including supplementary guidance [from Figure A2, IAEA, 2003[d]].

The first step in the methodology is to set out the assessment context. This clearly defines what is to be done and why, and provides the basic assumptions for the assessment. A set of detailed context components is provided that aim to allow those undertaking an assessment to demonstrate knowledge of what is required and those reviewing the assessment to clearly ascertain what was intended. The components are listed below.

- Assessment purpose.
- Assessment endpoints[e].
- Assessment philosophy, cautious or equitable assumptions.
- Repository system, e.g. deep/shallow.
- Site context, coastal/inland.
- Source terms and geosphere-biosphere interface.
- Time frames.
- Societal assumptions.

---

[d] IAEA (2003). "Reference Biospheres" for Solid Radioactive Waste Disposal: Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme, IAEA-BIOMASS-6, IAEA, Vienna.

[e] Multiple objectives can be addressed by assessing a number of endpoints.

The key reasoning behind this first step is to ensure that assumptions are transparent and that social, political and ethical aspects of assessments are addressed. Further information on each component is given below.

It was recognised that there can be a range of alternatives for assessment purpose. These may include demonstrating compliance with regulatory requirements, guiding research priorities, providing proof of concept, system optimisation etc. Additional purposes may now be identifiable as a result of knowledge and experience gained by those that have undertaken assessments.

A number of alternative assessment endpoints were detailed in the methodology, including:

- individual dose or risk;
- collective doses or risks, distributed over different temporal and spatial scales;
- doses to non-human biota;
- modifications to the radiation environment: distribution / concentration of repository radionuclides in the environment;
- fluxes into or through parts of the biosphere; and
- estimates of uncertainties or confidence.

There have been relatively few examples to date of collective doses being evaluated in long-term dose assessments, although Posiva has considered the dose distribution across the hypothetical more highly exposed population. Consideration may therefore be given as to whether this endpoint could be removed in the update of the methodology or the list rearranged to set out priorities. An endpoint that may be suitable for inclusion could be non-radioactive contaminants in the biosphere.

The assessment philosophy component is intended to set out whether cautious or equitable assumptions should be applied. Cautious assumptions may be appropriate for screening assessments whereas more equitable assumptions would be relevant to assessments to support optimisation. It is possible to combine both cautious and equitable assumptions in assessments however. For example, the use of best estimates with regard to radionuclide behaviour combined with cautious assumptions for human behaviour.

Alternatives mentioned in the methodology for repository system include the depth of the facility, the host geological medium and the waste type. Early information on the waste type is of value to allow data needs for potentially relevant radionuclides to be identified if they are not otherwise provided (see below). Working Group 6 of MODARIA has given further consideration to categories of facilities (Figure 2-3).

The site context is aimed at identifying the basic features of the biosphere that should be taken into account such as the areal extent, surface topography, current climate, soil types, surface and near-surface water bodies, fauna and flora etc. A full characterisation of a site is not required at the assessment context stage; rather, the intention is to define key features of the biosphere.

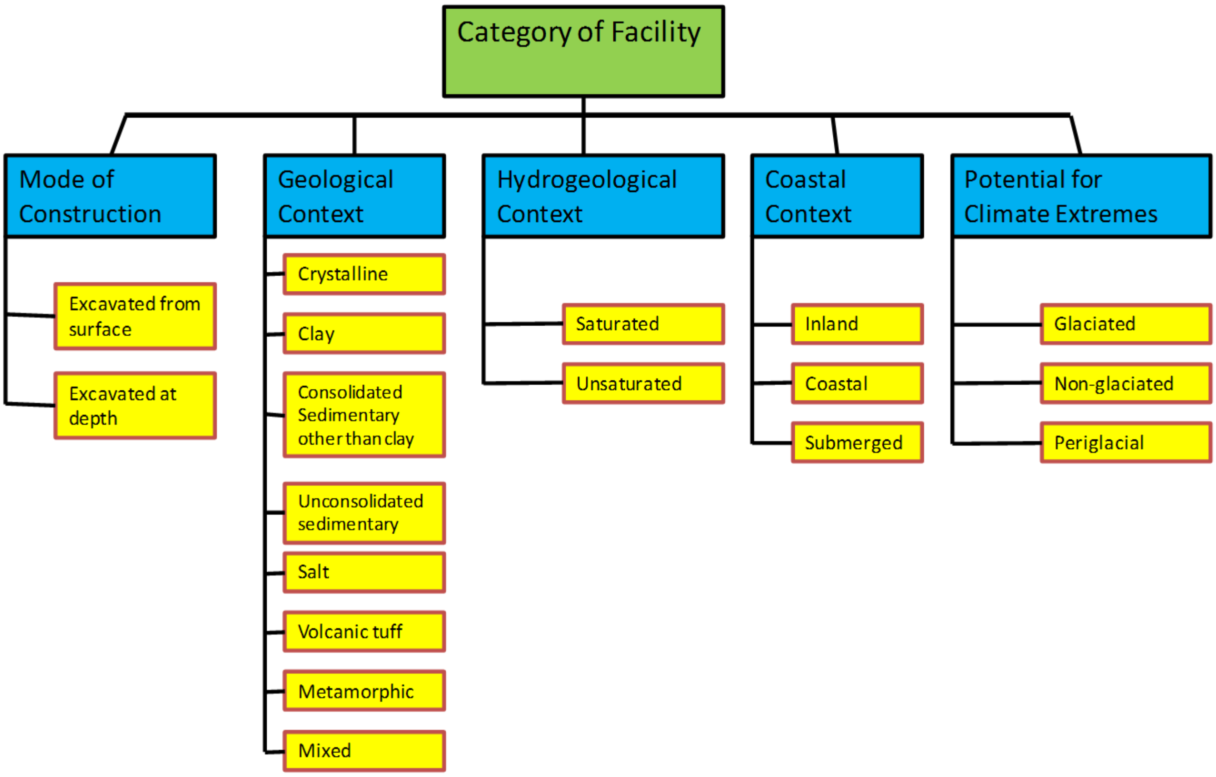

Figure 2-3. Categories of waste disposal facility (from MODARIA WG6, to be published).

The source term and geosphere-biosphere interface need to be defined as part of the assessment context. This should include determining release rates into receptors to help identify the radioecology parameters required. Interfaces could, for example, be a well or water body or sub-surface soil. Extraction rates for wells and groundwater hydrology need to be understood to ensure assumptions are realistic and consistent with the associated geosphere assessment.

The assessment timeframe should also be established at an early stage as this can affect the radionuclides that should be considered[f]. The different timeframes may be set out in guidelines from regulators and may require different levels of detail as timeframes increase. For example, quantitative assessments of dose may be required for the first few thousand years post-closure whereas safety indicators may be appropriate for longer timescales (e.g. 10,000 years or more). IAEA TECDOC 767 sets out the different levels of detail that could be expected at different times.

Societal assumptions relate to human behaviour and two alternatives were included in the methodology: (i) intensive or extensive farming and the use of modern technology; and (ii), the use of simple technology associated with subsistence farming. It may be appropriate to include additional societal assumptions such as hunter-gatherer, fisherman and aboriginal lifestyles to ensure that the alternatives described are not too limited in range in terms of the exposure pathways considered and their

[f] For example, a relatively immobile radionuclide may not reach the biosphere until after the specified timeframe. See also discussion of the implications of changes in requirements so as to address a different timeframe in Section 3.2.

parameterisation. It should also be considered that climate state will affect behaviour, which was not explicitly considered in the BIOMASS-6 examples. It may also be appropriate to raise the possibility for stakeholder engagement in defining societal assumptions.

After defining the assessment context, stage 2 involves the identification and justification of the biosphere system. This involves identifying the principal components of the system or systems and a set of tables is provided in the methodology to support this stage, in terms of potentially relevant aspects of characterisation. The approach to addressing system change should also be identified, again according to a defined procedure. The output of this stage will include identification of the biosphere system(s) to be considered, including more detailed information on climate type, topography and water bodies and how system evolution will be treated. In addressing environmental change, the applicable regulatory requirements should be taken into account, but stakeholders may also have relevant views that might need be taken into account, depending, for example, on who is the intended audience and readership for whom the assessment is prepared. Once the biosphere system or systems have been identified, stage 3 then involves development of a narrative of what the systems comprise in terms of system components. This may include quantitative and qualitative aspects and descriptions of potential exposure pathways that can then support the characterisation of potential exposure groups (stage 4). From the identified potential exposure pathways, corresponding human habits, consistent with the system description and assessment context, should be considered, taking account of current site habits and other sites analogous to projected future conditions at the site. In developing a revised methodology, it may be appropriate to include in this stage the possibility of considering exposure groups in the context of non-radiological contaminants. The output of stage 4 should be lists of characterised potential exposure groups. Whilst the potential exposure groups should be set out at a relatively early stage in the assessment process, there should be continued iteration throughout the assessment process to ensure the relevance of assumptions and avoid omissions.

Stage 5 of the methodology then involves the development of assessment models. Conceptual model objects should be identified from the system characterisation and information on potential exposure groups. Migration and accumulation pathways for radionuclides should also be evaluated through source-pathway-receptor analyses. Lists of features, events and processes (FEPs) have been developed to support this stage of assessment and help justify model assumptions. The relevant processes must then be represented mathematically and data protocols applied to support parameter value selection. The output of this stage should be justified definitions of the calculations to be made. Endpoint calculations should then be made (stage 6) and results reviewed against the assessment context objectives. Further iteration to improve model data and/or models should occur and further research requirements should be identified, as appropriate.

The BIOMASS-6 methodology included three quantitative example reference biospheres (ERBs) that were intended to demonstrate the application of the approach and guide priorities at an early stage of development of a disposal project. The three scenarios were:

- a drinking water well (ERB1);
- an irrigation Well, constant temperate agricultural system (ERB2a); and
- natural discharge of contaminated groundwater, constant agricultural and natural temperate habitats (ERB2b).

The main issues impacting on the headline results included assumptions at the geosphere-biosphere interface, such as the mixing of clean surface and deeper contaminated ground waters. Other pathways may also be important however, such as release in the gaseous phase or erosion of contaminated media. Semi-natural habitats may also present important pathways for exposure, for example, through the collection of wild mushrooms. The examples helped to demonstrate that there are relatively few key processes that dominate doses. However, omitting a process or exposure pathway can be a mistake and early elimination of a process is rarely justifiable, as input to the biosphere assessment can change as the assessment progresses. Variation in exposure group assumptions was not found to have a large impact on dose calculations so long as all exposure pathways were included, but different groupings of exposure pathways could still be of interest.

The BIOMASS-6 methodology included consideration of environmental change. The application of the methodology in the context of environmental changes was explored through a third set of example reference biospheres (ERB3). However, time and resources meant that only initial qualitative consideration was possible for the cases that included system change; none were carried through to quantitative assessment.

2.2 CLIMATE AND ENVIRONMENTAL CHANGE

Russell Walke presented.

Within biosphere assessments, there is a need to justify whether or not environmental change is to be taken into account. Examples of environmental change affecting the biosphere include land uplift, erosion and/or land use changes, all of which are affected by climate change. One of the aims of biosphere assessments is to build confidence by ensuring assessments are realistic; the surface environment will change on the timescales of interest so assessments need to justify how it is treated. The safety of facilities can be evaluated through the use of different scenarios to represent different hypothetical futures, but consideration needs to be given to how environmental change is addressed in relation to each scenario.

Within the BIOMOVS II programme that ran from 1991-1996, a reference biospheres methodology and FEP list were developed. Environmental change was identified as a key question to be addressed, recognising however that the representation of environmental change would depend upon the context and could range from no change through to smoothly varying climatic successions. Whilst recognised as a key question to be addressed, environmental change was not carried through to project examples due to a lack of tools and approaches to support consideration at that time. The need for further work on representation of transitions between climate states and landscape evolution was identified, which fed into the subsequent BIOMASS programme that ran from 1996 to 2001.

Within the BIOMASS programme, environmental change became a central question in the decision tree for identifying and justifying biosphere systems, driven by consideration of external FEPs. The terminology of ‘sequential’ versus ‘non-sequential’ representation of environmental change was introduced with the choice of approach largely depending upon the site and regulatory requirements. A step-wise decision tree to support the appropriate representation of environmental change in assessments was developed (Figure 2-4).

Example reference biospheres were included in BIOMASS. Example reference biosphere 3 (ERB3) explored ways of representing change in assessments, but this was discursive rather than being a full demonstration of approach. Nonetheless, it was found to be helpful to aggregate mechanisms of change to the categories of climate change, landform change and societal change.

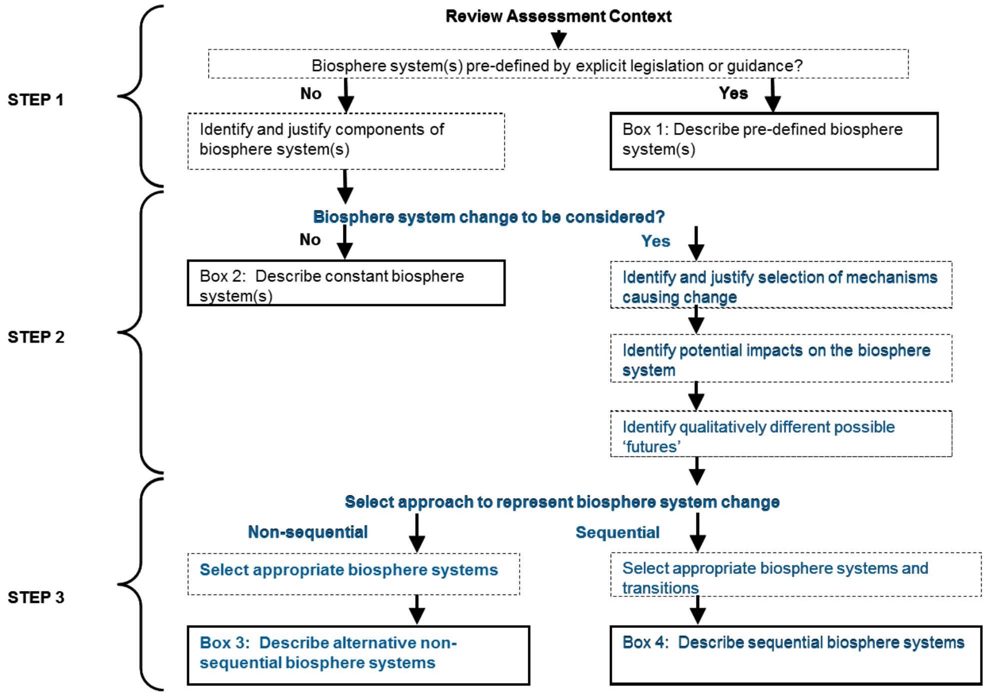

Figure 2-4. BIOMASS decision tree for environmental change

Following BIOMASS, an EC project, BIOCLIM, which had a specific focus on climate change, ran from 2000 to 2003. The project established long-term projections of global climate, highlighting the potential for an extended interglacial period influenced by greenhouse gas emissions. Downscaling of global climate was addressed and the concept of 'narratives' of environmental change was developed. Downscaling was explored in a series of case studies for which narratives were developed through to sequences of biosphere states and transitions between those states. The project did not go as far as modelling of those states and transitions. The steps followed in the BIOCLIM project were mapped back to the steps of the BIOMASS-6 methodology.

From 2009 to 2011, working group 3 of the EMRAS II programme collated experience of addressing environmental change in assessments. Reference models for analogue sites with different climates were considered as a means of looking at climate and biosphere conditions that could possibly occur in the future and a pronounced influence of increased irrigation rates due to drier climates on peak doses was noted. The landscape modelling approach that was being developed by SKB and Posiva was also reviewed. It was concluded that the analogue site and landscape modelling approaches were complementary and the two approaches could be used in combination.

The issue of environmental change has most recently been considered within an international programme by working group 6 of MODARIA. Climate change was recognised as a key driver to environmental change and has been the principal focus within the working group, which has aimed to develop a framework to support consideration of environmental change in assessments. BIOCLIM global climate projections have been updated to provide example climate projections, work that was supported by a parallel project run by Radioactive Waste Management Ltd (RWM). Approaches for downscaling global climate projections were reviewed, with an example for the UK from the parallel RWM project. Downscaled climate results are needed to provide inputs to long-term assessments for radioactive waste disposal beyond the biosphere components. The importance of environmental change to an assessment is determined by the type of facility and the site context. The types of environmental change that need to be considered will be largely determined by the timescale of assessment, which reflects both regulatory requirements and the hazards associated with the waste. For example, for near-surface coastal facilities the main focus for consideration of environmental change may be coastal erosion and sea-level rise, whereas for deep, inland facilities in northern latitudes, the main focus is more likely to be upon glacial-interglacial cycles.

Different modelling approaches are available for simulating climate that vary in both resolution and in terms of the timescales for which they can be applied. High resolution models tend to be applicable to short timescales whereas long-term climate models tend to have a low resolution. As such, low resolution climate models are required to evaluate long-term climate that then need to be downscaled to provide information relevant for specific sites. This was the approach taken in the parallel RWM project. The climate modelling was undertaken at Bristol University using the long-term global climate model GENIE to investigate carbon dioxide emission scenarios. The output from the GENIE model was used as input to snapshot calculations using a higher resolution climate model with an emulator being used to interpolate between the snapshots. This approach allows global climate to be evaluated over a 1 million year timeframe at a much greater resolution than would normally be possible.

The downscaling of global climate can be undertaken using a variety of approaches, which can be dynamic, physical-statistical or rule-based. A physical-statistical approach was employed in the parallel RWM project with global climate being downscaled to consider climate variation over the UK. The downscaling approach has been tested by comparing predicted to observed data, the approach was demonstrated to be good for evaluating temperature, but was less accurate in terms of precipitation in high altitude locations (Figure 2-5).

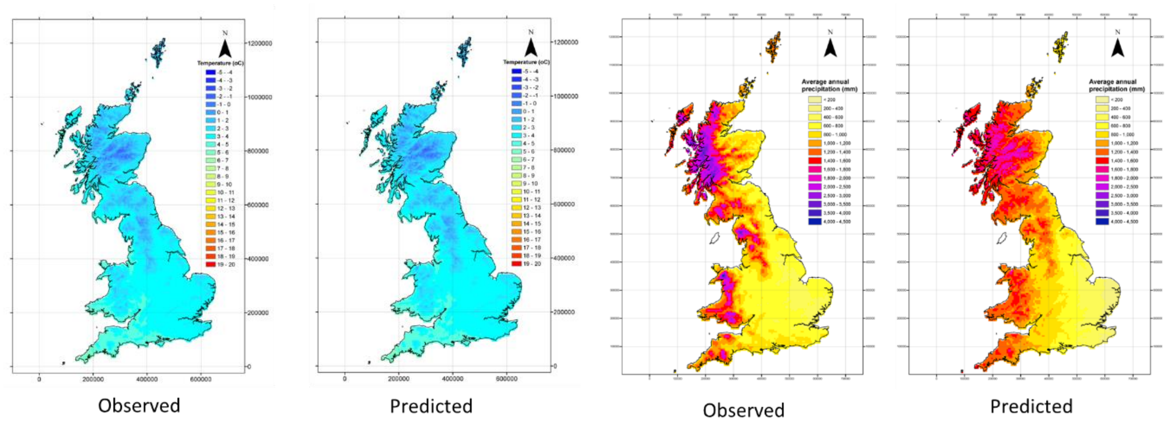

Figure 2-5. Comparison of observed and predicted data for mean January temperature (left) and mean annual precipitation (right) from the RWM project undertaken in parallel with MODARIA Working Group 6.

The output from the climate modelling provides the context for considering long-term landscape evolution. It was recognised that, in addition to climate, humans can have a significant impact on landscapes, potentially intervening against natural landscape evolution, which should be considered in assessments. A range of scenarios can be developed as a means of evaluating these and other influences, each of which could be subject to quantitative landscape evolution modelling or more qualitative approaches, as appropriate. This approach should provide a narrative of climate and landscape change for each scenario.

The implications of the work on climate and landscape evolution on quantitative safety assessment modelling has been considered within the MODARIA project and can feed into the BIOMASS-6 update. This includes discussion around the representation of change in assessment models, the balance between stylistic versus more complex representations, and the potential usefulness of present day information for analogue areas for improving understanding and informing on how to represent conditions into the future. The considerations relevant to deciding how to represent environmental change in quantitative assessment modelling were discussed within MODARIA working group 6 and are illustrated in Figure 2-6.

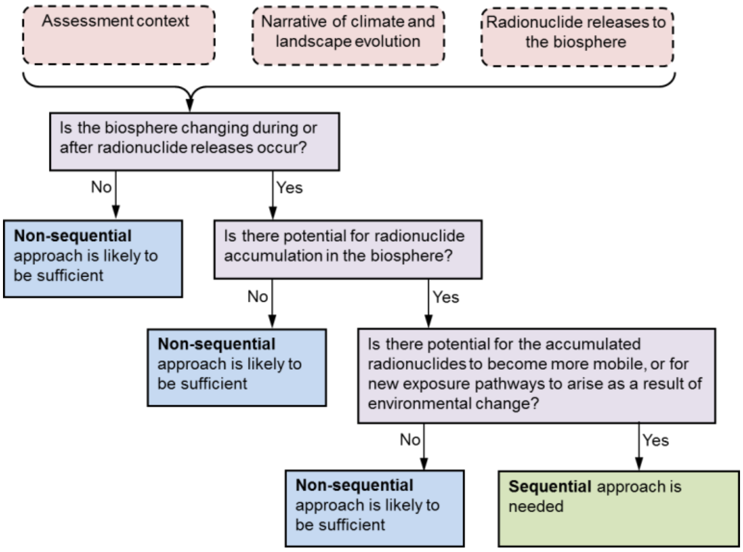

Figure 2-6. MODARIA WG6 considerations for representing environmental change in assessment models.

Discussion

The work within MODARIA has mainly focused on consideration of long-term climate (tens of thousands of years and longer). In the UK and elsewhere, there are coastal sites for the disposal of wastes for which site-wide environmental safety cases, or similar, will be required and for which shorter timescales will be of relevance. A project has been suggested for the MODARIA II programme that would focus on climate and environmental change over shorter timescales than those considered by MODARIA working group 6, i.e. with greater focus on the first 1000 years. A key issue in this context is global warming at high northern and southern latitudes relative to overall global warming, and its implications for the induction of thermo-mechanical instabilities in the Greenland, West Antarctic and East Antarctic ice sheets. There is accumulating evidence that these instabilities can be more substantial and expressed on shorter timescales than have previously generally been considered. Thus, coupling of global climate and detailed ice-sheet models is likely to require specific consideration. Results could be useful in relation to near-surface disposal facilities generally and to management and long-term remediation of legacy sites.

An argument can be made, depending upon regulatory requirements, for non-sequential representation of environmental change on the basis that transitions are unlikely to result in larger impacts than the two states that are transitioning. However, the use of a sequential approach can be beneficial, particularly in the moving of a radionuclide inventory from one state to another. Improved transparency offered by sequential modelling can help with ensuring proper accounting of the inventory. Decisions on the appropriate approach will depend on the context and on stakeholder expectations.

2.3 MODELLING PROCESSES AT THE GEOSPHERE-BIOSPHERE INTERFACE

Lara Duro presented.

The geosphere-biosphere interface (GBI) is a complex environment and has been a subject of interest in BIOPROTA for some time with the most recent report ‘an exploration of approaches to representing the geosphere-biosphere interface in assessment models[g]’ being published in December 2014. A peer reviewed paper based on BIOPROTA activities has also recently been published[h]. The project report provides a good summary of advances in the methods that can be followed to represent the GBI, having looked at the development of scenarios for different types of GBI, the use of structured procedures to develop conceptual models of those interfaces and identification of approaches to mathematically representing those conceptual models. Whilst mathematical models can be simple or complex, they must contain all the processes that occur at this interface.

The GBI is a region where radionuclide dilution and re-concentration processes can occur. It is less variable with time than the biosphere, but is likely to be significantly modified by landscape development over typical post-closure safety assessment timescales. The BIOPROTA GBI project put in place a formal methodology for its identification, characterisation and both conceptual and mathematical modelling that is analogous to what was done for the biosphere in the BIOMASS and BIOCLIM projects. Studies on the influence of climate change and landscape development on the GBI are now being taken forward in the IAEA MODARIA project.

There is a wide diversity of models applicable to the GBI, including landscape, hydro-geochemical, biogeochemical and permafrost modelling. There have recently been a number of important advances in hydrogeological modelling. For example, a first fully coupled 2D hydro-geochemical model was presented during a 2009 BIOPROTA meeting. The model was used to investigate the retention of radionuclides in quaternary sediments following a hypothetical release from the geosphere (Figure 2-7). The composition of the geology and sediments will affect the transport of radionuclides and this was considered in the model. For a complete description of the model and results see Grandia *et al*. [2011][i].

---

[g] Thorne et al. (2014). Available from www.bioprota.org.

[h] Smith et al. (2014). Recent developments in assessment of long-term radionuclide behaviour in the geosphere-biosphere subsystem. Journal of Environmental Radioactivity 131: 89-109.

[i] Grandia, F., Sena, C., Arcos, D., Molinero, J., Duro, L., Bruno, J.; Quantitative assessment of radionuclide retention in the Quaternary sediments/granite interface of the Fennoscandian shield (Sweden) Applied Geochemistry 26 (5) , pp. 679).

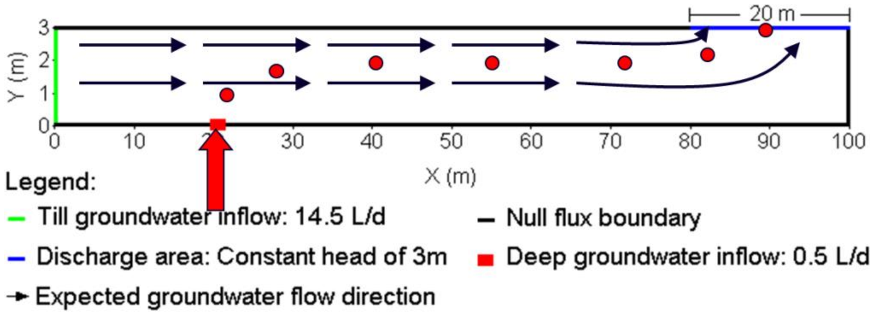

Figure 2-7. Illustration of the modelling of release of radionuclides from the geosphere and incorporation into sediments.

Whilst a simple representation of hydrology was used in the model, the geochemical representation was complex, but allowed the key geochemical processes affecting radionuclide retention to be identified (Figure 2-8). The model also allowed Kd to be calculated, illustrating that Kd varied both in space and time, as illustrated for Sr-90 in Figure 2-9. This led to a further work programme to consider how to represent hydro-geochemical impacts on radionuclide sorption over space and time in what has been termed a 'smart Kd' approach. A peer-reviewed paper on this approach has recently been published[j].

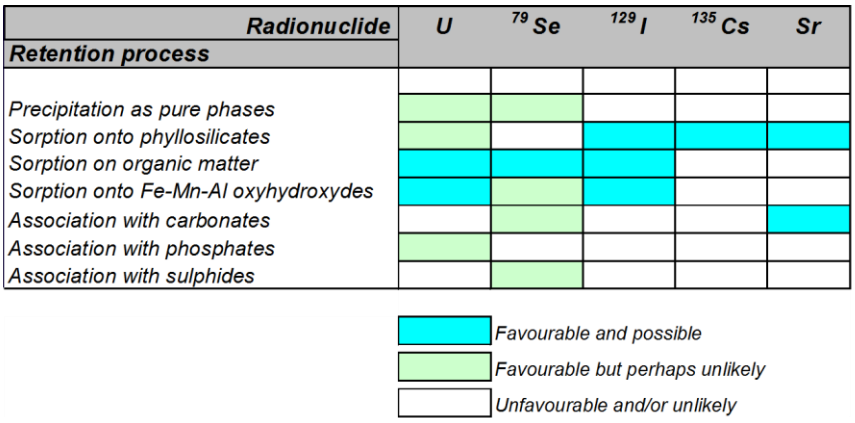

Figure 2-8. Geochemical processes affecting radionuclide retention.

Smart-Kd is a novel approach to improve the traditional constant Kd-based radionuclide transport models. The basic premise is that radionuclides are expected to be in such low concentrations that they do not significantly alter the overall chemistry. Under this condition, background geochemistry is decoupled from radionuclide retention processes and computed using mechanistic reactive transport models. At each time step, the computed background conditions, the selected retention models and an arbitrarily low radionuclide concentration are used to perform 0D batch calculations, with results providing a matrix of Kd values that is post-processed and used to feed a computer code with updated Kds during the radionuclide transport simulation.

[j] Trinchero et al. (2016). Modelling radionuclide transport in fractured media with a dynamic update of Kd values. Computers and Geosciences 86: 55-63.

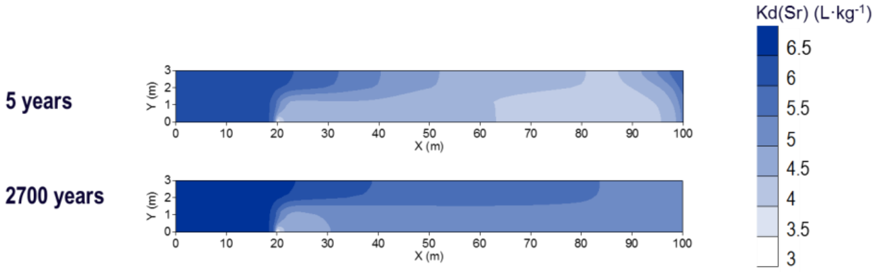

Figure 2-9. Variation of Sr-90 Kd in space and time.

The output of the model has been verified for a single trajectory discharge to the biosphere. However, radionuclides transported in groundwater will not behave as a single trajectory to the biosphere and multiple trajectories have therefore also been considered, using particle tracking data for around 4,000 transport pathways. The output of the model was compared with a FASTREACT fully coupled reactive transport simulation and good agreement was observed. The simpler approach was therefore in agreement with the more complex approach. The use of such a model will be beneficial in generating the parameters required to support long-term assessment models.

A reactive transport model has been developed for SKB, as reported in SKB report R-08-107. The retention processes considered in the model for the radionuclides Sr-90, Cs-137, U-235 and Ra-226 are detailed in Table 2-1. The model allows the retention of radionuclides at different points in the geosphere-biosphere system over time and space to be visualised. The equivalent Kd can also be computed and two types of equivalent Kd calculations have been tested, one for the spatial distribution of Kd at the end of the reactive transport simulation and one for the time-dependent Kd function in different media (e.g. till or clay). Results of the Kd calculations have been compared with published data and the results were evaluated at the time of the workshop.

Table 2-1. Retention processes in the SKB reactive transport model.

Radionuclide	Retention processes
^{90}Sr	Sorption in planar sites Precipitation of strontianite
^{137}Cs	Sorption in planar sites Sorption in type II sites Sorption in X_{FES} sites
^{235}U	Sorption on $Fe(OH)_3$ surface (strong and weak sites) (only in the Till) Precipitation as uraninite (only in the Clay)
Ra	Precipitation as radiobarite

Models for representing the GBI have therefore advanced significantly in recent years as a result of developments in software and the approach to mathematical modelling that has been adopted. As a result, it is no longer necessary to simplify conceptual models to the extent previously necessary. Remaining challenges include the addition of probabilistic and stochastic analyses to allow uncertainties and heterogeneities to be evaluated and to consider transfers to biota.

There are a number of ongoing developments to the model, including consideration of accumulation of radionuclides in organic soils, complexation with dissolved organic carbon, surface complexation with iron hydroxide and cation exchange in clay minerals. Further improvements required to reproduce observations include addressing:

- rainwater evaporation (results predict a greater dilution by recharge water than observed in measurements);
- organic matter degradation (currently considered constant in time and space, but will be affected a wide variety of physico-chemical characteristics of the system and by adaptations of microbiological decomposer communities to those conditions;
- plant uptake of selected elements proportional to transpiration; and
- weathering as a potential source of elements.

Discussion

The comparison of modelled versus observed Kd data indicated that the calculated Kd values were around an order of magnitude lower than the measured data. This was discussed at the workshop as potentially resulting from the spatial averaging of the modelled data or from the way in which Kd is measured in the field. Further analyses of the calculation results in front of the data reported by Sheppard et al. [2011] indicated a good correlation for Sr and Cs. Calculated Kd values for U were higher than that reported *in situ*, while for Ra the *in situ* measurements were higher than the calculated ones (see Table 2-2 below).

Table 2-2. Results of the calculated Kd values (in m^3/Kg) from the reactive transport model, compared with the range values of the in-situ measurements by Sheppard et al. (2011).

	Till			**Clay**		
	Calculated Abarca et al. [2016]	In-situ measurements Sheppard et al. [2011] min	max	Calculated Abarca et al. [2016]	In-situ measurements Sheppard et al. [2011] min	max
Cs	9.60	5.00	24.20	72.73	5.70	650.00
Sr	0.03	0.06	0.19	0.04	0.03	0.80
U	*0.13*	*0.005*	*0.06*	*0.03*	*0.11*	*18.00*
Ra	*0.0006*	*0.57*	*2.99*	*0.0006*	*0.80*	*28.00*

The model particle tracking studies to define input areas of radionuclides to the domain. Reaction, mixing and dilution are incorporated in the model.

In moving toward consideration of transfer to biota, the model is very useful in illustrating heterogeneity in radionuclide concentrations over space and time that could be combined with information on the spatial use of the biosphere by biota (e.g. through use of information on home ranges).

2.4 SOIL-PLANT SYSTEM MODELLING

Graham Smith presented.

Since the publication of the BIOMASS-6 methodology, there have been a number of developments with regard to modelling of soil to plant transfer of radionuclides. The first BIOPROTA deliverables with regard to this subject involved participants applying simple exposure models to look at different transfer pathways such as spray irrigation, which enabled models to be checked for the inclusion of processes of importance. Whilst models will not always require all processes, depending upon the context to which they are intended to be applied and the radionuclides of interest, the exercise provided the opportunity to consider whether exclusion was justified. Working group 3 (WG3) of the EMRAS II programme then considered the use of analogues and soil plant systems modelling, with the use of current conditions at other sites being used to inform on potential future conditions at sites of interest. Calculations were undertaken for a range of different sites with varying irrigation needs, based on current day climate data (Figure 2-10), leading to biosphere dose conversion factors (BDCF) at different reference sites for a range of radionuclides (Figure 2-11). The influence of soil type at different sites was also investigated (Figure 2-12), which illustrated the influence of Kd on dose at any given site.

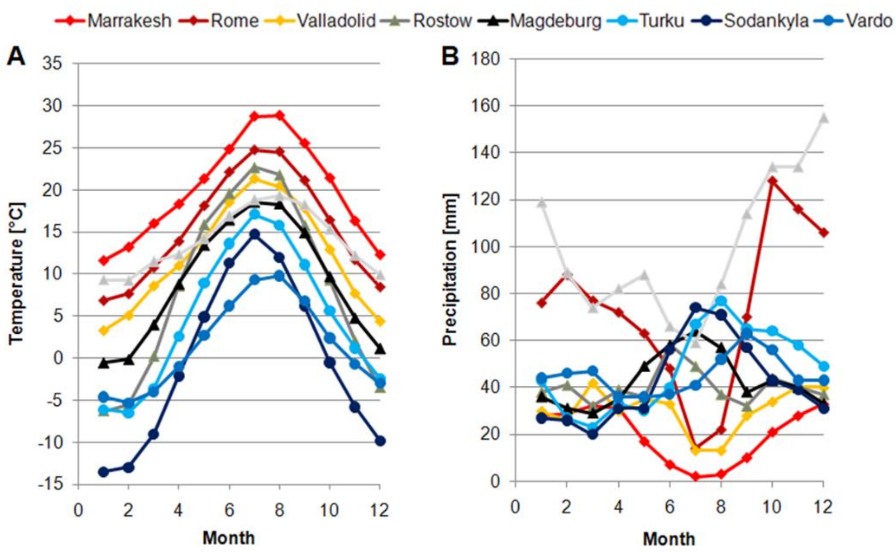

Figure 2-10. Consideration of current climate (temperature (A) and precipitation (B)) at different sites to inform on irrigation requirements [from EMRAS II, WG3, report in publication].

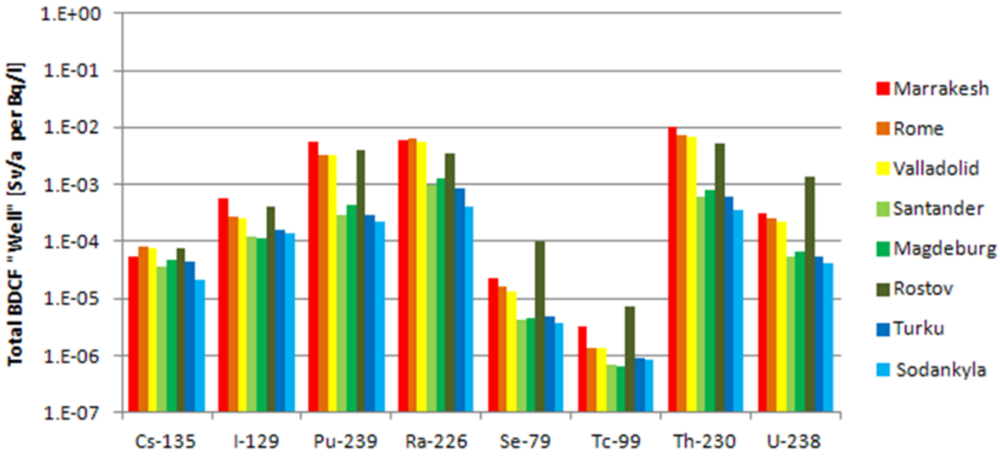

Figure 2-11. Calculated BDCF for radionuclides at different sites [from EMRAS II, WG3, report in publication].

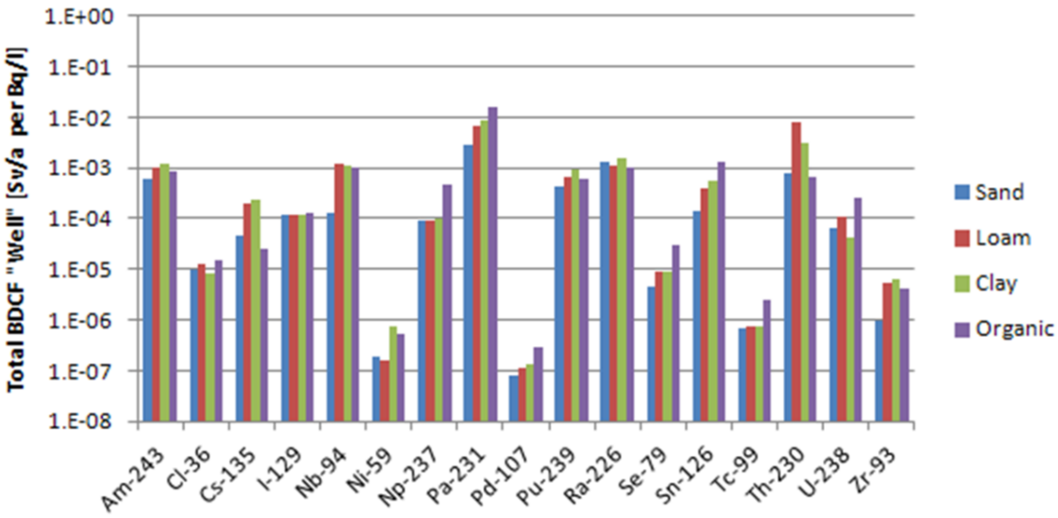

Figure 2-12. Influence of soil type on the BDCF for radionuclides at the Magdeburg reference region [from EMRAS II, WG3, report in publication].

WG3 of EMRAS II also undertook soil-plant system modelling for temperate, boreal and Mediterranean climates using real-site data, which illustrated how models and also vegetation differed. The way in which soils were represented in models varied, with some using multiple soil layers and others using a single compartment to take account of all processes occurring within soils and the difference the alternative approaches made and the type of calculation methods were investigated. The significance of foliar interception versus root uptake in different models was also evaluated with observed differences in model output leading to discussion between participants.

Additional examples of how accumulation in soil, irrigation etc. are represented in assessment models are invited as input to consideration of how this area has developed since the BIOMASS-6 programme.

2.5 SPECIAL MODELS FOR SPECIAL RADIONUCLIDES

Adrian Punt presented.

The BIOMASS-6 reference biospheres methodology made reference to requirements for biosphere modelling, noting that different aspects may need to be considered depending upon the radionuclides and the interfaces assumed between the geosphere and biosphere, and that there would be inherent variability in processes affecting radionuclides in the biosphere. However, no specific guidance on modelling approaches to address these issues was provided.

Subsequent to the publication of BIOMASS-6, there has been increasing recognition that radionuclides do not always behave in ‘standard’ ways and models may therefore have to consider different processes depending on a specific radionuclide’s behaviour in the biosphere. As such, BIOPROTA has undertaken a number of special-radionuclide focussed projects. For example, modelling of C-14, Se-79 and Cl-36 have each been considered in some detail.

Carbon-14 is a key radionuclide of interest in post-closure assessments for solid radioactive waste disposal, being release as C-14 bearing gas or as aqueous species. The main focus to date within BIOPROTA has been on the release of methane to soils and subsequent uptake by plants. The behaviour of C-14 in soils is complex with methane in soils potentially being converted to carbon dioxide as a result of microbial metabolism with subsequent emanation of carbon dioxide from soils to the plant canopy atmosphere where it may be taken up by plants for photosynthesis. The uptake by plants is however governed by plant canopy dynamics. The ability for plants to take up C-14 by root pathways remains uncertain. The specific projects undertaken within BIOPROTA to date include:

- BIOPROTA (2005): Model review and comparison for C-14. A report prepared within the international collaborative project BIOPROTA.
- Limer et al. (2009). C-14 Long-Term Dose Assessment: Quantitative Model Comparison and Development, Part I.
- Limer et al. (2011). C-14 Long-Term Dose Assessment in a Terrestrial Agricultural Ecosystem: FEP Analysis, Scenario Development, and Model Comparison.
- BIOPROTA (2013). Modelling Approaches to C-14 in Soil-Plant Systems and in Aquatic Environments. Report of a review and International Workshop held 12 – 14 February 2013.
- Smith & Smith (Eds) (2014). C-14: Data, Ecosystems and Dose Assessment. Report of an International Workshop, 1 – 3 April 2014, Aix-en-Provence.
- Smith (Ed) (2015). Long-term dose assessment for C-14: Report of an international workshop, Aix-en-Provence, 28-29 April 2015.

Work is continuing on the subject of C-14 in terrestrial systems in 2016 to compare models with real data.

There are two broad approaches to modelling C-14; specific-activity and process-orientated models. For specific-activity models, knowledge on pools of carbon in equilibrium is required, taking into account the dynamics of the C-14 release. For process-orientated models, knowledge of the system is required to allow processes to be adequately characterised. Both approaches therefore require system understanding as input to models.

Chlorine-36 is also a key radionuclide in post-closure safety assessments for which there were notable uncertainties in radionuclide behaviour and modelling parameters, for example relating to accumulation in soil and subsequent uptake in plants. Two projects have been undertaken in BIOPROTA on Cl-36:

- BIOPROTA (2006). Report of an international forum on Cl-36 in the biosphere, Chatenay-Malabry, 27-28 September 2006.
- Limer et al. (2008). Investigation of Cl-36 Behaviour in Soils and Uptake into Crops.
- Limer et al. (2009). Cl-36 Phase 2: Dose Assessment Uncertainties and Variability.

A key objective of these projects was to compare the scientific basis supporting alternative model approaches. Sources of variation in models included differences in exposure group assumptions (e.g. whether animals were fed only contaminated fodder/grain and the extent of self-sufficiency assumed), ingestion rates and dose coefficients. No source of variation was found to result in more than an order of magnitude difference between model outputs however. The majority of difference in model output related to soil to plant transfer calculations. Suggestions for further work were made as a result of the phase 2 project that remain outstanding, including:

- Potential differences between concentration ratio and specific activity approaches;
- Cereal uptake of Cl-36 (both in terms of human an animal consumption); and,
- Consideration of the potential for Cl-36 enrichment in milk products.

Selenium-79 has also been a radionuclide for which focussed work has been undertaken within BIOPROTA. Selenium is redox sensitive and displays complex behaviour in soils (Figure 2-13), being potentially present in four different oxidation states. Often within assessment models, a simplistic representation of complex behaviour is applied, based on a single Kd value that relates to total selenium. There is however a large variation in the literature data for Kd, which may result from the presence of different selenium pools, and gives rise to considerable uncertainty in assessments.

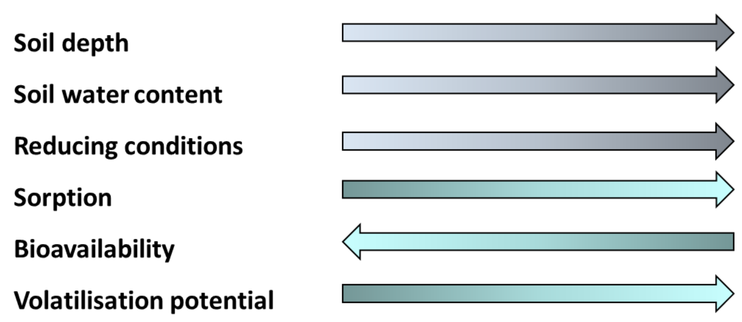

Figure 2-13. Selenium behaviour in a soil profile in relation to changing redox conditions.

Three work programmes have been undertaken to date within BIOPROTA:

- BIOPROTA (2008). Report of an international forum on Se-79 in the biosphere, Wettingen, Switzerland, 5-6 May 2008.

- Smith et al. (2009). Modelling the Abundance of Se-79 in Soils and Plants for Safety Assessments of the Underground Disposal of Radioactive Waste
- Smith et al. (2012). Se-79 in the soil-plant system. Phase 2: Approaches to modelling

The phase 1 project identified key aspects governing Se-79 environmental behaviour. A FEP analysis was also undertaken for a defined assessment context and a generic interaction matrix (conceptual model) was developed. During the phase 2 project, models were applied to a hypothetical unit release scenario, based on that applied to Cl-36, to provide a quantitative mechanism for exploring the significance of different models and data assumptions and to investigate prediction capabilities of conventional and new model approaches. The assessment also provided the means to investigate the degree of model complexity required for assessing Se-79 behaviour in soils and plants.

As a result of the Se-79 work programmes, the key processes and parameters for modelling behaviour in soils and uptake to plants were identified as Kd, cropping rates, soil to plant transfer, percolation rate and volatilisation rate. It was concluded that the use of process-orientated models helped to justifiably reduce the importance of Se-79 in repository safety assessments.

Overall, the work undertaken in BIOPROTA has demonstrated the importance of considering 'special' radionuclides in their own right. Such consideration leads to much greater understanding of the important processes, informs on model parameterisation and can help improve confidence in simpler models.

In taking forward the project to review and update the BIOMASS-6 methodology, this learning will be incorporated. It may also be appropriate to also consider other radionuclides in their own right, other than those that have received focus to date. Project participants are invited to identify any radionuclides with environmental behaviour that may warrant specific attention. For example, Sn-126 may be of interest, as it can be important in assessments, binds strongly to soils, but can form volatile compounds, such as tri-methyl tin.

Discussion

The use of specific-activity models was introduced within TRS 472 for mobile radionuclides such as C-14 or Cl-36 for which there are stable elements also present in the environment and it may therefore be appropriate to consider a similar approach for other radionuclides with stable elements under chronic contamination scenarios. A key question that should be asked is where improved models and inclusion of important FEPs could help reduce uncertainty associated with radionuclides that exhibit complex environmental behaviour.

In addition to the work undertaken within the BIOPROTA programme, the International Union of Radioecology (IUR) has also done some work on special radionuclides, reported in the IUR-6 report. This work may also be relevant in taking forward the BIOMASS-6 update project.

2.6 ADDRESSING CHEMICAL HAZARDS IN RADIOACTIVE WASTES

Graham Smith presented.

A work programme has recently begun on addressing chemical hazards in radioactive waste, which was discussed during the 2016 annual BIOPROTA workshop. The output from the discussions on this topic will be taken into account in the review and update of BIOMASS-6 project. From the discussions, it is evident that migration and accumulation of non-radioactive contaminants can largely be addressed (and in a consistent way to radionuclides), but there are issues around knowledge on toxicology, assessment timeframes and availability as well as coherence, of standards. Guidance on addressing non-radioactive hazards in the long term, after release from waste disposal facilities, is also largely lacking.

In the UK, the most recent regulatory guidance states that the developer or operator of a disposal facility for solid radioactive waste should demonstrate that the disposal system provides adequate protection against non-radioactive hazards. This is a relatively new assessment requirement. It is however recognised that the protection objectives may not be consistent and may not be suitable to apply directly to waste that presents both radiological and non-radiological hazards. As such, it should be demonstrated that the level of protection provided against the non-radiological hazards is no less stringent than if the standards were applied, for example by ensuring that materials are contained for at least as long as would be achieved by disposal within a facility for non-radioactive hazardous waste.

A request for information on national regulations and guidance on assessing non-radioactive hazards in radioactive waste has been made to BIOPROTA members. A response has been received from NWMO in relation to Canadian requirements. In Canada, it is explicitly recognised that radioactive waste may also contain non-radioactive hazardous substances and relevant standards are pointed to for both human and environmental protection. Comment is also given on the use of safety factors and levels of risk and natural background levels of metal contaminants in the environment.

Additional examples are requested. It is intended that inputs received will be compiled into an appendix to the report to illustrate requirements in different countries with regard to addressing non-radioactive hazards within solid radioactive waste disposal facilities.

2.7 ADDRESSING PROTECTION OF THE ENVIRONMENT

Adrian Punt presented on behalf of Karen Smith.

Non-human biota (NHB) assessment methodologies for radioactive waste disposal, at the time of the BIOMASS-6 programme, were in their infancy. Nonetheless, NHB were noted as potential receptors in addition to people. It was also recognised that the relevant ecosystems in terms of defining reference biospheres would likely differ for people and NHB, with natural and semi-natural systems being more relevant for the latter as opposed to managed systems for people. The importance of temporal and spatial scales over which data should be collected and applied was also recognised, along with the importance of the geosphere-biosphere interface in governing exposure and the potential for climate change to affect biota (e.g. the types of species present, productivity of systems and habits of animals). However, no specific methodological steps for demonstrating protection of the environment were described within the methodology or the reference biosphere examples.

There have been considerable developments in biota dose assessment requirements and methodologies since BIOMASS-6. For example, environmental protection objectives were included in the 2007 Recommendations of the ICRP that have been interpreted in the context of radiological protection requirements for geological disposal facilities[k]; biota dose assessments call for an additional line of argument and reasoning in building a safety case and provide a broader basis for risk-informed

---

[k] Weiss W (2012). Report of ICRP Task Group 80: Radiological protection in geological disposal of long-lived solid radioactive waste. Annals of the ICRP, October 2012 vol. 41 no. 3-4, 294-304.

decision making. Protection objectives are also included in the 2014 IAEA Basic Safety Standards (IAEA GSR Part 3) whereby it is recognised that:

> "*an integrated perspective has to be adopted to ensure the sustainability, now and in the future, of agriculture, forestry, fisheries and tourism, and of the use of natural resources*" (para 1.34)

and that assessments should consider:

> "*the potential for build-up and accumulation of long lived radionuclides released to the environment*" (para. 1.34)

In terms of methodological developments, since 2001 there have been a number of assessment tools that have been developed as a result of national or international programmes, including:

- Environment Agency R&D 128;
- ERICA assessment tool; and
- RESRAD biota.

The ICRP has also developed an environmental protection framework that is based around the concept of Reference Animals and Plants (RAPs) that provides a working system by which environmental protection can be demonstrated for planned and existing exposure situations. Whilst no international consensus has been reached on protection criteria for environmental protection, there has been considerable discussion around this issue and a number of different benchmarks and screening levels have been proposed, such as a 10 µGy/h screening value proposed as a result of the EC ERICA and PROTECT programmes and a set of derived consideration reference levels (DCRL) for the ICRP RAPs.

There has been a significant focus on aspects of the application of assessment methodologies and protection criteria with respect to NHB and solid radioactive waste disposal within BIOPROTA. Three projects having been undertaken to date, with reports available at www.bioprota.org:

- Sensitivity & knowledge quality of assessment models and parameters
- Approaches to demonstrating compliance with environmental protection objectives
- Scales for post-closure assessment scenarios (SPACE)

There has also been practical application experience, with assessments being undertaken in both generic and site-specific contexts, for example by EPRI, RWM, LLWR, SKB, Posiva and NWMO. Together, these developments provide a variety of information that can be considered within the BIOMASS-6 update. Particular focus areas could include spatial aspects of assessment, to ensure the focus on populations as the target for protection; the SPACE project considered spatial areas utilised by potentially exposed populations (PEPs), relative to possible human assessment scales. The results of the project lend confidence to the use of human averaging scales within NHB assessments for a variety of relevant radionuclides, but results are limited due to the use of a single simulated case scenario and one assumption around human area averaging. Furthermore, there were limitations in the study with respect to biota habits under different climate conditions, use of population scaling factors and consideration of habitat preferences and fragmentation.

Additional focus areas within the BIOMASS-6 update for NHB could include:

- Selection of geosphere-biosphere interface assumptions relevant to PEP exposure, such as natural upwelling areas rather than agricultural irrigation scenarios;
- The use of a tiered approach to deriving activity concentrations at different stages of assessment and the assessment context; and
- Approaches to the selection of PEPs for assessment, from the use of generic reference organisms through to ecosystem or community based representative species.

Additional suggestions for focus areas to be considered are invited.

2.8 DEVELOPMENTS IN INTERNATIONAL RECOMMENDATIONS AND GUIDANCE

Graham Smith presented.

There have been a number of developments in international recommendations and guidance since the publication of the BIOMASS-6 methodology. Not all are specific to radioactive waste disposal, but much is of relevance. For example, ICRP Publication 101, whilst not specific to radioactive waste disposal, gives guidance on the assessment of dose to a representative person, giving coherence between what is said with regard to exposure groups and what is included in assessments. Guidance is provided on the selection of habit data for a representative person, including the selection of day-to-day behaviours rather than extraordinary behaviour and approaches aimed at avoiding excessive conservatism in assessments.

ICRP Publication 122 was specific to geological disposal of solid radioactive wastes, defining appropriate standards for demonstrating radiological protection. For example, dose estimates should not be regarded as measures of health detriment beyond times of around several hundreds of years into the future, but should rather be used as indicators of the protection afforded by the disposal system. A dose constraint of 0.3 mSv/y is recommended for an expected evolution scenario or a risk constraint of 1E-5 /y for potential exposures from emplaced wastes.

There are also a number of ICRP task groups applicable to radioactive waste disposal considerations. For example, Task Group 97 is focussed on the application of the Commission’s Recommendations to surface and near-surface disposal of solid radioactive waste and Task Group 76 on their application to naturally occurring radioactive material (NORM). Strategies for NORM waste can vary in different countries, with some adopting long-term management of NORM rather than disposal.

The IAEA has also developed requirements and guidance since the publication of BIOMASS-6, including:

- IAEA (2011). Disposal of Radioactive Waste, Specific Safety Requirements, IAEA Safety Standards Series No. SSR-5.
- IAEA (2011). Geological Disposal Facilities for Radioactive Waste, Specific Safety Guide, IAEA Safety Standards Series No. SSG-14.
- IAEA (2012). The Safety Case and Safety Assessment for the Disposal of Radioactive Waste, IAEA Safety Standards Series No. SSG-23.

- IAEA (2014). Near Surface Disposal Facilities for Radioactive Waste. Specific Safety Guide, SSG-29.

The safety standard SSR-5 is particularly important with regard to radioactive waste disposal, setting out standards for disposal of all types of radioactive waste and disposal facility. Furthermore, SSR-5 states that the impact of non-radioactive material present in a disposal facility should also be assessed in accordance with national or other specific regulations, noting that this may be significant. The safety guide SSG-14 then sets out guidance on how to do assessments, with SSG-23 providing more in depth guidance on how to present a safety case.

In the UK, regulatory guidance has been developed for radioactive waste disposal. A risk guidance level of 10^{-6} /y has been adopted, which relates to an effective dose of around 20 µSv/y when the probability of receiving a dose is one. For situations where the probability of receiving a dose is less than one, there is the scope for doses to be greater whilst still meeting the risk guidance level. It is also recommended that realistic parameter values are used in assessments, since the standard adopted is already stringent, a point considered in the BIOMASS-6 document.

The US EPA sets site-specific clean up levels with regard to Superfund sites that, for carcinogens (both radionuclides and other chemicals), represent an increased cancer risk of 10^{-6} to 10^{-4} and it is risk levels rather than dose that are applied in relation to radiation clean-up levels. The levels applied are different from those stipulated by the US NRC, which are expressed in terms of dose.

Discussion

The NEA-OECD has a safety case working group from which relevant information may be gained for the BIOMASS update.

There is an issue with delicensing in the long term for disposal sites due to the potential for change from planned to existing exposure situations and resultant variation in the assessment criteria that should be applied. It is not just emergency situations that can result in existing exposure situations; waste disposal facilities that have not been constructed to current standards could also present existing exposure situations that require assessment.

Information on how regulators have interpreted international guidance within their own national frameworks would be beneficial in informing the BIOMASS-6 update, as well as information on how regulators have reviewed safety cases. Such information can provide learning on interpretation of recommendations and in relation to confidence in safety cases. Inputs to this are invited.

2.9 CONFIDENCE BUILDING.

Russell Walke presented.

Confidence is an important subject for radioactive waste disposal. Sufficient confidence in assessments of the long-term safety of disposal facilities is required to support decisions, taking into account the complexity of the systems and the considerable uncertainties associated with long-term assessments. It is not possible to predict the future and so reasonable assurance is sought; however, the confidence 'threshold' differs on a case by case basis. The degree of confidence that can be placed in results becomes increasingly important as calculated results get closer to safety criteria (i.e. as the "safety margin" decreases). The degree of confidence that can be placed in assessment results is a focus of regulatory review.

A systematic and scientific approach to assessments can help build confidence by explaining and justifying each step and helping to ensuring that the approach is fully transparent, logical and robust. Justification is an important part of communicating and explaining assessment approaches and assumptions. It is important that care is taken to justify both simplifying assumptions and the need for apparent complexities. The BIOMOVS II and BIOMASS-6 methodologies drawing on international experience and widely used practice, which can also help to build confidence that “good practice” is being applied. Quality assurance and verification are essential features, though validation is more challenging for the long timescales that are relevant.

Uncertainty will always be associated with long-term assessments and decisions must therefore be made in the presence of uncertainty. There are three broad types of uncertainty in assessments:

- scenario uncertainty;
- model uncertainty, which may be conceptual, mathematical or result from the software employed; and
- parameter uncertainty.

Each type of uncertainty can be managed in a different way to build understanding on how the uncertainty impacts on the assessment. For example, scenario uncertainty can be evaluated through the use of multiple scenarios to help ensure that nothing has been overlooked, with a ‘reference’ or ‘base’ case being used as a benchmark against which other scenarios may be compared. The base case may not be the most likely scenario. It may be appropriate to select a base case that stakeholders can readily relate to, such as a focus on current environmental conditions, with other scenarios then addressing environmental change. The way in which scenarios are presented can be important in determining how stakeholders may view the assessment.

In addressing model uncertainty, there is a need to ensure that models reflect the scenarios of interest. Test calculations can be undertaken that take account of different factors such as model discretisation or models could be validated against data sets or by model intercomparison exercises, where available. The knowledge base for developing models can also be enhanced through review of literature to establish precedence and best knowledge. Independent modelling can be undertaken, for example during regulatory review. It is not possible to validate all aspects of models that represent extremely long timescales extremely long timescales. However, validation of individual components of a model, such as the representation of radionuclide uptake from soils to plants, can lead to improved confidence in the models as a whole. These various approaches can together be used to build confidence in the assessment models.

To address parameter uncertainty, various approaches can be adopted such as the use of multiple deterministic bounding cases or the use of probabilistic sensitivity analysis to identify key parameters. Distributions of parameters can also be characterised to support probabilistic uncertainty analysis. A consistent approach to gathering probability distribution functions is, however, required. The way in which distributions are defined should be consistent and it should be made clear as to which parameters are included or excluded (not all parameters will be assigned distributions, for example dose coefficients). Furthermore, any residual uncertainty that is not represented in probabilistic calculations should be made explicit, and justification given for the choice of metric for comparison, such as the mean or median etc.

To ensure that nothing is overlooked in assessments, use can be made of extensive FEP lists. Such lists are not infallible. Nonetheless, these lists help to provide a transparent approach to identifying important factors that need to be considered. The lists can be used in either a top down or bottom up approach or as a mixture. For example, a top down approach could be applied to define scenarios from external FEPs whereas a bottom up approach may be used for model development.

We know that biosphere assessments require arbitrary assumptions that can be both challenging to conceive and to justify. The present day biosphere can provide a useful input, both in terms of the current site conditions and the use of analogue sites to inform on the types of conditions that could exist in the future. Landscape evolution models can also be employed, however, the use of current biosphere conditions is useful in allowing stakeholders to recognise and relate to the information presented and the use of analogues in addition to landscape evolution models can also give confidence to how site evolution is being represented into the future.

Alternative indicators, as detailed in IAEA TECDOC 767, are also a potentially useful way of improving stakeholder confidence in assessments. They can be used to illustrate different uncertainties at different timescales, using a hierarchy of indicators to address increasing uncertainty over time, such as radionuclide fluxes through barriers and comparison against natural fluxes in the environment.

Radiation dose can be confusing to some stakeholders and communication can be difficult. To address this, radiation risks can be communicated in relation to risks that people are willing to accept in day to day life, allowing risks to be put in perspective. The risks from radiation exposure can also be compared against chemical exposure risks when assessed on a common basis. Safety indicators other than dose can also be useful in taking account of uncertainties in future human lifestyles.

Complementary considerations have been used in assessments undertaken to date. For example, Posiva report 2012-11[l] is focussed on complementary considerations, setting out evaluation, evidence and qualitative arguments that lie outwith reports of quantitative safety assessment. Natural systems are considered to identify key processes and give confidence through comparison with other assessments and methods and results are compared against safety cases made for other repository projects to demonstrate comprehensiveness, consistency and reasonableness. Simplified bounding analyses of extreme, unrealistic cases for scenarios not considered in the main safety assessment are also presented and natural analogues used for the future developments in the surface environment of the site are presented.

Stakeholder engagement is a key part of the process of building confidence; programmes have failed in the past due to lack of stakeholder engagement. Engagement is not just about informing; rather, stakeholders can be consulted to gain valuable information as input to assessments such as how local people use the environment. This has the added benefit that stakeholders can feel they have some ownership to the results of an assessment. Training and educating stakeholders in ways to engage and communicate with their peers can also be a useful strategy. Examples of this approach are given in NRPA report 2016:5[m].

---

[l] Available from http://www.posiva.fi/en/databank.

[m] Available from http://www.nrpa.no/en/publications.

All of the points above need to be considered in the BIOMASS-6 update to ensure that confidence building is central to the approach taken to long-term safety assessments.

Discussion

In addition to stakeholder engagement, expert elicitation is also an important component and can help to ensure that the approach to presenting scientific information is appropriate. Annex BIII of the BIOMASS-6 report sets out a protocol for the derivation of data, including elicitation and use of expert judgement.

There was a considerable amount of work undertaken during the EC ERICA project with regard to stakeholder engagement that has been reported. These reports may provide useful information in support of the BIOMASS-6 update.

National regulations may stipulate how scenarios are to be formulated and labelled etc. and it should be recognised that this may not be most appropriate in terms of presenting material to the public. It may therefore be beneficial in such instances to generate different material for the regulatory and public audiences. Involving stakeholders in scenario development can be a key stage in building confidence to ensure that important local habits are taken into account in assessments. In reporting the results of a scenario, the use of complementary indicators in addition to numerical dose values can be highly beneficial in providing context. Linking stakeholder input to FEP lists may also be beneficial with all points raised by stakeholders being captured and addressed in a transparent manner.

The term ‘reference biosphere’ may not be the most appropriate term to use in the updated methodology. The starting point to undertaking a safety assessment should be to develop and demonstrate a good system understanding and to then consider how to move to a more manageable representation of this knowledge in assessment models.

2.10 SITE INVESTIGATION AND CHARACTERISATION

Adrian Punt presented on behalf of Mike Thorne.

The original BIOMASS-6 methodology concentrated on biosphere system description, but did not give any detailed discussion on how the biosphere at a specific site should be characterised through a site investigation programme. Whilst there was some experience of site investigations at that time (e.g. at Yucca Mountain in the US and LLWR in the UK), there has subsequently been much more detailed and integrated site characterisation programmes undertaken, for example by SKB, Posiva and Andra.

In terms of general observations from recent experience, site characterisation is multi-disciplinary; it has been found useful to generate discipline-specific descriptions and to then integrate these into an overall site-descriptive model with iterative feedback between disciplines. Whether structural integrity or radiation migration are the disciplinary foci, investigation needs are largely common. It therefore makes sense to develop biosphere systems descriptions for use in assessment modelling, using the same discipline-specific components that are adopted in site characterisation (Figure 2-14).

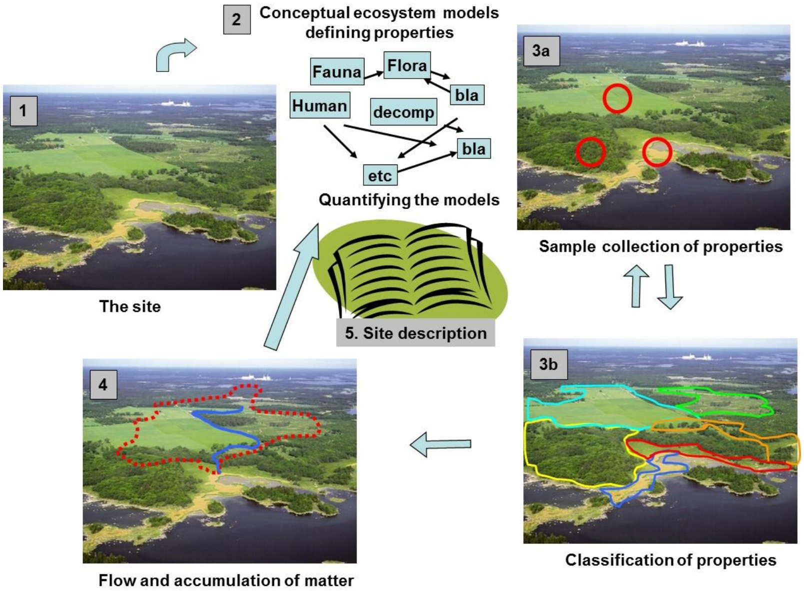

Figure 2-14. The SKB vision of the site characterisation process (from Tobias Lindborg, SKB).

The level of detail required in a site investigation programme is an important consideration. A characterisation programme can be performed for several reasons; for example, to provide a baseline survey or process-related data for impact assessments, potentially leading to very detailed biosphere characterisations. A key activity is then to extract the relevant information required from that generated by the characterisation programme to provide a simplified version for use in assessments. Data set management is therefore important, with data selection:

- Respecting the findings in the full dataset and associated analyses;
- Being robust against likely changes in the environment such that a single simplification should, for example, be applicable to an extended climatic period; and,
- Focussing on those aspects of the environment that determine radiological and chemical impacts of long-term releases from the repository.
- An understanding of how different parameters relate to external influences such as climate change is therefore important.

Careful consideration should be given to the appropriate spatial extent of site characterisation programmes. In some contexts, it may be appropriate to consider an area larger than that where contaminants are likely to arise to ensure that the programme is robust and that features present in the larger area can be included in the system description. Furthermore, where climate and landscape changes are likely to have a profound impact on a site, it may be appropriate to characterise analogue sites remote from the site of interest, albeit in less detail than at the actual site, since information on these sites is only required to inform post-closure assessment modelling of conditions substantially different from those of today. Paleo-environmental indicators may also be useful in gaining an understanding of how a site has varied in the past to inform on possible variations in the future although it is important to recognise that the past may not always be a good guide to the future.

Major projects require Environmental Impact Assessment in addition (for radioactive waste repositories) to post-closure safety assessments, for which there are common data needs. It is therefore reasonable to combine site characterisation activities to not only avoid duplication in effort, but also to avoid arbitrary differences in results for assessments undertaken at the same site. There should also be links between the operational and post-closure assessments for similar reasons. Furthermore, it may be beneficial to engage with stakeholders to ascertain information around any concerns, but also to gain information on the site under investigation from those local to the area.

Discussion

There is a European technical platform on geological disposal (IGD-TP) that includes a joint activity on site characterisation. The IGD-TP may therefore be able to provide useful input to the task of updating the BIOMASS-6 methodology with regard to site characterisation. Impact assessment requirements can vary internationally and RWM have previously commissioned work on this subject that may also be available as input.

The BIOMASS-6 methodology did not include links between assessment needs and how to do site investigations and this could be a difficult area to update. Practical experience would be beneficial to help ensure that any update on this area is both clear and relevant. Furthermore, the need for iteration between modelling and site characterisation to ensure that all data needs for an assessment are captured in the characterisation programme should be made clear. This aspect is considered, among others in a BIOPROTA project[n].

There are lots of data from natural analogues with the potential to support biosphere characterisation, including aspects considered within the BIOPROTA programme[o]. There is therefore potential to consider whether understanding gained from past characterisation studies can help inform on the future (by looking at the situation today versus when the programmes were undertaken) and to inform on how understanding from analogue sites can help define characterisation needs.

---

[n] BIOPROTA (2006): Guidance on Site-Specific Biosphere Characterisation and Experimental Research and Field Research Protocols. A report prepared within the international collaborative project BIOPROTA: Key Issues in Biosphere Aspects of Assessment of the Long-Term Impact of Contaminated Releases Associated with Radioactive Waste Management. Main Contributors: E Leclerc-Cessac, M C Thorne and G Thomson. Published on behalf of the BIOPROTA Steering Committee by ANDRA, France.

[o] BIOPROTA (2005): Application of Biotic Analogue Data. A report prepared within the international collaborative project BIOPROTA. Key Issues in Biosphere Aspects of Assessment of the Long-Term Impact of Contaminated Releases Associated with Radioactive Waste Management. Main Contributors: E Kerrigan (Task Leader), G M Smith and M C Thorne. Published on behalf of the BIOPROTA Steering Committee by UK Nirex Ltd., UK.

3. EXPERIENCE IN THE APPLICATION OF THE BIOMASS-6 METHODOLOGY TO SAFETY ASSESSMENTS

Presentations on experience in the application of the BIOMASS-6 methodology in assessments from workshop participants are summarised in this section along with other assessment experience relevant for the BIOMASS update work programme. A review of biosphere assessments undertaken by organisations for solid radioactive waste disposal facilities was also presented by the TST and is again summarised.

3.1 REVIEW OF BIOSPHERE ASSESSMENTS

Russell Walke presented.

An overview of some of the biosphere assessments that have been undertaken by various organisations responsible for solid radioactive waste disposal was presented to illustrate some of the experience that has been gained in applying the BIOMASS-6 reference biospheres type methodologies and to illustrate commonality in assessment approaches. Russell emphasised that the review did not provide a comprehensive list of assessments since the BIOMASS programme, but instead reflected those assessments that he had been involved with and understood the most.

Nagra Biosphere Modelling

Nagra biosphere model development began in the early 1990’s with the TAME (Terrestrial-Aquatic Model of the Environment) model, which was informed by BIOMOVS and BIOMOVS II and drew upon FEP screening to ensure that important processes were not omitted. The scope included a near-surface aquifer with radionuclide releases to the aquifer in groundwater. Both water and mass balances were important components. There is a stylised representation of the biosphere that is largely consistent with the BIOMASS-6 reference biosphere approach. The model has more recently been implemented as SwiBAC (Nagra report NAB 12-27), with some adaptation from the original TAME model, including:

- explicit representation of different crop areas;
- revision of parameter values to be consistent with IAEA publications (described in Nagra report NAB 13-49); and
- revision of the C-14 model (described in Nagra report NAB 12-26).

The current model, SwiBAC, which is a classic reference biosphere stylised model, is illustrated in Figure 3-1. A single compartment is used to represent the local aquifer and concentrations in the atmosphere are assumed to be in equilibrium with top soil. The model is not site specific and does not therefore require lots of site characterisation data. Environmental change is not included in the model.

JAEA and NUMO Biosphere Modelling

Biosphere models for Japan were developed by JAEA and NUMO between 1999 and 2004. There are upwards of 15 site-generic models for a wide range of GBI concepts with the intention being to use the various models to help screen volunteer community sites. The methodology used to develop the models was consistent with the BIOMOVS II approach, with some reference to the BIOMASS-6 approach. The methodology used the following steps:

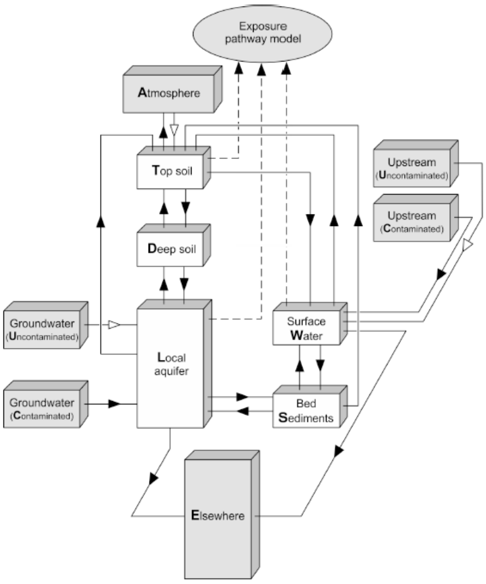

Figure 3-1. Nagra biosphere model with explicit compartments being represented with white boxes.

- assessment context;
- description of the biosphere system;
- identification and initial screening of FEPs;
- conceptual model development (including three iterations of interaction matrices for interactions, radionuclide migration and exposure to support development of compartment models);
- mathematical model and data; and
- implementation.

Environmental change was taken into account for some of the cases; examples include a river with a sequence of tectonic uplift, warming and cooling and erosive release to soil. Each of the models, which are implemented in AMBER, uses a stylised representation of the biosphere, with consistency in approach across all biospheres. Reports describing the models are not publicly available.

RWM Biosphere Modelling

The modelling programme of RWM (and its predecessors) has been developed over 25-30 years, with account being taken of the output from various international programmes that RWM has participated in. The most recent biosphere modelling work has involved:

- an update of the terrestrial/freshwater model in 2011 to frame the model in a BIOMASS-6 type approach and to take account of BIOCLIM through explicit representation of different climate states; and,
- development of an estuarine, coastal and marine environment model extension to the model in 2013 to facilitate explicit comparison with terrestrial/freshwater systems and to allow coastal

releases to be considered should a coastal community volunteer for the repository siting programme.

RWM's biosphere modelling has supported generic safety cases, most recently in 2010 and an updated assessment that is due to be published in October 2016. The approach to biosphere modelling is described in biosphere status reports within the disposal system safety cases (DSSC), and is consistent with a BIOMASS-6 type of approach, with the need for iteration between steps being recognised (Figure 3-2).

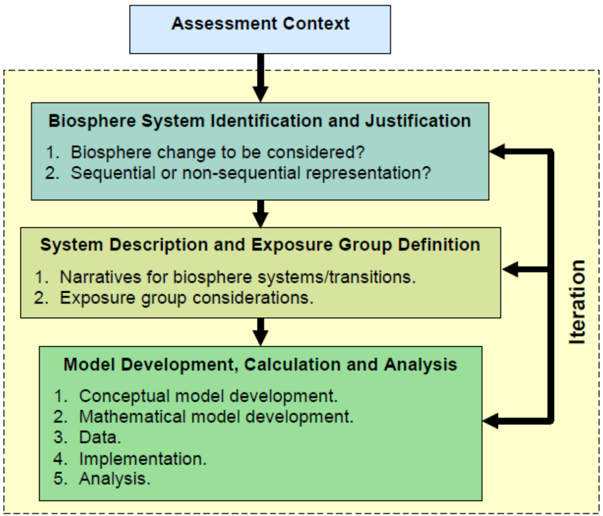

Figure 3-2. RWM approach to biosphere model development, calculation and analysis.

The RWM biosphere model includes near-surface aquifers with release to the biosphere being through abstraction of groundwater, natural discharge of groundwater to soils or discharge to the coastal/marine environment. The biosphere systems to be considered were identified from a review of mechanisms of change from a starting point of a temperate environment, which highlighted the importance of both climate change and human actions on the biosphere.

The consideration of climate change within the RWM model has been based on the output of BIOCLIM, which emphasised the potential for a long interglacial extending to over 100,000 years (Figure 3-3). In the absence of a site, potential changes caused by climate change are represented in a non-sequential manner. For each climate state, biosphere descriptions were generated with analogue climate data, generated in the BIOCLIM project, and used as a driver for soil hydrology and irrigation requirements. Consideration was also given to the behaviour of people under different climate conditions.

An interaction matrix approach was used to explore and develop the conceptual model, allowing interactions between principal components to be assessed in a structured way and to help ensure that there were no important omissions. The interaction matrix was audited against the NEA and BIOMASS FEP lists. In developing mathematical models, processes were then screened to determine whether explicit consideration was required. The resultant model includes two compartments to represent soils and the near-surface aquifer was defined by flow rate and discharge area, and used to derive discharge rate to the biosphere from which biosphere dose conversion factors were calculated.

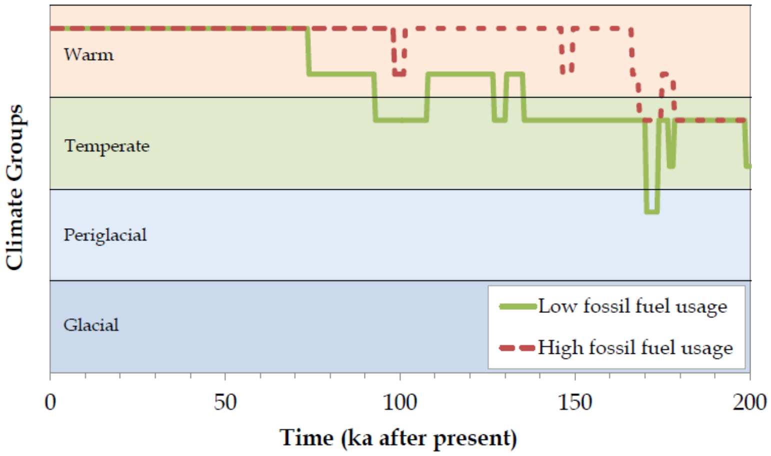

Figure 3-3. Climate states considered by RWM under reference and extended warming climate scenarios.

NWMO Biosphere Modelling for L&ILW Disposal

NWMO has undertaken a biosphere assessment for a deep geological repository (DGR) for low and intermediate level radioactive waste. The disposal concept is based around a proposed disposal site at the Bruce site on the edge of Lake Huron. Disposal would be at a depth of around 680 m in limestone. There is no groundwater flow at this depth with groundwater being very saline and stagnant. The site therefore offers a high degree of geological isolation. Only within the upper 80 m does groundwater become fresher and some flow toward the lake occurs.

The geosphere-biosphere system was modelled in an integrated way with the biosphere being part of a 'total systems' model. The BIOMASS methodology was followed in considering how biosphere change could be represented, with external FEPs being reviewed to determine the drivers for environmental change. Long-lived radionuclides will be present in the ILW and the assessment is therefore extended until the peak effects occur. The tight geology in the area results in a long assessment timeframe, hence glacial-interglacial cycles need to be considered with glacial cycles being associated with up to 3 km thick ice cover. Four biosphere states of interest are identified: temperate, tundra, glacial and post glacial (Figure 3-4**Error! Reference source not found.**). Transitions between states were not explicitly considered and the assessment focussed on exposures occurring during temperate and tundra climates, when people may be present at the site. The level of water in the lake varies with climate and discharge of groundwater can be direct to the lake or to the surface of soils due to irrigation. The model also considered release of radionuclides in the gaseous phase.

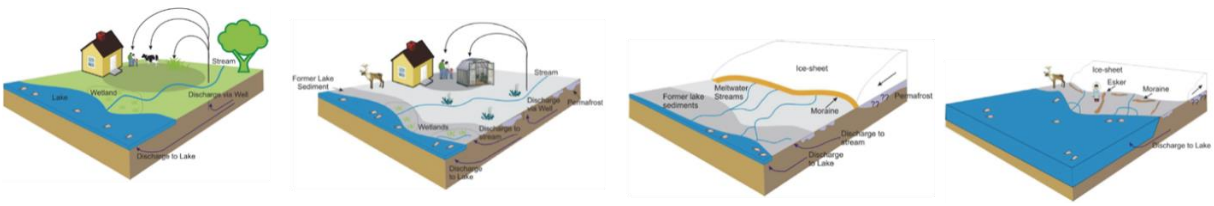

Figure 3-4. Illustrated conceptual biosphere models for climate states relevant to the NWMO DGR assessment (temperate, tundra, glacial and post-glacial).

The highest calculated exposures were associated with a temperate climate when agricultural land, streams and Lake Huron are all present at the site and these resources are exploited by local people. The model for the temperate biosphere system was based on Canadian Standards Association models that were developed by regulators for operational releases, and adapted for use on the DGR assessment. A DGR-specific FEP list was developed and a screening analysis of FEPs performed to help develop assessment scenarios. Conceptual models were also audited against the FEPs. The approach was therefore drawn from the BIOMASS methodology within an integrated assessment framework. The assessment has been subject to regulatory review and public hearings. A joint review panel favourably reviewed the assessment in May 2015, recommending that politicians approve the DGR.

The post-closure safety assessment report and supporting documents are available from opg.com.

Swedish Biosphere Modelling

SKB has undertaken a biosphere assessment in support of their 2011 license submission for the construction of a spent nuclear fuel repository at Forsmark. The disposal concept involves around 6000 copper canisters emplaced within a bentonite buffer at a depth of ca. 500 m depth in a crystalline bedrock. The site is subject to a boreal climate and is located close to the current coastline. Post-glacial land uplift is an important process at the site, resulting in a present-day rate of uplift of around 7 mm/y. The 2011 SR-Site assessment was the fifth iteration of assessment for a spent fuel repository and the second site-specific assessment for the Forsmark site. The assessment benefited from continued dialogue with regulators and a wealth of site information arising from a detailed site characterisation programme. The overall approach to the SR-Site assessment is illustrated in Figure 3-5.

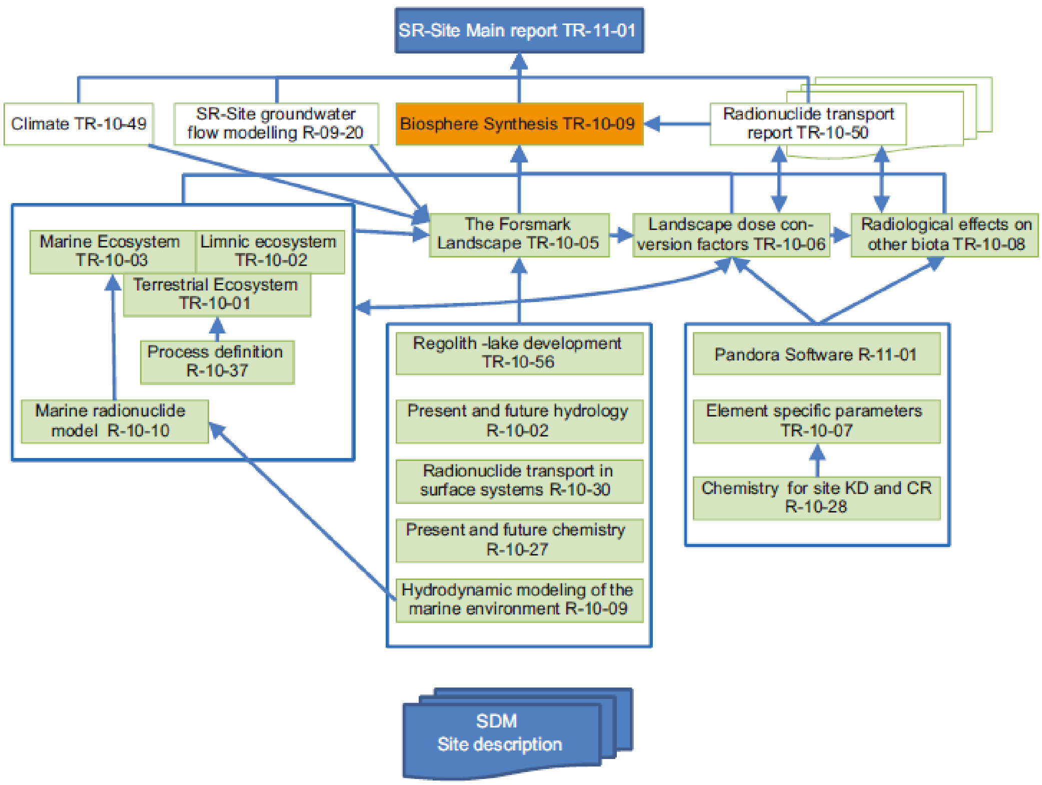

Figure 3-5. Document map for the SKB SR-Site assessment.

Modelling was used by SKB in order to support the interpretation of some of the data generated from the site characterisation programme, such as the development of near-surface regolith. This modelling also helped support the development of system understanding. The present-day progression of the landscape at the site, which is evident from walking from the coast to inland, has been used as an analogue of the future, with analogue sites (e.g. Greenland) also being studied for future cold climate conditions. A biosphere synthesis report (SKB report TR-10-09) describes the assessment method within the framework of BIOMASS and also summarises lessons learned from previous iterations of the assessment, providing transparency in the reasoning as to why particular modelling approaches have been adopted.

The SR-Site assessment considered long-term climate variation with a reference climate sequence being used to identify climate states that might occur at a time when a canister could fail. Over time, the Forsmark landscape will become increasingly terrestrialised and interpretive modelling has been used to identify catchments and sub-catchments that could develop throughout the landscape (Figure 3-6). Areas within these catchments/sub-catchments that might become contaminated via groundwater discharge are termed ‘biosphere objects’ and each is represented with a classic stylised compartment model with the potential for objects to develop over time into different ecosystem types. Unit landscape dose factors (LDFs) were calculated for each of the biosphere objects. Potential radionuclide releases to each biosphere object were considered and the highest LDF across all objects was used for dose calculations. In most cases, the highest LDF was associated with a small biosphere object.

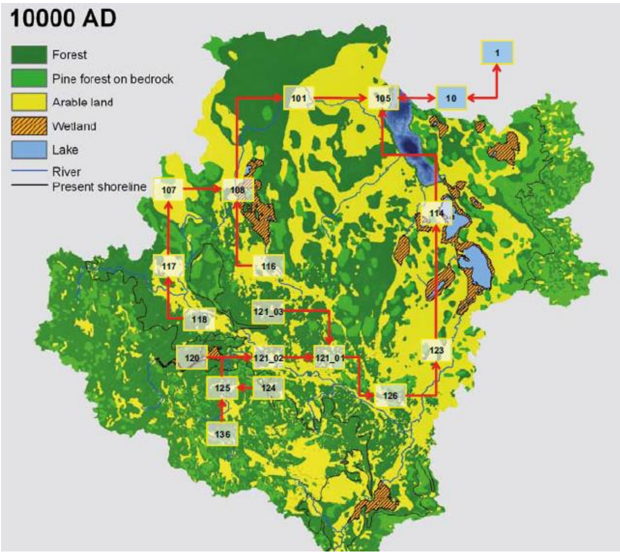

Figure 3-6. Illustration of the linking between biosphere objects within the SR-Site assessment.

In order to review the SR-Site assessment, SSM has undertaken independent modelling. A reference biospheres approach, consistent with the BIOMASS-6 methodology, was used to develop models for different systems without explicit consideration of landscape evolution. An interaction matrix was used to explore interactions within each biosphere system and to support model development. A finer level of model discretisation was used than that of SKB to ensure that the timescale of radionuclide migration and accumulation was appropriate.

In 2014, SKB submitted the SR-PSU assessment to SSM in support of the license submission for the extension of the existing SFR facility for L&ILW, which is located c. 60 m beneath the Baltic Sea. With land uplift however, the SFR site will become terrestrialised over time. The representation of the biosphere within the SR-PSU assessment was based on the approach adopted in the preceding SR-Site assessment, with ‘biosphere objects’ being used. However, a more integrated model approach was used for SR-PSU, in which time-dependent radionuclide release fluxes from the geosphere were fed directly into the biosphere models.

Releases from SFR will occur earlier than those from a spent fuel repository and an alternative reference climate evolution was selected based on global warming. Digital elevation and shoreline displacement models were used to inform regolith and lake development, which in turn supported the development of a quantitative landscape development model (Figure 3-7). There was therefore a large amount of information used to support model development.

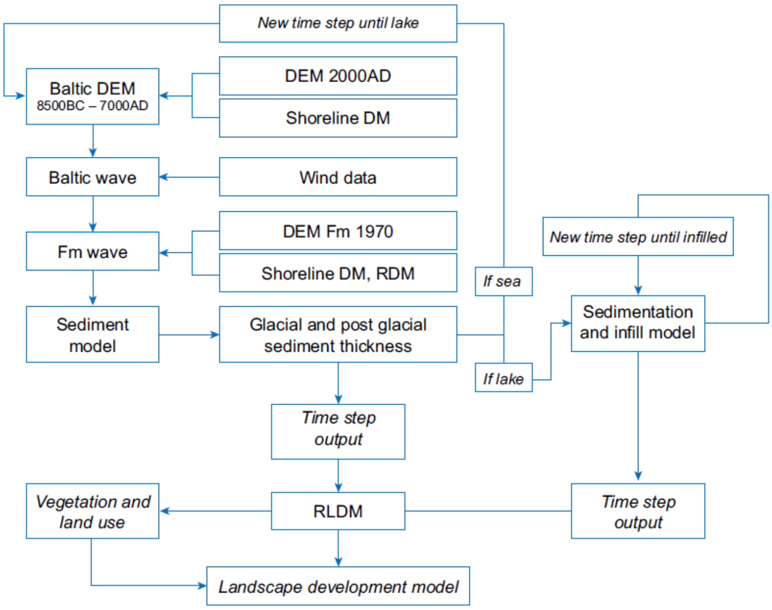

Figure 3-7. Information flows and models in support of the landscape model development for SR-PSU.

Identification of release locations within objects was supported by particle tracking and groundwater flow modelling. Each object was then modelled using an iteration of the SR-Site compartment model, with the addition of organic compartments to allow C-14 in organic material to be explicitly represented.

A probabilistic modelling was used for the main SR-PSU calculations and deterministic calculations undertaken for comparison against the SR-Site LDFs. Variant calculations were also performed that considered alternative climate cases, alternative release areas and biosphere object delineation.

The main biosphere object for radionuclide release in SR-PSU does not progress through a lake stage, which is unusual for the Forsmark area and is, hence, a key area of review by SSM in terms of confidence around the landscape evolution of this object. C-14 uptake by lake fish was an important exposure pathway in previous assessments; this pathway is significantly reduced by discharge to an object that does not progress through a lake stage.

Reflection on Biosphere Modelling

In reflection, there is a lot of experience since the BIOMASS-6 project that can be drawn upon in refining and updating the reference biospheres methodology. However, whilst many assessments have been framed against BIOMASS, few have applied the methodology in precisely the same step-by-step approach, but have rather adapted the framework provided so as to best meet their particular assessment needs. This highlights the importance of starting with the assessment context to help ensure that assessments are developed that are proportionate to the needs of those commissioning the assessment. The objective in updating the methodology should therefore be to define the top-level framework of steps as guidance and highlight tools that may be helpful (e.g. interaction matrices, drawing on case studies etc.). It may also be useful to use examples to explore specific issues and, from this, develop guidance, conclusions and generic examples. A reference well model could be developed that could be used to discuss typical parameter ranges and the different exposure and transport pathways. Further examples could be used to explore when it is important to represent environmental change, by assessing examples of when environmental change could lead to an increase or decrease in exposure results, or to explore integration of assessments with regard to impacts on biota and/or chemotoxic impacts.

Discussion

The BIOMASS project did not intend to develop a full suite of possible example reference biospheres; the purpose of the examples was to help in the development and illustration of the methodology.

The overall methodology has broad application beyond long-term biosphere assessments. For example, the methodological steps can also be applied to the long-term impact of operational releases or to management of legacy sites.

3.2 APPLYING BIOMASS METHODOLOGY TO POSIVA'S BIOSPHERE ASSESSMENT

Kirsi Riekki presented.

In 2012, Posiva submitted a construction licence application for a spent nuclear fuel repository at Olkiluoto in south-west Finland. The application was supported by a biosphere safety assessment (BSA-2012) to which the BIOMASS methodology had been applied. A further licence submission is currently in preparation for the operation of the facility that is due to be submitted to the regulatory authority (STUK) in 2020. This submission will again be supported by a biosphere safety assessment designated BSA-2020. It is intended that the enhanced BIOMASS methodology will be applied in support of this assessment.

Finnish regulatory requirements have been revised since the 2012 assessment. The implications of the changes are that for time periods over a few thousands of years, stylised models of the surface environment are to be used to take account of alternative lines of landscape evolution; alternative possibilities of climate evolution and impacts on the disposal system are to be addressed; and, sensitivity analyses are to be undertaken for different scenarios and for the migration of radionuclides in the biosphere. These aspects were not included in the construction licence biosphere assessment and are therefore new areas for applying the BIOMASS methodology in BSA-2020.

The longer timescale of assessment has been interpreted in light of alternative climate cases and possible climate conditions for the Olkiluoto site. Climate cases consist of a reference global warming case and an extended global warming scenario whereby temperate conditions continue for the next

50,000 years. Extreme climate scenarios have also been identified, including early periglacial, extended periglacial and extreme ice-sheet thickness scenarios. The early periglacial case has been adopted for BSA-2020, assuming periglacial conditions arise in 17,000 years from present. The remaining extreme climate scenarios are not being taken forward within the biosphere assessment, but will be applied to other aspects of the repository safety case. As such, temperate, periglacial, glacial and submerged conditions have been identified as the important climate conditions to be considered in BSA-2020. No probabilities are being assigned to the climate cases.

The BIOMASS approach and the approach developed by MODARIA WG6 to address climate change will be applied in BSA-2020. The assessment steps of BIOMASS have already been considered:

- Purpose of the assessment: Development of BSA-2012 for operational licence application.
- Endpoints: From regulations, similarly to BSA-2012.
- Assessment philosophy: Probabilistic approach as a new addition. Relates to level of conservatism.
- Repository system: The processes of the system are known and propagated into the assessment (FEPs).
- Site context: Site-specific biosphere modelling with additional site data from the continued site monitoring programme from that applied in BSA-2012.
- Source terms and GBI: Enhanced from BSA-2012 with clearly defined boundary applied by all safety case discipline groups.
- Time frames: Interpreted directly from regulations
- Societal assumptions: Regulations define the assumptions for 10,000 years (similar behaviour as currently) but for longer time, climate necessarily affects the societal assumptions.

The biosphere safety case work flow chart for the 2020 licence submission is given in Figure 3-8. The biosphere description will be supported by the extensive environmental studies that have been performed at the site and reference area, and will describe both the past and current status of the surface environment, including element cycling. Formulation of scenarios will be an overall safety case group activity to ensure that there is consistency in all aspects of the safety case. Scenario formulation will be focussed on credible lines of evolution of the system. Surface environment development will then be addressed through extrapolation of knowledge of past evolution at the site into the future, taking into account continued land uplift and climate variations. Radionuclides to be evaluated in the assessment will then be identified using highly cautious transport and dose models and parameter value selection. Those radionuclides selected for assessment will be included within assessment models that will be based on a simplified representation of the surface environment with biosphere objects being identified that are connected hydrologically, with time-dependant radionuclide activity concentrations being calculated across the biosphere. Exposure analysis will assume maximum use of local resources by people with annual doses to the most exposed and other exposed people being calculated to give a dose distribution across the local population. Typical absorbed dose rates to biota will also be evaluated. The conceptual models that will be used in BSA-2020 for the initial 10,000 year assessment period are similar to those in BSA-2012.

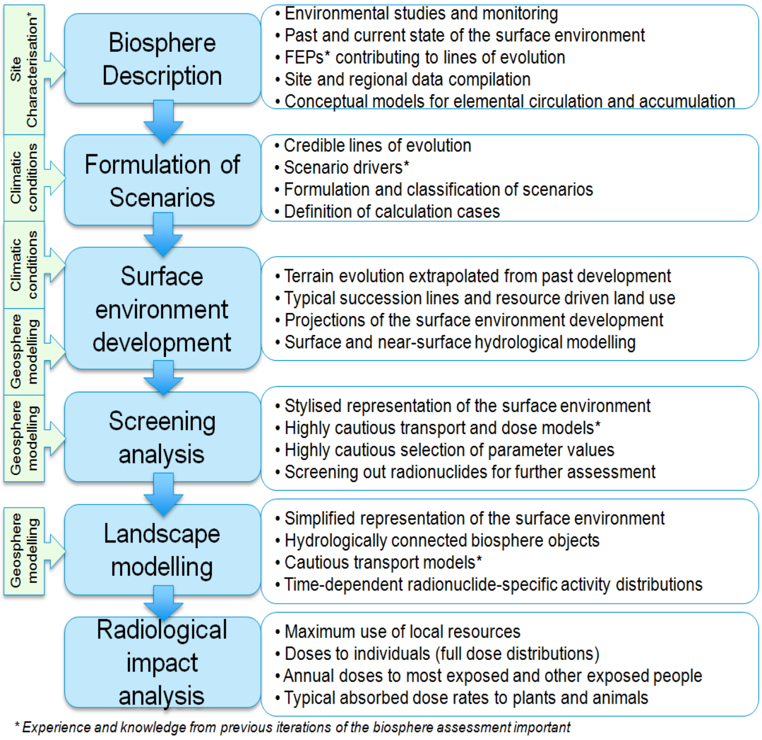

Figure 3-8. Work flow chart for BSA-2020.

BIOMASS-6 includes discussion of knowledge and data management, recognising that this is an resource-intensive and important aspect of assessments. For BSA-2020, the inclusion of probabilistic modelling means that input data selection will be even more important than for the deterministic approach in BSA-2012. Weaknesses in the safety case 2012 data management by Posiva have been pointed out by STUK and an updated data management strategy has therefore been implemented for the 2020 safety case. Knowledge quality assessment will be performed for both data and models and a new data review protocol has been established for data to be accepted for input to the safety case. Interaction between different assessment groups is important with regard to data management to ensure consistency in data and assumptions applied throughout the safety case.

The output from MODARIA WG6 is also being applied to BSA-2020 with the pronounced role of climate and land uplift noted as external FEPs in the assessment. Climate modelling is an important aspect for the 2020 safety case, but is not directly part of the BSA-2020 work, as it forms an important aspect of the whole safety case with the timescale extending past the biosphere focus of up to 120,000 years. The results of the climate work will however be included as input to BSA-2020. The overall safety case workflow, and role of climate modelling, is illustrated in Figure 3-9. In line with discussions within MODARIA WG6, all processes recognised as leading to biosphere evolution need to be taken into account in BSA-2020. The output from WG6 provides a useful approach to performing dose assessment under varying climate conditions. The approach supports conceptualisation of possible future exposure routes that can be supplemented through the use of data from analogue sites for the qualitative characterisation of surface environments and hydrology that could be representative of a site under different climate regimes. The use of analogue sites was considered by WG3 of the IAEA EMRAS II programme, which is also providing useful input to BSA-2020.

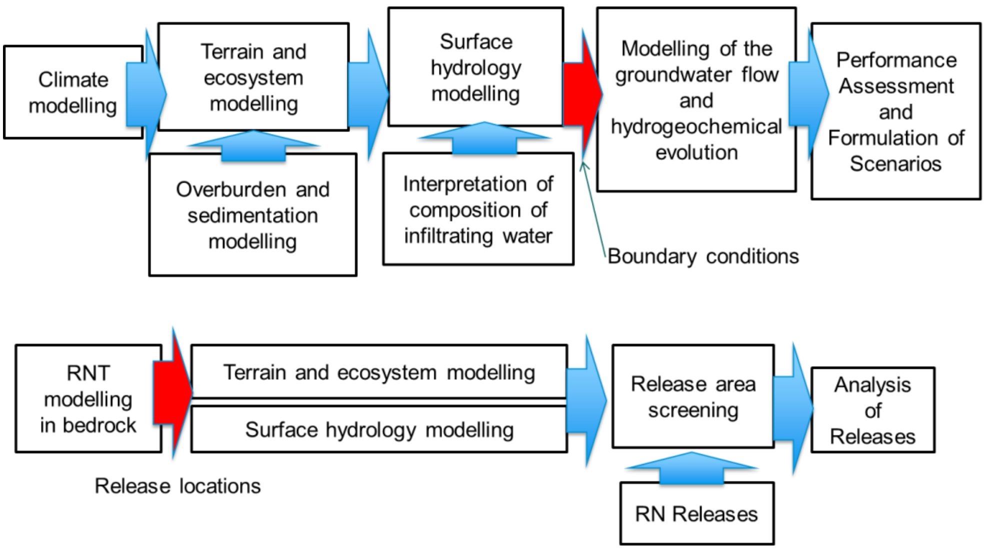

Figure 3-9. Role of climate modelling in the overall safety case work flow for the 2020 operational licence safety case.

International reference methodologies are therefore beneficial when compiling site assessment programmes for radioactive waste disposal facilities. The methods need to be applied taking into account national regulations and requirements. Posiva is therefore keen to continue involvement in the development of these approaches that will support ongoing activities with the 2020 safety case.

Discussion

In taking forward the 2020 safety case and supporting BSA-2020, STUK has been regularly consulted and invited to meetings to ensure common understanding on approaches. In taking forward the probabilistic approach to biosphere assessment, scenario uncertainty will be addressed separately to model parameter uncertainty so that the important parameters affecting model output can be clearly identified. Care in presenting the results of the probabilistic analyses will be required.

3.3 APPLICATION OF BIOMASS METHODOLOGY BY ANDRA FOR SITES IN OPERATION AND PROJECTS' SAFETY ASSESSMENTS.

Elisabeth Leclerc presented.

BIOMASS-6 has been an important input to the development of Andra's strategy to defining, describing and modelling the biosphere. The strategy has been applied both with regard to operational and post-closure assessments and to both existing surface disposal facilities and planned long-term geological projects. No safety function is attributed to the biosphere, which is essentially the last step in modelling the transfer of radionuclides and chemical toxins to humans, being the part of the environment that is easily accessible to human activities. It is defined as the global sum of all ecosystems comprising all living beings and the environments in which they live.

The focus of BIOMASS-6 was on water pathways for the transport of radionuclides and the Andra method has been based on this for liquid releases, but with some specificities and adapted methodology for atmospheric releases. There are five steps involved in the Andra strategy to defining, describing and modelling a biosphere system, based on the BIOMASS-6 approach as illustrated in Figure 3-10.

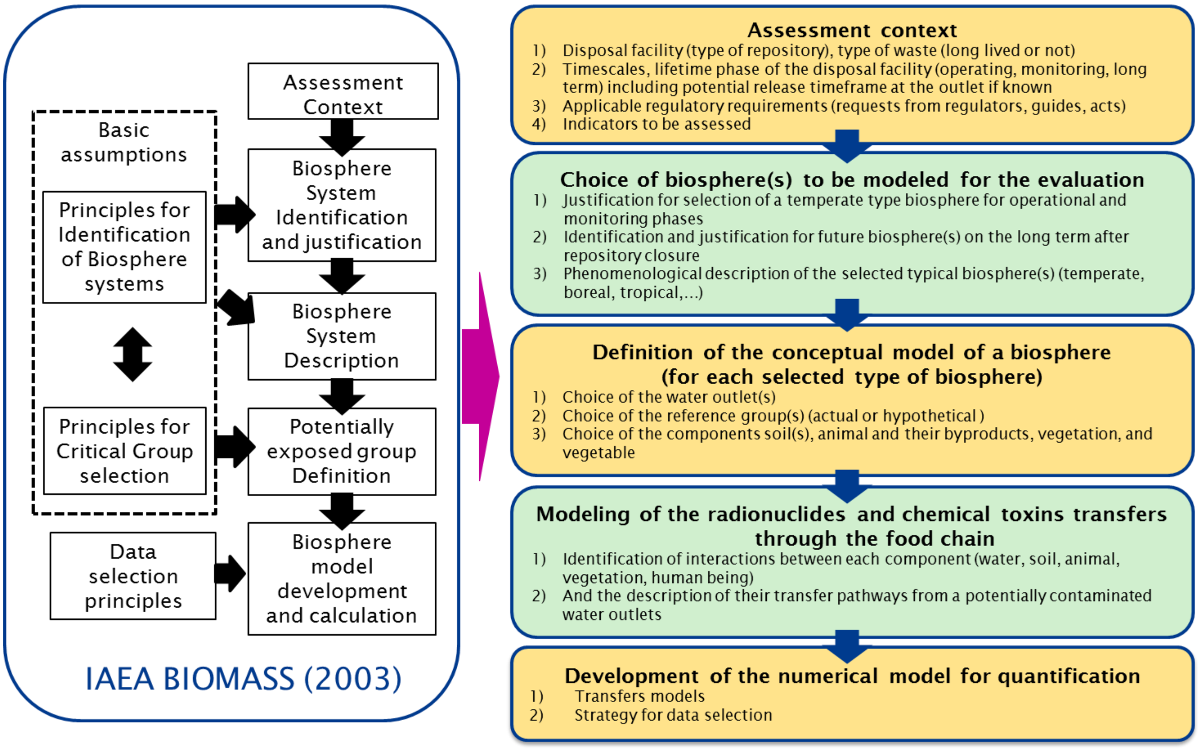

Figure 3-10. Andra's step wise approach to defining, describing and modelling biosphere systems.

The approach has been applied to routine atmospheric operational discharges from the Aube disposal site for low and intermediate level short-lived wastes in north-east France. The disposal facility has a number of operational storage areas and the application of the biosphere model has enabled releases to be related to doses received by local people. The BIOMASS-6 methodology was a useful input to the operational assessment, particularly with regard to the selection of site environmental characteristics, development of exposure scenarios and defining a strategy for data selection. In undertaking the assessment, each item of the biomass methodology was addressed.

In defining the assessment context, the source was identified as a discharge tower from the compaction of radioactive waste packaging platform from which continuous atmospheric routine releases occur. Since the site is existing, the actual biosphere is known and realistic exposure groups could be defined. Mean data were used as input to the assessment with sensitivity analyses being performed to evaluate uncertainty and sensitivity. Transfer pathways specific to the site were also identified.

A temperate biosphere was chosen for the entire operational phase and a conceptual model developed based on the environmental characteristics and components of the site. There have been a lot of *in situ* studies undertaken at the site and the conceptualisation was therefore based on site observations.

The habits of local people were also taken into account in selecting reference groups for exposure analysis. The area is largely rural with forests present. Leisure activities linked to forests, such as hunting, were therefore included. As only small freshwater bodies are present, no fishing in rivers was taken into account, but fishing in a pond was considered. Kitchen gardens and consumption of locally produced meat products etc. were evaluated. The BIOMASS-6 approach provides a structured mechanism to explore all of the potential transfer pathways of radionuclides to humans through consideration of average or specific behaviours or the use of representative groups or individuals. This approach was applied, as illustrated in Figure 3-11.

Different reference groups were used to explore all potential local transfer pathways with activities of each group being checked to ensure all relevant transfer pathways were captured and any not taken forward could be justifiably excluded. There are other industries near to the site, including other disposal sites and a cement plant. Exposure of workers at the cement plant, which is closer to the Aube facility than other disposal sites, was therefore evaluated.

For an atmospheric discharge source, there are only a few transfer pathways that need to be evaluated, including external exposure to radionuclides in air, inhalation, deposition of radionuclides to soil and ingestion of foods following food chain transfer. An atmospheric dispersion model (IMPACT 1.8) was applied to evaluate radionuclide transport through air and a biosphere model platform (SAMM), developed by Andra, was then used to then evaluate radionuclide transfer through different biosphere compartments. A further and integrated (atmospheric dispersion and dosimetric calculations) model (CERES) was used to check the model calculations. Results indicated an order of magnitude difference in dispersion calculations by applying different software. This uncertainty was therefore allowed for into the dose calculation.

In selecting input data, site-specific data, supplemented with data from IAEA TRS472, were used for transfer of radionuclides. Soil characteristics from site surveys were also used to inform parameter selection. Site meteorological data were also available, along with information on food consumption and self-sufficiently and other human habits. Other sources (such as the ICRP) were used as necessary, for example in selection of inhalation and ingestion dose coefficients and respiratory volumes. For specific human habits (farmer, kitchen gardener, hunter etc.) the 95th percentile was selected from available data.

Groups potentially exposed	Detail of activities leading to potential exposure
All activities	Ingestion of contaminated water
Crop farmer	Major crops (cereals, etc.)
Animal farmer	All animal farming (cattle, sheep, goats, pigs, reindeer, horses, ostriches, etc.)
Village dweller	Vegetable garden
	Yard
	Habitation
Fisherman	Fish (freshwater or not)
	Shellfish, seafood
Hunter	Game
Gatherer	Mushrooms, berries
Tourist	Occasional (swimming, walking, picnicking)
Specific activity	Vine growing, sawmill, quarry, etc. on the basis of local observations
Multi-activities	Covering agriculture, animal farming, vegetable gardens and yards, hunting, fishing, leisure activities

Selection of reference groups for Aube facility	Activity
No	Atmospheric release, no drinking water from pond
No	
Animal farmer	Cows
Village dweller	Kitchen gardening, pork, poultry, habitation
Hunter-Fisherman-gatherer	Game : ; mushrooms Pond drain
	Champignons, baies
No tourist	No swimming habits in ponds and surface water
Worker : Specific activity	CIRES, cement plant
Multi-activities	

Figure 3-11. Identification of exposure groups for the Aube facility on the basis of the BIOMASS-6 methodology.

The approach has also been applied to the post-closure phase for the Cigéo geological disposal facility. Again, a step-wise methodology was employed, consistent with BIOMASS-6. The assessment context was based on the 2005 feasibility dossier and a 2016 safety option dossier. The choice of biospheres was based around a natural climate evolution assumption, but also included a perturbed climate linked to anthropogenic effects. The choice of climate scenarios and associated biospheres was driven by French Nuclear Safety Authority guidelines of 2008 that introduce the notion of typical biospheres, defined as biospheres that are representative of a particular climate state. Such biospheres are only to be considered plausible and justifiable for periods over which those climatic conditions can exist. Climate changes over a timeframe of 1 million years were considered, resulting in three climate-based biosphere types – temperate, warm and cold biospheres. Temperate and cold typical biospheres are plausible under any climate change scenario, but the cold biosphere could only occur after 50,000 years (at the earliest) in the context of a natural evolution of the climate. A warm typical biosphere could only occur in the case of a perturbed evolution of the climate and could persist for around 600,000 years. Each of these plausible biospheres was considered and biosphere descriptions produced.

The source from the geosphere to the biosphere (i.e. the GBI) is a major uncertainty. Current and future groundwater discharge points were identified as a result of hydrogeological modelling and radionuclide transport simulation for both the short- and long-term. Hypothetical reference groups were then selected. The site is within a rural area and the behaviours representative of the habits and resources of a typical rural biosphere for the area were therefore considered with all potential transport pathways of radionuclides to humans being taken into account. The choice of hypothetical reference groups was then based on the potential for groundwater discharge points to support groups and the food habits under different climates. If a water source was not sufficient to support the assumed group, then the water outlet area was excluded. Results from local habits surveys were used as the basis for human behaviour assumptions under a temperate climate. Data from analogue sites were used to evaluate possible habits for other climates, such as Spain for a warmer biosphere.

Two types of pathway modelling were used – a compartmental model and a specific-activity model based on isotopic dilution. The specific-activity model was used for Cl-36, H-3 and C-14. The compartmental model was used for all others. Two GBI's were also considered – a borehole into a surface aquifer and a borehole into a deep aquifer located below the disposal facility.

The experience gained in applying the approach to operational and post-closure scenarios has allowed important parameters governing exposure to be identified. These include:

- Dilution of the outlet (water or atmospheric), and particularly the GBI for sub-surface disposal;
- Food habits (consumption and self-sufficiency);
- Concentration of stable isotopes for specific-activity models; and,
- Models and software.

Models and software result in around an order of magnitude difference in dose calculations. Assumptions for food habits were found to result in up to a factor of 3 difference in the dose calculated for exposure groups.

The collection and management of assessment data can be a large-scale activity and the time needed to undertake this activity in support of assessments should be taken into account in work plans. Having a structured (e.g. tabulated) format for data collation (type of parameter, spatial and temporal scale, monitoring frequency etc.) can be beneficial in helping to identify monitoring and survey requirements, allowing data (e.g. source term, meteorology, hydrology, human habits, soil, agricultural practises etc.) to be recorded and updated throughout the site characterisation programme.

In taking forward the BIOMASS-6 update work programme, a number of suggestions were put forward, based around the experience of Andra in applying the methodology.

- A strategy for characterisation of sites could be developed that is focussed on dose calculations.
- Experience in the use of analogue site data to represent possible future climate conditions could also be drawn upon.
- Consideration could be given to the selection of sequential biosphere types (based on climate states) versus sequential biospheres including transitions between them and the implications for assessments in terms of radionuclide behaviour. The implications of erosion on radionuclide behaviour might also merit specific consideration.
- Thought could also be given to discussion of models to represent different biospheres or specific pathways, for example, radionuclide transfer in natural and semi-natural ecosystems compared with agricultural systems or atmosphere to pond water.
- Criteria for GBI outlet/localisation selection
- Note could also be made on model and modeller uncertainty arising from different interpretations of input data and the need for quality assurance in model input data to avoid user errors.
- Experience in the use of deterministic and probabilistic approaches could also be discussed with respect to demonstrating compliance with safety targets.
- Approach philosophy for operational versus post-closure phases.
- Approaches to addressing chemical toxicity and impacts on the environment should also be considered, particularly with respect to safety criteria / reference values and ensuring consistency in assessments.
- Non-human biota impact assessment

3.4 SKB REPORT R-14-02 ON FEP HANDLING AND EXPOSURE PATHWAY ANALYSIS

Ulrik Kautsky presented.

SKB has worked with interaction matrices and FEPs since the early 1990's with the first matrix for the biosphere being published in 2001, after the finalisation of the BIOMASS-6 methodology. The matrices are intended to demonstrate understanding of the system, illustrating process linkages between diagonal element features. Numerical models can then be used to describe those processes and calculate transfers of elements between compartments. The importance of different processes has been illustrated in the SKB matrices through the use of colour coding. Tables have also been used to describe in more detail each of the processes. It is important in developing matrices for the biosphere to include external FEPs, such as climate. There can however be issues with some diagonal elements interacting with themselves, particularly where organisms are included. For example, if carnivores are included as a diagonal element, they will consume other animal categories such as herbivores, but also other carnivores. This can be difficult to handle in an interaction matrix.

The interaction matrix for SR-PSU (reported in SKB R-14-05) was developed during 12 intensive days of focussed working by 12 experts. The different experts naturally had different views and several iterations were required to capture them and agree on nuances between different disciplines. The interaction matrix approach helps to trigger identification of missing interactions and stimulates justification as to why processes are excluded from a model. The approach also encourages assessment teams to speak a common language, thus addressing some nuances between terminologies and concepts in different disciplines. Furthermore, interaction matrices can be useful in supporting site investigation planning. Interaction matrices are very complex however, which limits their usefulness with regards to getting an overview of understanding. Both FEP lists and interaction matrices can be very useful in supporting model development, but system and process understanding is key. Such understanding is developed primarily from site investigations.

Three reports have been published by SKB that describe marine, terrestrial and lake and running water ecosystems (reports TR10-03, TR-10-01 and TR-10-02, respectively). Each of these reports provides the site description, generic data, process explanation and parameters needed. There is considerable detail in each of the reports, providing overall site understanding. Whilst considerable time has been spent in generating these reports, they will prove invaluable in supporting future assessments. The time spent is therefore very worthwhile.

The system understanding developed by SKB was used in a systematic FEP analysis to identify which process interactions needed to be considered in the safety assessment. Around 45 processes were identified as being important for inclusion. A useful way to represent identified processes is to develop a box model, which illustrates interactions (

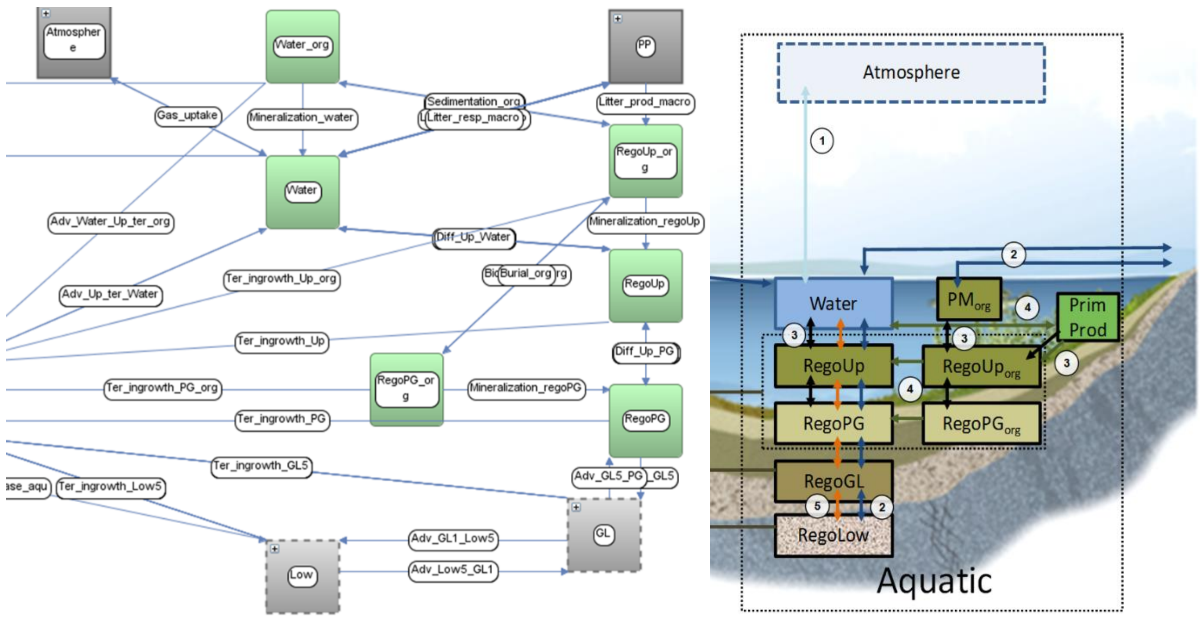

Figure 3-12). The modelling platform Ecolego was used by SKB to draw the interactions in a box model form. The box model can help to identify if any processes have been missed and encourages consistency in nomenclature between assessment groups. Ecolego is a particularly useful tool, allowing the transfer matrix to be illustrated as either a box model or as an interaction matrix.

Not all FEPs are directly included in radionuclide transport and dose calculations, but could be used in background modelling. All of the FEPs that were identified as being important to consider were allocated to one or more biosphere activities (e.g. radionuclide transport modelling, dose calculations for humans or biota, landscape modelling etc.) as illustrated in Table 3-1.

For exposure pathway analysis, SKB followed the method of the Agency for Toxic Substances and Disease Registry (ATSDR) of 2005. This involved systematic identification of the environments and types of media from which exposure might occur, both for terrestrial and aquatic environments. The different exposure pathways were then identified (i.e. inhalation, ingestion, external irradiation) and combined with the environmental media. The approach was useful in identifying critical exposure groups. The availability of resources to support exposure groups was also considered. For example, the ability of areas to sustain a group of people through food production and drinking water availability were considered. The use of technology to enhance production was considered along with the use of gardens to produce crops for families. Additional resources that were considered included the use of peat combustion for heating and the transformation of wetlands to agricultural land. This consideration of resource availability helped in explaining why it was not necessary to propagate some exposure pathways to the safety assessment.

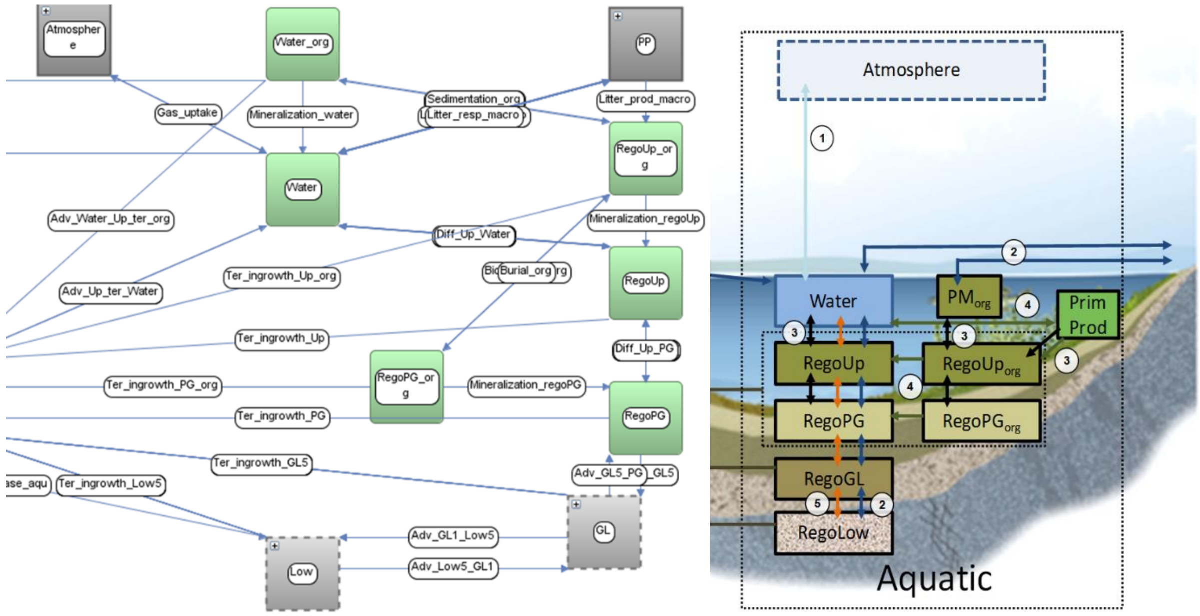

Figure 3-12. Ecolego box model (left) illustrating interactions between different aquatic features with regard to C-14 transport in the biosphere (right).

Discussion

The examples given from the SKB report provide useful experience on how to organise and present information in developing the updated methodology and on approaches to developing interaction matrices. For example, the importance of developing a good site understanding, particularly of the processes governing interactions between key parts of the system, and the use of this understanding in developing matrices that are representative of that system should be highlighted. Further matrices can then be developed that illustrate how radionuclides interact and move within the system that supports the development of a box model that incorporates information on human and wildlife interactions within that system. The sequence of activities is an important consideration. It is suggested[p] that diagonal elements in an interaction matrix should be limited to no more than 13 or the matrix will become unmanageable. Matrices within matrices can then be used to consider aspects in more detail.

Much of the data used by SKB in support of safety assessments has been derived from site investigations, but other sources have been drawn upon. For example, primary production has not been measured and alternative data sources were therefore required. Mass balances have been used as a means of checking models.

Table 3-1. Illustration of the mapping of FEPs.

Components, variables and processes		Radionuclide model					Supporting activity						
		Transport modelling			Dose calculations		Landscape modelling	Hydrological modelling	Ecosystem-specific parameters				
		Aqua	Mire	Agri	Humans	NHB			Aqua	Mire	Agri	K_d/CR	Human NHB
Bio01	Bioturbation	X		X					X		X		
Bio02	Consumption	X	X		X	X	X		X	X	X		X
Bio03	Death	X	X				X		X	X			
Bio04	Decomposition	X	X	X			X		X	X	X		
Bio05	Excretion	X	X						X	X	X	X	
Bio06	Food supply				X		X		X	X	X		
Bio07	Growth						X				X		
Bio08	Habitat supply				X	X	X		X	X	X		X
Bio09	Intrusion			X	X								X
Bio10	Material supply				X		X		X	X	X		X
Bio12	Particle release/ trapping	X	X						X	X	X		
Bio13	Primary production	X	X				X		X	X	X		
Bio14	Stimulation/inhibition						X		X	X	X		
Bio15	Uptake	X	X		X	X			X	X	X	X	X
Bio16	Anthropogenic release			X	X						X		X

[p] Nilsson S and Smith G M (1994). The Rock Engineering System (RES) Methodology Applied to the Biosphere Part of Safety Analysis. SKB Arbetsrapport 94-61, Stockholm.

Bio17	Material use			X	X						X		X
Bio18	Species introduction/ extermination				X	X			X		X		
Bio19	Water use			X	X								X

3.5 ADDRESSING CHEMICAL HAZARDS IN RADIOACTIVE WASTE: MSPAF METHODOLOGY

Rodolph Gilbin presented.

IRSN has developed an assessment approach to address multi-substance impacts on biota. The approach is called msPAF, based on Quantitative Risk Estimation (% affected species at a given exposure level). The objective is to achieve a consistent and integrated approach to environmental risk assessment (ERA).

There is a wide diversity of radionuclides and chemicals that may need to be considered for a source term. Irrespective of the stressor, risk is generally characterised through an ERA-type approach. There is guidance on ERA at an EU level. There are four phases to an ERA: problem formulation, exposure analysis, effect analysis and risk characterisation. Knowledge of the toxicity of a substance of interest is therefore required in order to evaluate risk. The approach has been used for decades with regard to chemicals and, more recently, has been developed for radionuclides whereby predicted no effect dose rate (PNEDR) is compared against the predicted exposure dose rate (PEDR) to derive the risk quotient (RQ).

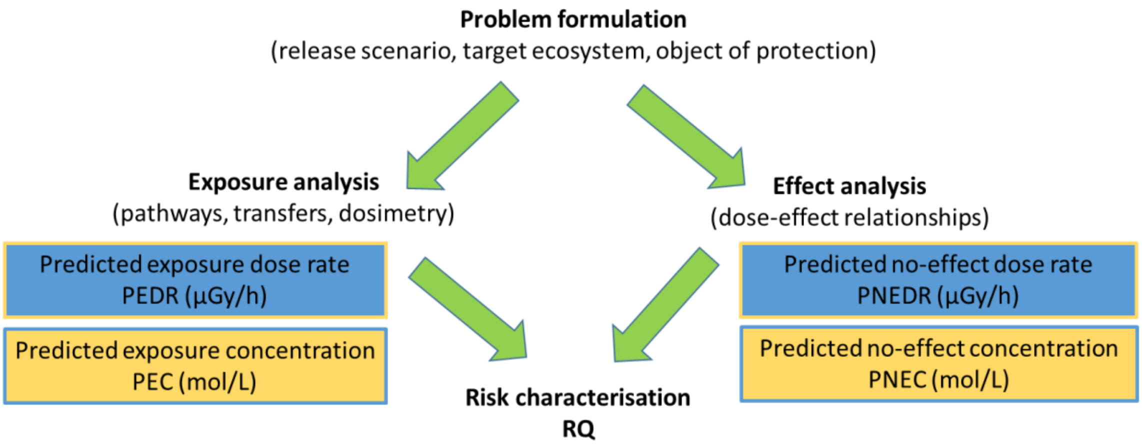

Figure 3-13. Phases of an ERA type approach.

A species sensitivity distribution (SSD) approach is commonly used to derive predicted no effect concentrations (PNEC) for chemicals and has also been applied to derive a PNEDR for radionuclides. The approach is based on available toxicity data with the concentration ensuring that 95% of species are protected being selected. For a multi-substances risk assessment, a SSD would be required for each substance. However, collating risk across different substances is not straightforward. For example, if a substance in isolation causes a 10% effect and another causes a 50% effect, combined the effect may not be a simple summation to 60% effect.

A number of approaches for addressing mixtures of substances have been developed, such as independent action or response addition where the effects of a mixture equates to the joint probability of effect from all the chemicals, or concentration addition, which is based on chemicals having the same mode of action, but with variation in the relative potency of the individual chemicals. The concentration addition method uses toxic units that can be summed. The choice of whether to use a concentration addition or independent action approach is based on the slope of the SSD curve. Where similar curves are evident then concentration addition can be used. Substances with different SSD slopes are treated as having independent action.

The approach has been used by IRSN in a case study focused on substances, including radionuclides, discharged from nuclear power plants to the Rhône River. The choice of concentration addition or independent action approaches altered in terms of worst case calculations according to the mixture of substances released and the river flow rate. The method allows the contribution of each substance in a mixture to be estimated and the risks from different discharge sites to be compared. The relative effects of chemicals versus radionuclides can also be compared. Furthermore, irrespective of their nature, substances can be ranked in terms of toxic units in order to identify substances with high-risk of impact to ecosystems. The approach is therefore helpful in selecting management options, such as optimisation of effluent treatment according the main hazards for both existing and planned facilities.

In addition to application to nuclear power plant discharges, the approach is also being developed for application to releases from former mine sites. There is also interest in the application of the approach to radioactive waste case studies. Application would require a source term for both radionuclides and non-radioactive substances to be defined.

References are available on the approach:

- Mathews *et al.* (2009). A probabilistic assessment of the chemical and radiological risks of chronic exposure to uranium in freshwater systems. Environmental Science and Technology 43: 6684-6690.

- Beaugelin-Seiller *et al*. (2009). A common ecological risk assessment on freshwaters for chemical and radiological toxicity: the uranium case. Radioecology 2008, Bergen, 16-21 June 2008. Radioprotection 44: 913-918.

- Garnier-Laplace *et al.* (2009). A screening level ecological risk assessment and ranking method for liquid radioactive and chemical mixtures released by nuclear facilities under normal operating conditions. Radioecology 2008, Bergen, 16-21 June 2008. Radioprotection 44: 903-908.

- Beaumelle *et al.* (2016). Ecological risk of mixtures of radioactive and stable chemical compounds predicted by multi-substance species sensitivity distributions. Setac Europe Meeting, Nantes, 24 May 2016.

Discussion

The SSD curves are primarily based on individual exposures under laboratory conditions and the species tested are not therefore likely to be representative of the diversity that would be present at a site. Also, the SSD approach requires at least 12 test species and works on the hypothesis that the response across species will be representative of the sensitivity of animals in the field. Thus, there are questions as to the robustness of this approach. The same approach is applied however to both radionuclides and chemicals allowing a comparable estimate of effect, with uncertainties equally applying to both radionuclides and chemicals.

Whether or not the approach could be used to derive concentrations of radionuclides and chemicals in a repository release equating to the same level of effect was queried. However, such an approach could at least support the screening of chemicals and radionuclides in assessments and allow substances, including radionuclides, to be ranked according to risk or need for further assessment.

3.6 STATISTICAL LANDSCAPE EVOLUTION MODELLING AS INPUT TO SENSITIVITY ANALYSIS OF STYLISED RADIONUCLIDE TRANSPORT AND DOSE MODELLING

Ari Ikonen presented on behalf of Jari Pohjola, Jari Turunen and Tarmo Lipping of Tampere University of Technology.

The Pori department of Tampere University of Technology in Finland has been undertaking some interesting work on combining methods for probabilistic modelling of the transport of radionuclides in the environment. The focus of the team is on statistical or probabilistic 4D (3D plus time) landscape development modelling that can feed into stylised radionuclide transport and dose models. A statistical topography model has been developed and combined with a statistical extrapolation model of land uplift to project probability distributions of locations and sizes of water bodies. The model is not a prediction of the future, but is rather illustrative (a “plausible future”). Uncertainty and sensitivity analyses have been performed for a stylised lake-farm model and work is now continuing to extend the model to allow lake sediments and other ecosystems to be included.

A range of topography data have been used to inform the model, including Finnish maritime administration data, seismic measurements and sonar measurements. Different uncertainties are associated with the different data sources and PDFs were established for all topography data points as input to the probabilistic digital terrain model. The same semi-empirical model used by SKB and Posiva for land uplift, an important process for the local landscape, was employed and extrapolated into the future. Again, the uncertainty of the source data was considered with statistical distributions being available for all points in the terrain model.

The model is currently being used to produce best estimate projections of the terrain around Olkiluoto and to identify water courses. The probabilities of alternative terrain characteristics over time can be evaluated by varying the inputs to the land uplift model with terrain being represented in 3D. This 3D representation can then be used to visualise lake forms etc., including probability estimates for lake depth (Figure 3-14). Probabilistic river network analysis has also been performed. The majority of the work presented was undertaken as part of a PhD project[q].

---

[q] Pohjola J. (2014). Dissertation: Probabilistic modelling of landscape development and surface water body formation. Tampere University of Technology, Pori, Finland.

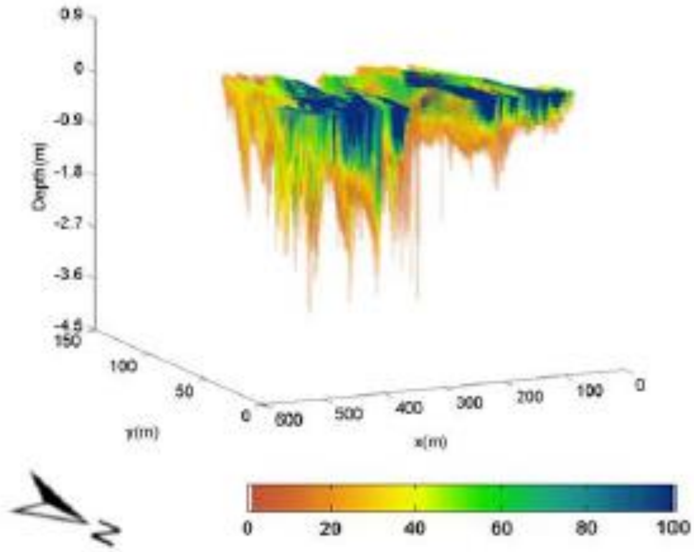

Figure 3-14. Illustration of lake 3D probability.

A lake-farm model has been developed using a simple modelling approach (Figure 3-15). The model includes one lake water and two lake sediment compartments. Use of lake water for irrigation on a small farm and for drinking water are considered, along with the consumption of fish. Sensitivity analysis can be performed to identify the most important processes. The BIOMASS-6 approach has been used in documenting the sensitivity and uncertainty analysis of the model. The main feedback from this exercise is that clearer guidance is required for those without prior experience of the approach. The BIOMASS-6 approach was also considered to be unclear with regard to information that should be explicitly included in an assessment and that provided for “only” information.

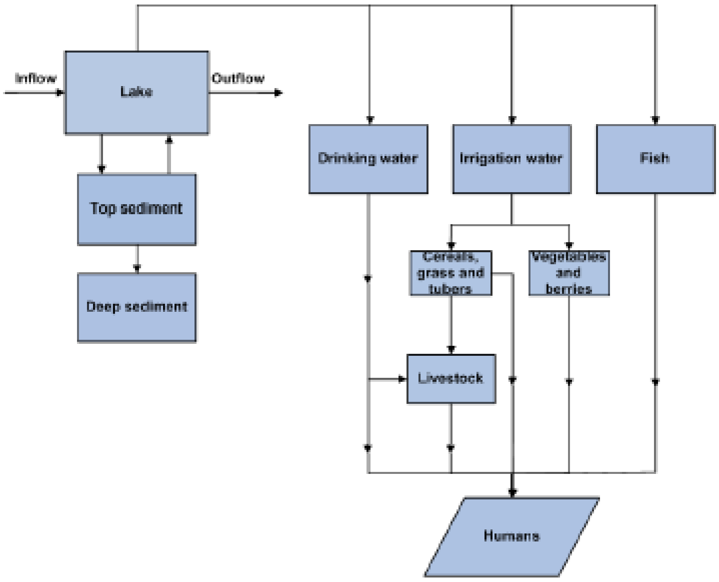

Figure 3-15. Lake-farm model structure.

Discussion

The approach described would be well suited to application to regions of Fennoscandia, but also other areas that are subject to considerable environmental change (e.g. those affected by coastal erosion). Lake sedimentation and erosion have not been included in the model to date however as the focus has been on main landforms. Such expansion would, however, be technically feasible.

4. DISCUSSION ON FORWARD WORK PROGRAMME AND LINKS TO THE IAEA MODARIA II PROGRAMME

This section provides a summary of the discussions on the forward programme for reviewing and updating the BIOMASS-6 methodology and links to the IAEA MODARIA II programme, including a presentation from Gerhard Pröhl (IAEA).

4.1 BIOSPHERE MODELLING FOR LONG-TERM SAFETY ASSESSMENTS OF HIGH LEVEL WASTE DISPOSAL FACILITIES: PROPOSAL FOR A WORKING GROUP WITH THE IAEA MODEL TEST AND COMPARISON PROGRAMME, MODARIA II

Gerhard Pröhl presented.

A consultancy meeting was held at the IAEA at the beginning of March, during which the programme for MODARIA II was discussed.

Performance assessment for radioactive waste repositories continues to be a subject for which additional work may be warranted to support the demonstration of long-term safety and compliance with dose criteria. Long-term dose assessments are partially built upon a sound scientific basis (e.g. with regard to radionuclide transport processes), complemented by plausible assumptions (e.g. for human living habits).

Within the MODARIA I programme there was a working group on the development of a common framework for addressing environmental change in long-term safety assessments of radioactive waste disposal facilities. The objectives of the working group were to evaluate the consequences of the long-term development of climate and landscape by identifying relevant carbon dioxide emission scenarios and relating long-term carbon dioxide concentrations in air to the evolution of landscape and biospheres. The framework that was developed is considered to be applicable to a wide range of facilities and site conditions and it has been suggested that the framework should be incorporated into an update of the BIOMASS-6 methodology. Objectives for MODARIA II therefore include the application of the methodology to identify plausible developments for real sites with regard to climate and landscape and to analyse existing concepts for long-term dose assessment, both in respect of the scientific basis and complementary plausible assumptions. Further objectives are to update the BIOMASS-6 methodology to address conceptual and/or information gaps, and to develop guidance on site characterisation and data requirements, both in terms of the type of information and the level of detail required. It is important to be aware that long-term assessments are complex and a key requirement is to develop confidence, which means that assessments should be detailed enough, but not so detailed that they are not perceived as credible. In extending and refining the BIOMASS-6 methodology, it may be useful to include quantitative estimates of exposure that illustrate how uncertainties can be addressed and illustrate the practical application of the methodology. The aim should be to build on the past methodology, drawing in application experience and scientific developments.

The IAEA have a range of safety requirements and standards publications that relate to the disposal of radioactive waste, including:

- SSR-5 that sets out the safety requirements for the disposal of radioactive waste;
- SSG-14, which is a safety guide for geological disposal facilities for radioactive waste; and

- SSG-23, which provides guidance on the development of a safety case and safety assessment for the disposal of radioactive waste.

The safety guide SSG-23 includes a chapter on radiological impact assessment for the post-closure period, which contains elements from BIOMASS-6.

The BIOMASS-6 methodology sets out six assessment steps from setting out the assessment context through to biosphere model development and calculation. Example biospheres were also included that were intended to illustrate the application of the methodology with comparison made between the different scenarios in terms of radionuclides and exposure groups through a relative representation of results (Table 4-1). In moving forward, a suggestion is to look at underlying parameters in assessment scenarios and consider how they drive the results. Ideally, the output of MODARIA II would be a methodology with examples that identify which radionuclides and exposure groups are the principal ones for different scenarios.

Table 4-1. Relative doses for example reference biospheres (arable farmer for agricultural well = 1).

Radio-nuclide	Scenario		Arable farmer	Live-stock farmer	Horti-culture	Game-keeper	Fisher-man	Villager
I-129	1A	Drinking water	0.18					
	2A	Agricultural Well	1.0	0.7	0.9			0.5
	2B	Natural release of GW	0.01	0.02	0.01	0.03	0.01	0.01
Np-237	1A	Drinking water	0.30					
	2A	Agricultural Well	1.0	0.8	1.8			0.7
	2B	Natural release of GW	0.16	0.16	0.16	0.57	0.16	0.16
Tc-99	1A	Drinking water	0.18					
	2A	Agricultural Well	1.0	0.9	0.9			0.5
	2B	Natural release of GW	1.6	1.6	1.6	5.2	1.6	1.6
Nb-94	1A	Drinking water	0.00					
	2A	Agricultural Well	1.0	1.0	1.0			1.0
	2B	Natural release of GW	0.48	0.49	0.48	1.2	0.65	0.48

Within the IAEA EMRAS II programme, working group 3 looked at environmental change, based on the BIOMASS approach. Both dynamic modelling of environmental change and the use of analogue sites were considered. A narrative of climate and landscape development was then the focus of working group 6 of the MODARIA I programme.

As a result of the various programmes, it is evident that doses arising from agricultural wells are greater than for drinking water wells and are also greater than for doses arising from the natural discharge of groundwater. Dose conversion factors are also increased in warmer climates where there are greater water deficits driving the use of irrigation water. Knowledge has also developed with regard to the behaviour of radionuclides, particularly the need for careful selection of environmental transfer parameters for radionuclides with complex speciation such as Se-79. Commonly, parameters are selected to be conservative, but it would be good to link parameters to climate conditions to avoid excessive conservatism in assessments. Specific attention is also required for natural and semi-natural environments and the presence of complexing agents in organic matter and sorption to organic matter.

To support long-term assessments, it is considered that we need reference biospheres that include environmental change in a site context that includes inland, coastal and freshwater sites. Up to three relevant reference biospheres could be selected and defined with evaluation used to determine whether an agricultural well scenario is a kind of worst case to consider for assessments. It could also be useful to consider the relevance of environmental transfer parameters in representing the long-term behaviour of long-lived radionuclides in the environment and the impact of erosion of the long-term distribution of radionuclides in a landscape.

The MODARIA II programme will run from late 2016 to 2019 and, like previous IAEA work programmes, will involve one plenary meeting per year with interim working group meetings between. The first Technical Meeting will take place from 31 October to 4 November 2016.

4.2 DISCUSSION ON THE COLLABORATION BETWEEN AND INTEGRATION OF THE MODARIA II AND THE BIOPROTA WORK PROGRAMMES

Reports from IAEA programmes are published after the end of the programmes and the MODARIA II reports would therefore be available sometime after 2019. However, if interim reports are required then that can be agreed. The schedule of the BIOPROTA project can therefore be incorporated within the work plan.

Results from the BIOPROTA project in 2016 will include discussion material on how the BIOMASS-6 methodology has been used and identify what has been useful and where revisions may be beneficial. This work could be presented during the first Technical Meeting of MODARIA II as working material to support that programme and to inform discussion with a wider group of interested parties. This will provide a good starting point for MODARIA II as well as providing further input for completion and reporting of the BIOPROTA project by the end of 2017. Time is planned to be allocated during the first MODARIA II Technical Meeting to include presentation of progress and to progress work on the BIOPROTA activity to ensure that BIOPROTA is fully recognised within the programme. Discussion on collaborative working between the two programmes will continue as the MODARIA II programme develops.

Following the identification of points for enhancing the BIOMASS-6 methodology, including those from the BIOPROTA 2016 work, a programme for improving the methodology will be developed for implementation in subsequent years of the MODARIA II programme.

It is recognised that it is not just radionuclides that are potentially hazardous in radioactive waste, other chemicals are also present. Chemical hazards in radioactive waste were not considered in the original BIOMASS-6 methodology, but there is now an increasing requirement for people to explicitly address such hazards in assessments and a coherent approach is required. There are no current plans within the IAEA to address this need, but it is recognised that this will be needed. There will also be a need to address the protection of the environment.

4.3 FORWARD PLAN

The proposed work programme of the BIOPROTA project will be updated to take account of the presentations and discussions during the workshop. The updated plan will be distributed to sponsors and technical contributors to the project as part of on-going interim and draft documentation.

APPENDIX A. MEETING PARTICIPANTS

The workshop was attended by the following participants.

Participant	Organisation
Lara Duro	Amphos21
Yves Thiry	Andra
Elisabeth Leclerc	Andra
Alexander Diener	BfS
Danyl Perez-Sanchez	Ciemat
Beatriz Lourino-Cabana	EdF
Laura Milelli	EdF
Taku Tanaka	EdF
Jürgen Hansmann	ENSI
Markus Hugi	ENSI
Ari Ikonen	EnviroCase
Frederic Bernier	FANC
Geert Biermans	FANC
Koen Mannaerts	FANC
Maryna Surkova	FANC
Anna Filonova	FMBC
Graham Smith	GMS Abingdon
Gerhard Pröhl	IAEA (by video conference link)
Rodolphe Gilbin	IRSN
Alessandro Proverbio	LLWR
Neale Hunt	NWMO
Tiberio Cabianca	PHE
Kirsi Riekki	Posiva
Lauri Parviainen	Posiva
Russell Walke	Quintessa
Adrian Punt	RadEcol Consulting
Karen Smith	RadEcol Consulting
Ray Kowe	RWM
Jordi Vives	SCK
Ulrik Kautsky	SKB
Maria Norden	SSM
Shulan Xu	SSM