Interpretation and Modelling: Biosphere, to support the development of an Integrated Site Descriptive Model

NDA
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745.1R 001 CMM Report

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**Bibliography**

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ABSTRACT

In 2008, as a part of its Managing Radioactive Waste Safely programme, the UK Government published a White Paper setting out a framework for managing higher activity radioactive waste in the long term through geological disposal.

The Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA) has been given the responsibility for implementing geological disposal of the UK’s higher activity radioactive waste. In advance of a candidate site being identified, a programme of research has been started so that, when required, surface-based site investigations could be implemented in a timely and efficient manner; and that the necessary arrangements are in place so that resources will be available to support the subsequent implementation of site characterisation.

The overall aim of this report is to contribute to the establishment of a framework to produce conceptual and descriptive models for the biosphere, and to review the resources and technologies available to process site-characterisation data in a systematic way. The key objectives were to provide RWMD with an authoritative account for the biosphere discipline of:

- The processes and tools that have been used on other international radioactive waste management programmes for processing, interpreting and modelling biosphere data acquired through site characterisation.
- Any additional processes and tools that are used for similar purposes in other sectors that may be applicable to a UK-based waste management site characterisation programme.
- The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in the UK.
- The extent to which the required resources may vary in different geological environments and the identification of any gaps in available resources to support a UK-based site-characterisation programme.

Information reviewed within this report has been obtained from publicly available sources (such as published literature and conference proceedings), from organisation websites, from academic material (both published literature and internet based) and from approaches to individual organisations to request additional information and reports. International programmes on disposal of solid radioactive waste, environmental impact assessment and radiological protection contributing to an understanding of site-characterisation requirements have also been considered.
EXECUTIVE SUMMARY

In 2008, as a part of its Managing Radioactive Waste Safely (MRWS) programme and following recommendations made by the independent Committee on Radioactive Waste Management (CoRWM), the UK Government published a White Paper setting out a framework for managing higher activity radioactive waste in the long term through geological disposal.

The Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA) is responsible for implementing this programme. No candidate site for a geological disposal facility has yet been identified. However, a Site Characterisation Project has been commenced. The objectives of this project are to:

- Undertake sufficient preparatory work such that, when required, the surface-based site investigations could be implemented in a timely and efficient manner; and
- Ensure that the necessary arrangements are in place so that resources will be available to support the subsequent implementation of site characterisation.

Once a candidate site or sites for a geological disposal facility have been identified, detailed surface and subsurface site characterisation investigations will be undertaken, leading to the development of an integrated Site Descriptive Model.

Characterisation of the biosphere is important because it is the receptor within which any impacts from deep geological disposal will occur after closure of the facility. The development of site conceptual models provides a basis for predictive mathematical modelling and assists in the definition of features, events and processes (FEPs) during the site characterisation process.

For the purposes of the Biosphere Studies work programme, the biosphere is considered to be the near-surface and surface environment, including the atmosphere, ecosystems, terrestrial and marine water bodies, soil and the upper part of bedrock.

The overall aim of this report is to contribute to the establishment of a framework to produce conceptual and descriptive models for the biosphere by investigating:

- The processes and tools that have been used in international radioactive waste management programmes for interpreting and modelling the biosphere.
- Any additional processes and tools used in other industry sectors for interpreting and modelling the biosphere that may be applicable to a UK waste management site characterisation programme.
- The availability of resources for undertaking such a programme of interpretation and modelling in the UK and the extent to which these may vary in response to variations in the geological environment at the site(s) being characterised.
- The identification of any gaps in available resources to support a UK-based site characterisation programme.

This has been achieved through review and evaluation of programmes adopted in the UK and internationally, by the radiological assessment community and other sectors, for the characterisation of the biosphere on a site-specific basis.
The report has been obtained from publicly available sources (such as published literature and conference proceedings), from organisation websites, from academic material (both published literature and internet based) and from approaches to individual organisations to request additional information and reports.

**National programmes**

Worldwide there is general agreement that the only viable long-term strategy for the storage and/or disposal of high level/heat generating waste is in deep geological formations. Current activities in most countries are focused on the development of strategies for site selection, the development of repository and near-field engineering solutions and safety assessments. Several countries have constructed underground test and research facilities (e.g. Sweden, Finland, France). However, to date only the USA has an operating deep geological repository, the Waste Isolation Pilot Plant (WIPP).

Site characterisation programmes identified across national organisations are typically linked to model development for the primary purpose of assessing impacts on man and the environment, including systematic definition of FEPs and the use of interaction matrices to describe key features of the environment.

**Other Sectors**

Approaches to site characterisation in other sectors have been investigated, including mining (and uranium tailings management), dams, oil and gas, carbon capture/sequestration, waste disposal and environmental clean-up.

Large projects have generic requirements to assess impacts on the environment and local populations. Formal Environmental Impact Assessment (EIA) and Environmental Impact Statements (EISs) are routinely required for larger projects in developed countries, and this process drives the majority of environmental investigation and characterisation activity. Assessments cover a range of impacts including those on climate, geology and soils, flora and fauna, and human populations.

EIA typically requires the establishment of environmental baselines, although often limited to collection and compilation of monitoring or survey data and interpretation or description of site characteristics. The level and scope (especially timescales) required to be addressed by other sectors generally fall well short of those required in radioactive waste disposal and they appear to have little novel to offer a UK geological disposal programme.

**Tools**

There are a large number of tools available for data processing and interpretation and for modelling of geosphere-biosphere systems. Models may represent systems with varying degrees of complexity (1D, 2D, 3D – even 4D if time evolution of hydrological and hydrogeological conditions is included in ‘3D’ models).

Data management and manipulation is a key issue in all large-scale characterisation projects. Geographical Information Systems (GIS) provide generic platforms for data manipulation and modelling and are widely employed for database, data and model output visualisation, spatial modelling and interpolation. ArcGIS is the most widely employed GIS in this context.
Two notable integrated catchment modelling systems are identified, SHETRAN and MIKE SHE. Both offer a similar range of capabilities, with SHETRAN having been applied previously in the UK nuclear waste management programme. Widely employed, comprehensive groundwater modelling packages include ModFlow, ConnectFlow, FeFlow and GoldSim.

**Strategic Approach**

The fundamental objectives underlying biosphere characterisation, for the purposes of this review, are to establish “what is there”; and to establish “what could be there in the future” (although the prediction of how biosphere characteristics change is not part of this study). This review has identified a staged process to site characterisation, consisting of:

- Developing a conceptual site model;
- Identifying features and processes present on the site and/or in the region;
- Developing an interaction matrix to identify interactions between those features and processes which may be relevant to radionuclide flow through the environment;
- Measuring and parameterising those key components; and
- Revising the conceptual model to take account of new information.

Depending on the site selected, there may be situations where there is no release to biosphere. For other sites, the biosphere region receiving the greatest radionuclide impact may be distant from the disposal site, so that understanding geosphere transport mechanisms is necessary to ensure relevant biosphere regions are characterised.

Rigorous data recording and checking procedures are essential to guarantee the quality of data defining the site characterisation.

**Determining Confidence of Site Understanding**

The required level of confidence in site understanding can be linked to the MRWS process (particularly with respect to stages 4, 5 and 6) and the key issue is to determine when it is justified to move from desk- and surface-based investigations to sub-surface intrusive investigations. In this context, it is noted that site characterisation may be an iterative process with the site conceptual model and interaction matrix revised as data are obtained at various stages. It is also necessary to understand the sensitivity of the results to key parameter values and to identify limiting characteristics, especially the rates and dominant pathways for transport of contaminants through the geosphere to the geosphere-biosphere interface zone.

**Resource Vulnerability**

Potential resource vulnerability has been considered in the areas of: processing, modelling and interpretation.

It is considered unlikely that basic measurement skills and tools (in hydrology, meteorology, ecology etc.) will be vulnerable, as these are widespread disciplines. Specialist investigative equipment (e.g. borehole drilling rigs and subsurface mapping equipment) is available in UK, although limitations on availability could cause temporary delays. The requirement for experimental data to determine site-specific characteristics (e.g. soil Kd
values) could also be rate limiting due to time taken to commission and complete, but should only represent temporary delays.

The only discipline which may become skills limited appears to relate to modelling, specifically support of a specialist model or application. Conceptual modelling is rarely rate limiting and the development of interaction matrices is a widespread approach. Many of the model platforms identified are distributed widely on a commercial basis.

**Conclusions**

In summary, site characterisation forms the basis for impact assessments as part of a safety case. The generalised overall approach should include breakdown of the biosphere/environment into functional units and evaluation of parameters in required/key areas (e.g. landscape, hydrology etc.), and an iterative process of characterisation and modelling. Quality control on data acquisition must be an integral part of the programme.

Of the national programmes reviewed, the approaches adopted in Sweden and Finland offer the most useful examples to inform the development of a UK site characterisation programme.
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<td>As Low As Reasonably Achievable</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<td>CoRWM</td>
<td>Committee on Radioactive Waste Management</td>
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<td>DBE</td>
<td>Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (German waste management organisation)</td>
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<td>DBM</td>
<td>Descriptive Biosphere Model</td>
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<td>DGR</td>
<td>Deep Geological Repository</td>
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<td>DOE</td>
<td>(United States) Department of Energy</td>
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<td>DSSC</td>
<td>Disposal System Safety Case</td>
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<td>DEM</td>
<td>Digital elevation model</td>
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<td>EA</td>
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<td>European Commission</td>
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<td>EIA</td>
<td>Environmental Impact Assessment</td>
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<td>EIS</td>
<td>Environmental Impact Statement</td>
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<td>Environmental Safety Case</td>
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<td>EU</td>
<td>European Union</td>
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<td>FEPs</td>
<td>Features, Events and Processes</td>
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<td>GBIZ</td>
<td>Geosphere-Biosphere Interface Zone</td>
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<td>GDF</td>
<td>Geological Disposal Facility</td>
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<td>GIS</td>
<td>Geographical Information System</td>
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<td>GRA</td>
<td>Guidance on Requirements for Authorisation</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<td>HLW</td>
<td>High Level Waste</td>
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<td>HPA</td>
<td>Health Protection Agency</td>
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<td>HSE</td>
<td>Health and Safety Executive</td>
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<td>IAEA</td>
<td>International Atomic Energy Agency</td>
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<td>ICRP</td>
<td>International Commission on Radiological Protection</td>
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<td>ILW</td>
<td>intermediate level waste</td>
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<td>KBS-3</td>
<td>Kärnbränslesäkerhet-3 (Nuclear Fuel Safety #3)</td>
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<td>LLW</td>
<td>Low Level Waste</td>
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<td>LLWR</td>
<td>Low Level Waste Repository</td>
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<td>MRWS</td>
<td>Managing Radioactive Waste Safely</td>
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<td>NII</td>
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<td>NRPB</td>
<td>(UK) National Radiological Protection Board (superseded by the HPA)</td>
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<td>NWMO</td>
<td>Nuclear Waste Management Organization (Canadian waste management organisation)</td>
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<td>ONR</td>
<td>Office for Nuclear Regulation (an agency of the HSE).</td>
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<td>Post-Closure Safety Case</td>
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<td>SDM</td>
<td>Site Descriptive Model</td>
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<td>SIIFD</td>
<td>Site Investigation and Information Flow Diagram</td>
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<td>SKB</td>
<td>Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company)</td>
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<tr>
<td>WIPP</td>
<td>Waste Isolation Pilot Plant</td>
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1 INTRODUCTION

This report has been produced by Coffey Geotechnics Ltd in association with Eden Nuclear & Environment Ltd (Eden NE) and SJ Scientific (SJS) under contract to NDA RWMD.

1.1 Context within the Managing Radioactive Waste Safely Programme

In October 2006, the UK Government and the Devolved Administrations published a response to the recommendations made by the independent Committee on Radioactive Waste Management (CoRWM) accepting CoRWM’s main recommendation that geological disposal, preceded by safe and secure interim storage, was the way forward for the long-term management of the UK’s higher activity radioactive wastes.

Published as a part of the Managing Radioactive Waste Safely (MRWS) programme, a White Paper [1] set out the UK Government’s framework for managing higher activity radioactive waste in the long-term through geological disposal. This is consistent with approaches adopted by other Member States across the European Union [2].

The Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA) has been given the responsibility for implementing geological disposal. The implementation process envisaged is that once a candidate site or sites for a geological disposal facility (GDF) have been identified, the RWMD will undertake surface-based investigations at the site or sites.

The process of investigation would comprise detailed surface and subsurface investigations, and would be required to acquire and interpret information on the geological, hydrogeological and environmental conditions at one or more sites throughout all stages of the development and implementation of a GDF for the long-term management of higher activity radioactive wastes.

Selection of a site is undertaken as a staged process, as outlined in the MRWS White Paper (see Figure 1, from [1]). Following an Expression of Interest from a community, a sub-surface suitability test will be conducted to screen out sub-surface volumes which would not be suitable and remaining areas would be invited to consider a Decision to Participate.

For those communities at Stage 3 that make a Decision to Participate, there would first be a desk-based study phase (MRWS Stage 4) to investigate a number of potential sites (even if there is only one volunteering host community), before proceeding to surface-based investigations, possibly at more than one potential site (MRWS Stage 5). The most detailed investigations would proceed at the finally selected site and involve underground operations, including the drilling of boreholes to various depths to investigate local geology in more detail (Stage 6). The strategic evolution of investigations through the MRWS stages has been outlined by RWMD [3].

A consultation on approaches to undertaking desk-based identification and assessment of Potential Candidate Sites was held in 2011 [4]. DECC have responded to this consultation [5]. Although the process to be followed at Stage 4 has not yet been determined in detail, it seems likely that the assessment would involve gathering geoscientific information, demographic information, environmental information, topographic information, etc. for each of the Potential Candidate Sites and evaluating them against agreed criteria (such as, but
not necessarily limited to, geological setting, potential impact on people, potential impact on the natural environment and landscape).

**Figure 1. MRWS Staged Site Selection Process**

From [1].

Without prejudice to the process to be followed, a Site Characterisation Project has been commenced and forms a part of the research programme of the RWMD. The objectives of this project are to:

- Develop approaches to the design and implementation of information-led investigations (surface and underground investigations, etc.) to meet the needs of information users within RWMD, Regulators and other key stakeholders;
- Undertake sufficient preparatory work such that, when required, the surface-based site investigations could be implemented in a timely and efficient manner; and
- Ensure that the necessary arrangements are in place so that resources will be available to support the subsequent implementation of site characterisation.
Analogous work, undertaken as part of national programmes elsewhere to develop a GDF [e.g. 6, 7, 8, 9, 10], has considered the overall approach to site characterisation, interpretation and modelling, including:

- The various stages of interpretation;
- The role of models in interpretation;
- The significance of conceptual models in developing an understanding of site conditions;
- The overall role of model testing in site characterisation;
- The selection of tools for interpretation and modelling;
- Use of Site Investigation Flow Diagrams (SIFDs) as an aid to visually describing the flow of information from data acquisition, through the various stages of processing and interpretation;
- Issues related to establishing when sufficient information has been obtained from a site-characterisation programme;
- Overall conclusions regarding interpretation.

The approach in the UK is being developed to present the information derived from site characterisation activities in the form of a single integrated Site Descriptive Model (i.e. a model describing, amongst other matters, the site geometry, properties of the bedrock and water, and the associated interacting processes and mechanisms), which will be used to address the information requirements of end users.

1.2 Development of a Site Descriptive Model

Taking into account the experience of sister organisations engaged in radioactive waste disposal it is anticipated that the characterisation of the site will best be undertaken by the development and progressive updating of a single integrated Site Descriptive Model (SDM); that is, an integrated model describing the geometry, properties of the bedrock and water, the associated interacting processes and mechanisms, and the surface environment, that will be used to address the information requirements of all the end users [11]. Such an approach will ensure that:

- The understanding of the different aspects of the geosphere such as the geology, hydrogeology and hydrochemistry is developed in a consistent manner; and
- The different end users base their design and assessments on the same understanding and evidence base.

Site characterisation requires careful planning, clear objectives and a structured programme recognising spatial and temporal variability and ensuring that good quality data are obtained, reported and archived in a way that facilitates interactions between different end users of the information, including facility design, operational safety assessment, post-closure safety assessment and environmental impact assessment.

There are several elements to the preparation of a SDM, including:

- Definition of the volume of ground that needs to be included in the model;
- Subdivision of the model into functional or geometric units so as to permit the description of spatial variability in a meaningful manner; and
- Assignment of parameters (values and/or statistical distributions) to the defined functional or geometric units.
It is anticipated that, in a similar way to the approach adopted by SKB and Posiva, the integrated SDM will comprise information from a number of clearly defined disciplines that will form the basis for discipline-based sub-models to be described in individual chapters of the SDM. SKB notes that [12, p. 9].

“A Site Descriptive Model (SDM) is an integrated description of the site and its regional setting, covering the current state of the biosphere as well as ongoing natural processes of importance for long-term safety. The SDM summarises the state of knowledge of the site at the conclusion of the complete site investigation (CSI).”

The discipline-based models that are likely to be developed for UK sites comprise the following:

- Geology, geological evolution, paleoclimate and historical development of the site;
- Regolith development and formation;
- Surface, near-surface and deep hydrogeology;
- Surface water, and shallow and deep groundwater hydrochemistry;
- Geotechnical;
- Transport properties;
- Thermal properties (primarily in the context of potential HLW and spent fuel disposal); and,
- Biosphere (terrestrial ecosystems, limnic ecosystems, marine ecosystems).

In turn, many studies and much underpinning information will be required to develop understanding of components of the SDM and the partitioning of the SDM into disciplines for convenience of analysis and reporting needs to be complemented by putting into place arrangements for integrating information across disciplines (such as has been undertaken by the SKB SurfaceNET group, see [13] and reports summarised therein).

A much simplified diagram, based on a previous presentation by NDA, is illustrated in Figure 2, below. This illustration is clearly oriented towards the terrestrial environment but could be readily broadened to include features and activities of greater relevance to the coastal environment. Features such as vegetation mapping and animal surveys (wild and domestic) may also be incorporated.

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1 Note that the SDM is not the same as the report on it. The SDM includes the underlying databases, results from model runs and detailed documentation on each of its discipline-based components. This is illustrated further in Figures 2 and 3.

2 SurfaceNet is a group established by SKB for the purpose of evaluating, compiling and integrating site descriptions and numerical models for the surface systems in the Forsmark and Laxemar-Simpevarp areas as a preparatory step towards establishing overall SDMs, intended to support the safety assessment, environmental impact assessment and the design of a potential repository for nuclear waste.
The SDM will provide an understanding of the current characteristics of the site and, where relevant, the historical development of conditions at the site to support the conceptual understanding. As noted by SKB [12], it will also provide “parameters and models to be used in further analyses within Safety Assessment (SA), Repository Design, and Environmental Impact Assessment.”

SKB provides an example of how the different component parts of the SDM may be assembled into a SDM report and a series of supporting discipline related reports (see Figure 3).
1.3 Developing a Descriptive Biosphere Model

For the purposes of the site-characterisation programme, the biosphere is considered to be the near-surface and surface environment, including the atmosphere, ecosystems, terrestrial, estuarine and marine water bodies, soils and sediments, and the upper part of bedrock.

Characterisation of the biosphere is important in the context of deep geological disposal because it is the receptor within which any impacts of the disposal become manifest. Whilst components of the geosphere (and processes within it) are considered to have safety functions, this is not the case for the biosphere.

Reflecting on guidance provided by the environment agencies, NDA has noted previously [11] that the Descriptive Biosphere Model (DBM) component of the SDM will need to provide part of the basis for the operational safety assessment for a GDF at a particular site and for the post-closure safety assessment for such a GDF. One purpose of characterising the biosphere is thus to enable assessments of impact to be made (a) during the period of

* See text: thermal properties of the repository system are more relevant for HLW and spent fuel disposal.
operation of the repository and (b) over long timescales following closure of the GDF. This is considered further in Section 2.

It is important to understand that biosphere characterisation implies a range of activities to support development of the DBM and embraces, but does not relate exclusively to, gathering information in support of undertaking dose assessments. In this review we concentrate on those aspects relevant to developing the DBM component of the SDM and do not address directly those aspects relating to predictive modelling for the purposes of supporting either short-term (period of authorisation) or long-term (post-closure) assessments of impact.

Although the DBM component of the SDM, as defined above, does not include prediction of the future evolution of the conditions at the site, there will be considerable overlap in the information required to support the development of the DBM, the development of the Environmental Safety Case (ESC) and that required for the purposes of Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), the presentation of an Environmental Impact Statement (EIS), the engineering design of the disposal facility and to demonstrate confidence to the key stakeholders that the potential disposal facility site is adequately understood [e.g. 11].

The information required to compile the DBM includes [11]:

- Historical and current climate and development\(^3\);
- Description of the geological and geomorphological development of the site during the Quaternary;
- A detailed topographic model;
- The surface-water hydrology including historical development, detailed description of the current regime and mathematical modelling for future predictions;
- A detailed description of the near-surface hydrogeology, coupled with some mathematical modelling;
- The sampling and analysis of surface water and groundwater to better understand the flow characteristics in the biosphere and to understand biogeochemical interactions in the subsurface that modify the chemistry of surface and groundwaters\(^4\);
- A description of the soils and vegetation present at the site, together with an account of their historical development since the last glaciation\(^5\);

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\(^3\) In some circumstances climate prediction may also be relevant; for example, to understand the biosphere at the time of facility closure.

\(^4\) In particular, changes in the chemistry of percolating meteoric waters due to interactions with the soil and subsoil need to be taken into account, e.g. consumption of oxygen.

\(^5\) Often the relevant timescale is defined as the time since the end of the last glaciation, since this is the effective period over which vegetation has developed. However, even at the maximum glacial extent some 20,000 years ago parts of southern Britain were beyond the boundaries of the ice sheet and the relevant period may thus be extended further back.
- Ecological surveys to identify terrestrial and freshwater biota at the site area;
- Measurements of pre-existing radioactivity in the near-surface environment;
- Dependent upon the location of the site area, estuarine and marine systems may need to be described in terms of geometry, water and sediment transport and the distribution and abundance of biota; and
- A detailed description of human communities and land use in the area, including their historical development.

The DBM is prepared on the basis of interpretation of data collected from a wide range of sources [11].

1.4 Information Flow and Integration

The output from the Site Characterisation Project referenced in Section 1.1 was presented in a series of Status Reports [14, 15, 16]. The primary focus of these studies was to develop an understanding of geosphere characterisation. In this context, the studies developed a conceptual flow of information to explicitly represent the linkages between the various activities (data acquisition, interpretation, integration, etc.) to indicate, for each item of data that is acquired, how it is acquired, how it is progressively interpreted and how it is used for the development of discipline-related descriptive site sub-models. The diagram showing the various items of data, interpretation activities and uses of information and the various linkages between them is given the title of a “Site Investigation Flow Diagram” (SIFD).

Integrated SIFDs for the first three stages of site characterisation (desk study, regional surveys and the first drilling campaign), were developed and presented in [16]. These can be adapted to illustrate the information flow to construct a DBM (see Section 2.3 of this report).

Typically, assessments of the potential impacts arising from the disposal of radioactive wastes describe mechanical disturbance to the ecosystem (e.g. due to construction and operation of the disposal facility), hydrological impacts on the ecosystem (e.g. due to drawdown of the water table during construction and operation) and the transport and accumulation of radionuclides, and non-radiological contaminants, through the geosphere and in the biosphere. Significant changes to the biosphere may occur over the long timescales for which GDF performance is required to be considered. Therefore, biosphere characterisation needs to be undertaken with the requirements of subsequent impact assessment in mind.

1.5 Key Objectives

The overall aim for this project is to contribute to the establishment of a framework to produce a DBM and to identify the resources and technologies available to process site characterisation data in a systematic way. As described in Section 1.1, a progressive approach to site characterisation is anticipated through MRWS Stages 4 to 6. Although not exclusively, the current project is focused mainly on the requirements at MRWS Stage 5 (surface investigations).

Based on the Contract Technical Specification [17] the specific objectives of this report are to provide RWMD with an authoritative account for the biosphere discipline of:
The processes and tools that have been used on international radioactive waste management programmes for processing, interpreting and modelling biosphere data acquired through site characterisation;

Any additional processes and tools that are used in other sectors for processing, interpreting and modelling biosphere data acquired through site characterisation that may be applicable to a UK-based waste management site characterisation programme;

The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in support of the UK characterisation programme;

The extent to which the required resources may vary in response to variations in the geological environment at the site(s) in the UK that are being characterised; and

The identification of any gaps in available resources to support a UK-based site characterisation programme.

In addition, key conclusions and recommendations are presented with respect to site-specific characterisation and modelling techniques which may be appropriate in the UK.

1.6 Scope of Work

The primary focus of this review is approaches to the interpretation and translation of environmental data to support the development of site descriptions as part of site characterisation programmes [17]. The link to subsequent assessments has also been considered.

Along with approaches proposed or adopted in the UK, the review presented here describes the various methodologies, tools and techniques that have been employed in the development of the biosphere elements of SDMs for radioactive waste disposal programmes in a number of countries. The review has extended to work undertaken by national radioactive waste disposal bodies, associated academic studies and other research available in the scientific literature. The other national programmes that have been reviewed are those of:

- Canada
- Finland
- France
- Germany
- Sweden
- Switzerland
- United States

These reviews are not comprehensive, but are considered to be sufficient to draw conclusions on approaches adopted elsewhere, which are of relevance to the UK position. In their generic Disposal System Safety Case (DSSC) [18], the NDA has identified three illustrative geological disposal concepts for different host rocks. These are summarised below (from [19]).

- Higher strength rocks (crystalline igneous and metamorphic rocks or geologically older sedimentary rocks).
Lower strength sedimentary rocks (geologically younger sedimentary rocks).
- Evaporites (anhydrite, halite or other evaporates).

Overlying strata may comprise a variable sedimentary sequence or may not be present at all in the case of higher strength rock types extending to the surface.

The use of generic geological settings does not imply that any specific sites are being considered. The host rock descriptions correspond to three distinct general rock types that are considered potentially suitable to host a disposal facility for higher activity wastes, based on studies carried out in the UK and internationally, and which occur in the UK.

These illustrative geological disposal concepts are described in the GDF Design Report [20].

This review has also investigated methodologies, tools and techniques employed in other sectors of industry which potentially generate contaminated discharges and require environmental impact assessments and which may provide additional techniques applicable to a UK-based radioactive waste management site characterisation programme. The sectors considered in this study are:

- Mining (including Uranium tailings);
- Dams (and other major civil engineering works involving significant excavation and environmental impact);
- Oil and gas;
- Carbon capture/sequestration;
- Conventional waste disposal (landfill);
- Environmental clean-up.

Information of relevance has also been considered from the fields of academic applied research and food quality, as well as non-sector-specific information (such as other reviews of international approaches).

As defined in the previous Site Characterisation Project reports [14, 15, 16], this report addresses primarily the Stage 0 (desk study) and Stage 1.1 (regional survey) data acquisition and interpretation, appropriate to MWRS Stage 4 and Stage 5, although some reference is made to the Stage 1.2 (site specific intrusive investigations) appropriate to MRWS Stage 6.

1.7 Methodology

Information evaluated within this report has been obtained from publicly available sources (such as published literature and conference proceedings), from organisation websites, from academic material (both published literature and internet based), from key word searches of the internet and from approaches to individual organisations to request additional information either on specific topics or more generally (for instance, internal reports which are unrestricted and can be cited).

Information obtained has been summarised to represent the activities and programmes undertaken in other countries or in other disciplines and has been evaluated in the context of developing a site characterisation programme appropriate to UK requirements.
1.8 Structure of this report

This report is structured in 9 sections, which address a number of key areas, as follows:

- Section 1 (this section) provides an introduction to the topic and scope;
- Section 2 identifies the broad components of the biosphere;
- Section 3 identifies the strategic approach to interpretation and modelling of information in a site-specific context;
- Section 4 provides an overview of UK and international guidance on site-specific factors relevant to site characterisation;
- Section 5 reviews approaches adopted by UK and international agencies tasked with radioactive waste management and disposal;
- Section 6 summarises approaches which have been adopted in other sectors (such as the extractive industries, conventional waste disposal and land remediation);
- Section 7 summarises specific tools available, particularly for data processing and interpretation;
- Section 8 identifies the vulnerability of resources (such as the use of specialist software and continued maintenance or availability) which might influence the adoption of specific approaches;
- Finally, Section 9 summarises the core observations and recommendations arising.
2  DESCIBING THE BIOSPHERE

It is important that the biosphere be identified in as site-specific a manner as possible so that credible narratives for future biosphere states can be developed in a way that will support post-closure risk assessments (though the specification of post-closure risk assessment activities relevant to defining future states of the biosphere lies outside the scope of this report).

2.1  Components of the Biosphere

The biosphere can be described in short-hand as the 'living' part of the environment [21]. Nonetheless, as SKB [22] has noted, building an understanding of the biosphere requires characterisation of both the living (biotic) and the non-living (abiotic) components and of the interactions within and between these components. For example, abiotic factors such as climate determine the range of viable ecosystems, while biotic factors will, in turn, influence abiotic factors such as evapotranspiration.

In general, the biosphere is taken to comprise the atmosphere, surface and near-surface environment, including any near-surface aquifers, together with the organisms living therein. Root penetration may extend several tens of metres below the soil surface. Microbial activity may extend several hundred to a few thousand metres below surface. Whilst deep microbial action may be regarded as a feature of the geosphere (see for example the discussion put forward by SKB [23] identifying microbial activity as part of the far-field hydrogeochemistry), or even of the immediate disposal facility near-field, the term ‘near-surface’ to define the biosphere must be interpreted with considerable caution, depending on the characteristics of interest within a local setting.

The biosphere acts as the receptor for any contaminants that may be released from the geosphere, defines their distribution in the environment, and is where key end points relating to the effectiveness of the disposal system are determined. These endpoints include potential environmental concentrations and potential exposures of humans and other organisms. In particular, in assessment modelling, the transport of radionuclides through the biosphere is represented so that concentrations in environmental media (e.g. soil or surface water) can be estimated. In turn, these concentrations are used to estimate the radiation exposures of humans (focusing on the potentially most exposed group within the population) and of non-human biota. The biosphere therefore provides a context for determining the consequences of potential releases of radionuclides and other contaminants from the deeper disposal system.

An illustration of the main components of the terrestrial biosphere within a lowland temperate climate region is provided in Figure 4 (from [24]).

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6 The IAEA (2011, para 2.2) cited here, defines the biosphere as that part of the environment that is normally inhabited by living organisms, and further defines the 'accessible biosphere' to identify those elements of the environment, including groundwater, surface water and marine resources, that are used by people or accessible to people.
Note: This schematic representation is not intended to provide an exhaustive description of all potential biosphere types and components (see text). From [24]

This is not intended to be exhaustive and many additional features may be relevant in a local context, particularly with respect to transitional states (e.g. brackish water or estuarine conditions, mires and other wetlands), uplands, moors and other ecologically important (and often sensitive) environments as well as a range of agricultural and non-agricultural land uses and practices.

In the context of a radionuclide-specific review, relevant to deep geological disposal, the international BIOPROTA programme identified the following as potentially relevant components of the biosphere requiring characterisation [25]. This list is not necessarily exhaustive.

- Bioturbation
- Capillary rise
- Extent of canopy cover
- Cropping losses (plants and animals), including losses due to ingestion
- Rates of decomposition and mass of decomposition products
- Erosion
- Fertiliser addition
- Precipitation and infiltration
- Presence of micro-organisms and fungi
- Soil organic content
- pH
- Redox potential
- Soil hydrology
- Weathering processes
With respect to biota, additional considerations relevant to site characterisation would include definition of the area of interest, identification of species and communities (including transient species and potential inward migration from adjacent areas), habitat types and observations regarding the potentially transitional nature of some ecosystems (for example sand dunes or heathland).

Specific ecosystem development is a function of many factors including Quaternary history, geological structure and geological succession, meteorological conditions, topography, soil type and human activity (see for example the discussion by Ikonen et al. [26] in the context of developing a BDM for a disposal facility at the Olkiluoto site in Finland). Moreover, the biosphere is not a static environment. Organisms are dependent on, and interact with, the geosphere (see below) and each other and are influenced by seasonal and longer-term climatic effects. Measures of biomass and bioproduction are only part of a complex picture of species distribution, biodiversity, population dynamics, habitat development and exploitation, seasonal habitation and life-cycle patterns of reproduction, distribution and niche occupancy.

A ‘snapshot’ approach to the biosphere can be an over-simplification. The wide range of potential environmental components and linked ecosystems will have implications for the type of data collected and the need to consider spatial and temporal variability, both during data collection and in subsequent site-descriptive modelling.

2.2 The Geosphere-Biosphere Interface

The approach to developing a SDM outlined in Figure 2, Section 1.2, emphasises the interactions between the component descriptive models. A clear understanding of these interactions needs to be developed in order to clarify the scope and boundaries for developing the DBM. In particular, the interactions between the biosphere and geosphere characterisation programmes need to be addressed and an interdisciplinary approach to characterisation activities will be required, both within each domain and across their boundaries. For example, the hydrogeology and hydrogeochemistry of the biosphere and geosphere are intimately related both within the biosphere and geosphere domains and across their boundary.

The Geosphere-Biosphere Interface Zone (GBIZ) represents the conceptual domain where processes in the upper geosphere (such as groundwater flow) become available to, or otherwise influence, the biosphere processes and vice versa (e.g. modifications to the chemistry of infiltrating meteoric water in the soil zone). The GBIZ is not a physical boundary and in defining site characteristics it is important not to introduce an artificial divide between features, events and processes within the geosphere and biosphere. The change from bedrock groundwater to the bioavailable region takes place continuously in the top bedrock, the overburden (including both mineral and organic soils, and the glacial till underlying superficial fluvial sediments) and aquatic sediments. However, it is appropriate to recognise that there is a conceptual region where the geosphere and biosphere meet and overlap. Approaches to modelling the GBIZ have been reviewed recently within the BIOPROTA programme [27].

Transport through the geosphere associated with groundwater flow can vary greatly, depending on whether flow is through porous or fractured media, contrasts in the hydraulic conductivity, variations in topography and other site-specific factors. In addition, groundwater-surface water interactions depend both on the nature of the surface water
body and of the bed sediments, which can act to modify the physical flow regime. In addition, the chemical properties of the sediment (e.g. the mineralogy and organic content) may provide a retardation barrier for the upward movement of groundwater and contaminants.

Gas generation and transport to the surface and subsequently to atmosphere may also be important.

Other characteristics of the deeper biosphere and upper geosphere which affect storage capacity and time to equilibrium include the soil/subsoil interface. The nature of the subsoil and its interaction with groundwater, subsurface gases and biological organisms will influence upward transfer of contaminants into the topsoil.

Thorne et al. [28] have summarised the complementary purposes of the geosphere and biosphere characterisation programmes in terms of both overlap and differentiation in emphasis.

“Both biosphere and geosphere characterisation activities are driven by the requirements of the various end users, including engineering design, environmental assessment, operational safety assessment and post-closure safety assessment. However, the strength of the relationship differs between the geosphere and the biosphere. Whereas geosphere characterisation is most closely related to engineering design and post-closure safety, biosphere characterisation is strongly related to environmental assessment, operational safety assessment and post-closure safety assessment.”

Problems with the treatment of the GBIZ are associated with defining the boundary conditions for both far-field and biosphere models and derivation of the source term for biosphere modelling from the far-field modelling. The GBIZ is not a separate modelling domain and the processes and events affecting the transport of radionuclides within the GBIZ should not be considered to be unidirectional; for example changes in land-use, originating in the biosphere domain, will also have an effect on the (upper) geosphere [29].

2.3 Information Flow

To achieve a site-specific description of the biosphere at a proposed location for a deep repository, a thorough investigation of the different functional entities (e.g. primary producers), and their properties (e.g. primary production), in the ecosystems is needed (as discussed by Lindborg et al. [30] in the context of developing a licence application for a deep repository for spent nuclear fuel on behalf of SKB). The characterization of the biosphere can primarily be made by identifying and describing important properties of different surface ecosystems, but also by providing information relating to climate and current and historical land use, as these are factors that affect today’s biosphere. Functions and processes other than those studied in the context of natural science (e.g. social structures and cultural heritage), are being increasingly recognized as integral features in landscape modelling, and are thus also important to consider when analysing landscape change, both in terms of development and preservation of land use and land status.

A Site Investigation and Information Flow Diagram (SIIFD) is presented in Figure 5 relevant to the development of a DBM.
Figure 5. Site Investigation and Information Flow Diagram Relevant to the Development of a Descriptive Biosphere Model
The information flow presented in Figure 5 is similar to that previously proposed by Nirex [31] and adapted by Thorne et al. [28] in a review of biosphere characterisation studies. However, the Nirex information flow diagram emphasised the end use of the DBM for radiological and environmental impact assessments.

2.4 Site Description and Interpretation

The development of the SDM, and of the component descriptive models, is not a simple factual description of the characteristics of the site at the time of the investigation programme. It will require the input and interpretation of modelling studies, for instance in the case of the DBM input will be required from hydrological and hydrogeochemical models, to develop an overall, consistent understanding of the site, to identify and understand anomalies in data and to identify priorities for further data collection. In turn, this requires the development of at least conceptual models of some components of the biosphere and an interpretation of conditions adapted to meet the needs (or at least to show cognizance of the needs) of information end users.

In addition to a description of current conditions, it is essential that the biosphere model adopted is suitable to quantify processes affecting, for example, turnover of organic matter in catchment areas. By placing an emphasis on the fluxes of matter and energy, the ecological and physical constraints on a system can be shown to reduce the potential range of future states of the ecosystem, hence reducing uncertainties in estimating radionuclide flow and in turn radiological consequences to humans and the environment.

2.5 Integrated Biosphere Approach

It is important to use a modelling approach that is not limited to a single ecosystem, but includes the totality of ecosystems local to the site, and it is necessary to identify the mechanisms and dynamics of transfers within and between specific ecosystems or sub-ecosystems in order to form an understanding of long-term sustainability.

The aim of this report is to present a strategy to describe, interconnect and model surface ecosystems, including their functions and processes, at a currently unspecified site for a geological disposal facility for higher activity wastes. To study the fluxes of matter within and between surface systems, the biosphere at any given site can be distinguished into three broad ecosystems: terrestrial, surface water (including streams, rivers and lakes) and estuarine-coastal-marine systems, as outlined in Figure 6.
This illustration has been developed and substantially modified from an original presented by SKB (Figure 4 from [30]).

In practice many sub-ecosystems can also be identified. For example, terrestrial ecosystems may be characterised as forest, scrubland, heath or agricultural land. Surface waters may be characterised as lakes, ponds and rivers. Marine systems may be characterised as coastal waters and open seas. In addition, many transitional or successional states may be recognised such as estuaries, coastal dunes, mires and moorlands.

Each system or sub-system incorporated within the biosphere descriptive model should be defined to enable characterisation as a stand-alone element, with an intrinsic turnover of matter and energy, and with well-defined interfaces across which exchanges of matter and energy may occur with other systems.

At the current time, when no specific site has been identified for characterisation, a broad approach such as that outlined in Figure 6 above may be appropriate. As a specific site, or range of sites, is identified further sub-division of the broad ecosystem components will be required.

To describe a site at different spatial and temporal scales we need an array of discipline-specific descriptions and models, including those related to hydrology and hydrogeology, hydrogeochemistry, water exchange and radionuclide transport in a coastal region, human
activities and land use, carbon turnover and fluxes of organic matter, nutrients and various essential and non-essential trace elements.

2.6 Spatial Scale

Surface ecosystems can be defined in several different ways [32], but in practice it is typical to define them in terms of an area above bedrock [22]. This means that the ecosystem is delimited spatially rather than in terms of a given discipline.

With an integrated biosphere approach, based on spatially-distributed data and descriptive models, it is possible to understand the causes and consequences of spatial heterogeneity and how the heterogeneity varies both with scale and with the influence of management on natural and human-dominated ecosystems [30].

To describe a site at different spatial, and temporal, scales would require an array of discipline-specific descriptions and models. The site descriptive approach adopted by SKB identifies a number of fundamental units to determine spatial scale. For the terrestrial system, modelling was undertaken at the watershed scale [33]. Similarly, the use of lakes as a fundamental unit for lacustrine systems was determined by the possibility of monitoring lakes separately [34, 35]. For marine systems, the spatial scale may be more arbitrary. Wijnbladh et al. [36] describe an approach based on 20x20 m grid cells. Whilst potentially convenient this represents no obvious natural ecosystem boundary. Of itself, this is not a critical comment on the approach adopted; indeed, the grid resolution was applied to divide the area studied into 28 sub-basins based on the bathymetry of today and future drainage areas [37]. Model output was presented for the whole area and for the individual basins. Pools and fluxes of matter were summarised for each basin and coarse-grained mass balances were calculated per basin for a large number of elements. Nonetheless, whilst the concept of ‘fundamental units’ to describe ecosystems is apparently simple, and certainly appealing, there should be recognition that definition of such units has an inherent arbitrariness and the basis for defining spatial resolution needs to be described for any specific site investigation.

Awareness of spatial scale and spatial variability may be linked to temporal considerations (see section following). If the requirements of end users, for example linked to post-closure safety assessments, relate to a range of biosphere states or characteristics that might exist in the future, but which do not currently occur locally, the adoption of more extended regional coverage or the identification of more isolated discrete areas within a larger regional area might be appropriate.

It is also important to note that the biosphere region receiving the radionuclide flux may be located at some distance from the site of disposal. Hence, it may be necessary to characterise regions in the immediate vicinity of the disposal facility and further afield if geosphere considerations imply significant entry of radionuclides to these areas.

The considerations noted above emphasise the need for inter-disciplinary communication when developing each of the component parts of the integrated SDM.

2.7 Temporal Considerations

It is important to understand the features, events and processes leading to the current biosphere characteristics of a site, as well as determining in an objective and largely quantifiable fashion the prevailing characteristics. One of the purposes for understanding the processes that have historically influenced development of the site is the understanding of potential influences in the future and predicting most likely future environmental states.
Thorne et al. [28] have noted that different views exist on the degree to which projections of future environmental characteristics should be a component of the site characterisation programme. They observe that,

“In Sweden and Finland, site characterisation is restricted to interpretation of past and present characteristics, with the projection of future characteristics being a responsibility of safety assessment. In France, interpretation of past and present conditions, and projection of future conditions, is more closely integrated. However, the distinction is less significant than it appears at first sight. In all three programmes, data collection and interpretation are clearly and strongly determined by the applications in which the information will be used. Hence, in the Swedish and Finnish programmes there is a strong emphasis on characterising ecosystems and quantifying land uplift, whereas in the French programme the emphasis is on geomorphological studies and investigation of the hydrological and hydrogeological implications of landform evolution.”

Whilst true in general, SKB has also recognised the close relationship between the information in the SDM and its use for other purposes, notably post-closure safety assessment. Thus, SKB [37] notes that

“The site descriptive model is used by repository engineering to design the underground facility and to develop a repository layout adapted to the site. It is also essential for safety assessment, since the model is the only source for site-specific input. Another important use of the site descriptive model is in the environmental impact assessment.”

Given that, “processes and interactions between components in the biosphere … may be important in a safety assessment for radioactive waste disposal” [38], SKB goes on to note in their biosphere synthesis report [39],

“For the time frames of a deep geological repository, the effects of landscape development and ecosystem succession on transport, accumulation and exposure also need to be considered.”

However, SKB was also careful not to permit cross-over of purpose within the framework of SDM documentation. Assumptions about the future were carefully kept within the framework of scenario specification. Thus, again, SKB [37, p.14] states that,

"it is not the task of the site description to present any predictions of the future evolution of site conditions. This is completed within safety assessment based on the understanding of the current conditions and of the past evolution as compiled in the site description. It is also not the task of the site descriptive modelling to evaluate the impact on current site conditions of the excavation or the operation of a repository at the site. This is carried out within the framework of repository engineering and as part of the environmental impact assessment, but again based on input from the site description.”

By excluding predictions, which are always subject to uncertainty, the SDM can thus stand as a factual record of the historical development and current state of the site. Indeed, the extended interactions between SKB and the INSITE and OVERSITE expert site investigation review teams of the Swedish Radiation Safety Authority and its predecessors, SKI and SSI, effectively ensure that the SDM can form the prior and uncontested ground for subsequent safety assessments.
In the UK, both in the present programme and in previous studies conducted as part of the Nirex investigations in the 1990s [40, 41, 42, 43, 44, 45], site characterisation to develop a DBM emphasises the understanding of past and present characteristics and, for instance, includes a reconstruction of Late Quaternary history so as to inform geological and hydrogeological interpretations of the site.

As implied above, with respect to spatial scales to be considered, it is possible to characterise areas which provide valuable information for other end users, including those addressing potential future states, without necessarily introducing detailed causative mechanisms for such change within the DBM. Generally, the identification of causative mechanisms becomes of more importance when current site characteristics are to be projected into the future. At the same time, an understanding of causative mechanisms can be of relevance to the SDM. For example, climate is a major factor affecting the biodiversity [46]. Likewise, understanding climate history and land uplift it is possible to identify different types of groundwater arising at various epochs and thus to have a better basis for estimating the spatial extent of water bodies of these types at the present day than would arise simply by interpolating between sparse borehole samples.

2.8 Human Impacts on the Environment

Human activity impacts on the biosphere at many levels, which may have both a direct and an indirect influence on the transport of radionuclides into and through the environment. The biosphere may be held to have a cultural, as well as an environmental, importance and many archaeological features of interest impact on land use, or land-use restrictions.

In the short term, both past and present, the environment may be impacted most directly by agricultural practices and by industrialisation or urbanisation of an area. These affect habitat types and ranges, to the detriment of some species and habitats and to the benefit of others. Irrigation or drainage of land affects groundwater bodies and surface water flows, volumes and properties. Fertilisation may alter soil structure. Crop planting may affect depths of root penetration. In the UK, much of the environment has been influenced by cultivation and even areas that are not used for intensive agriculture are generally 'semi-natural' (i.e. reflecting low intensity grazing such as upland fell areas, commercial forestation, or coastal stabilisation measures including the establishment of groynes, dredging and saltmarsh planting). In such cases, removal of agricultural or other human influences may also have a dramatic impact on current site characteristics.

In the medium term, activities such as flood protection schemes may affect water balances, and exploitation of natural resources (such as fish or wildfowl) may affect population numbers and community composition. In the longer term, the indirect effects of greenhouse gas emissions may alter climate patterns at both local and global scales.

Site characterisation needs to address current conditions, but also needs to identify those components that have influenced and/or continue to influence the land use, or may contribute to site development in the longer term. The assumed or determined influence of human communities on the biosphere is important in describing the manner and degree of exploitation of environmental resources. Except in the narrowest sense of 'current', which at the extreme simply means the condition at the time assessed, it is important to recognise that human activity can bring significant changes within an ecosystem over the period likely to elapse during the planning, permitting and construction of any major infrastructure works (e.g. of the order of a decade or more).
Whilst predicting the future status of the site is outside the scope of SDM, human activity can result in very rapid changes to the site characteristics. Consequently, understanding past and present activities may indicate the range of states that could potentially exist at the site in the present day⁷.

⁷ Any programme of site investigations is open to the challenge that it may in itself change the area under investigation. Where relatively large-scale investigation is being undertaken (e.g. through the installation of deep drilling sites), accompanied by significant infrastructure investment (e.g. the provision of new or improved road links to those sites) and where the purpose of the investigation is well known (e.g. the potential for locating a repository at a site), changes to both land use and within the local community may be elicited due to the perceived benefits or deleterious effects of such a repository.
3 STRATEGIC APPROACH TO INTERPRETATION AND MODELLING

Site characterisation models build an understanding of the system. They are more complex than impact assessment models, which have necessarily to be simplified representations of the environment due to the large-scale and long-term nature of the assessments required to be undertaken. This extra complexity, and associated data collection, processing and modelling, is required in order to understand the physical and ecological aspects of the site. Indeed, it is likely that the characterisation of the biosphere at any specific site will require a programme addressing both seasonal and inter-annual variability and will therefore require several years.

In order to manage this scale and complexity, site characterisation should proceed in a structured way and iterative fashion, with interpretation and modelling contributing to a detailed understanding of the site. As Thorne et al. [28] have previously remarked

“Site characterisation as a whole and biosphere characterisation in particular are best undertaken within a staged framework. Data freezes permit effective reporting of the work at the end of each phase, but there is no requirement to halt the ongoing work during the interpretation and reporting of the information available at each data freeze.”

This is considered further in Section 3.2. Components of the system are likely to include:

- Meteorological conditions
- Geology
- Surface and near-surface hydrology (groundwater, surface water wells etc.)
- Soil type and composition
- Topography
- Land use
- Flora and fauna

The translation of detailed site characterisation models into simplified assessment models will tend to be easier to achieve for more physically structured aspects of the environment, like hydrology/hydrogeology, than for ecosystem/ecology aspects. Human activities (including but not limited to agriculture) are also likely to be of relevance, but are not necessarily the main focus of biosphere characterisation. Human activities, in this context, are addressed primarily for their influence upon the biosphere.

3.1 Acquisition and Interpretation of Site Data

Acquisition of data should focus on the purpose of the investigation and then identify the types of primary data that may be obtained that will enable this purpose to be achieved. An example of such a purpose is to establish groundwater flow patterns at the site. Relevant primary data can then be identified, for example, the use of borehole logging to establish water tables or pump testing to establish connectivity.

The spatial resolution of the data should be appropriate to the scale of the variability in the feature or process it is representing. A nearby meteorological station will provide adequate resolution of climate data (rainfall, temperature etc.) for the site, and it would, in general, be sufficient to characterise the general water flow pattern at the site over distances of the order of 100s of metres.

Thorne et al. [28] have noted that within the framework of the MRWS programme,
“site characterisation (including biosphere characterisation) may need to be carried out for several sites prior to site selection and then additional studies may need to be carried out at the selected site. However, as demonstrated in the SKB programme, it may be appropriate to carry through a comprehensive programme at more than one site prior to site selection. It must be recognised that the characterisation of the biosphere at a specific site will require a multi-year programme. Both overseas and UK experience indicates that a period of around seven years may be necessary. This involves an initial baseline survey (including a radiological survey), time-series monitoring (e.g. of meteorological and hydrological characteristics), and additional focused surveys on topics identified as important to the various users of the site characterisation data.”

Although the primary focus of this report is the interpretation and modelling of data that has been acquired within a site characterisation programme, it is recognised that historic data may also be used. Data sources referenced in Figure 5, Section 2.3, include many existing compilations to support the development of site descriptions as part of site characterisation programmes. The qualification of pre-existing data is an important issue, although it lies outside of the scope of this report. At the same time, the integration of pre-existing data with new data has to be addressed in compiling an SDM and it is recognised that part of a site investigation programme may include the acquisition of new survey data collected over a limited area, or at particular locations, on a systematic basis to resolve anomalies in the pre-existing data.

In the context of current investigations, controlled handling of data and workflow is crucial to guarantee the quality of data and subsequently any characterisation and model results. Primary data from site investigation work should be reviewed and approved by the person responsible for the activity producing it and stored in a database, with rigorous recording and checking procedures. Quality Control checks should be performed on all measurement techniques to ensure that they are functioning correctly.

3.2 An Iterative Approach to Biosphere Characterisation

Development of an SDM (and the biosphere component of the site model) may start with a conceptual description of the site and of the key components. Building up a more complete understanding may include a discipline-specific approach. For example, the biosphere component of the SKB SDM for Forsmark (Section 4 of [83]) presents discipline-specific information on:

- Regolith and Quaternary geology;
- Hydrology and near-surface hydrogeology;
- Hydrochemistry;
- Ecosystems;
- Human population and land use.

These discipline-specific descriptions are only weakly related to each other and do not require an overall system model. Modelling studies explore particular aspects of the surface system (hydrology and near-surface hydrogeology, nutrient cycling in ecosystems, use of hydrochemical data for interpretation of flow systems, solute transport). These modelling studies represent explorations of particular issues rather than being embedded in an overall system model. These discipline-specific studies are then brought together to
provide a conceptual and semi-quantitative description of the site that is then refined through additional measurement programmes and modelling studies.

As information becomes more complete, an overall system model may be advanced which then allows testing of additional information against current understanding of the site and an iterative process of refining data acquisition and interpretation can be adopted as outlined in Figure 7. In broad terms this consists of:

- Developing a conceptual site model (i.e. through breakdown of the biosphere/environment into functional units);
- Identifying features and processes present at the site and/or in the region;
- Developing an understanding of interactions between components of the environment;
- Measuring and parameterising those key components and the interactions between them;
- Reviewing and updating the conceptual model in the light of new information (i.e. explicitly recognising the iterative nature of characterisation and modelling)

This process, and, more particularly, the measurement and parameterisation of key components and their interactions then enables the development of a descriptive biosphere model.

**Figure 7. Illustrative Site Characterisation Programme**

> *For example, convert borehole transducer signal to units of water level.*

Depending on the level of prior knowledge, this illustration assumes that site characterisation begins with the construction of a conceptual description of the site. The acquisition of information naturally leads to a review and reappraisal of the conceptual description until a sufficiently detailed characterisation is reached for the purposes required.
It is important also to recognise that the biosphere region receiving the greatest radionuclide flux (or receiving the radionuclides of greatest potential environmental impact) may be at some distance from the site of disposal. Consequently, understanding transport mechanisms through the geosphere is a necessary step to ensuring that the biosphere regions of relevance are selected for characterisation.

3.3 Modelling of Site Data
The iterative nature of site characterisation means that it is important that any modelling to establish current characteristics can be reconstructed and traced back to the primary data. Thus, the data used in interpretation and modelling should be supplied from a controlled source, using tracking and versioning systems to ensure that the details of the data, assumptions and models are recorded.

Biosphere characterisation may result in wide range of parameter values for sites and is undertaken both to identify and parameterise key transfer processes and to identify relevant receptor groups. This includes potentially exposed human groups (arising from diet, habitation and other considerations) and non-human biota, which may form, on occasion, the most sensitive receptor.

3.4 Determining Confidence of Site Understanding
The level of confidence in site understanding is linked to the MRWS process (see Figure 1, especially with respect to stages 4, 5 and 6). The key questions can be identified as:

- When is it justified to move from desk- and surface-based investigations to subsurface intrusive investigations (which represent a considerable escalation in terms of cost and effort)?
- When has sufficient information been gathered to perform a safety assessment?
- What features in the biosphere are potentially limiting to the construction of a GDF?

The key is in the iterative nature of the characterisation process. A preliminary assessment is performed using a set of data, the important parameters are then identified, further data on these parameters are obtained and a refined assessment performed. Once the sensitivity of the results to the values of the important parameters has been explored and characterised then there can be confidence in site understanding. This has been explored in previous studies undertaken by, or on behalf of, the NDA, and is summarised in Figure 8 from a presentation made by the NDA.
There is no absolute basis on which to conclude that site characterisation is sufficient. Nonetheless, in the context of a radiological assessment for a prospective geological disposal facility, Posiva [47] has described a Knowledge Quality Assessment (KQA) process which has a broad applicability for biosphere characterisation. The process has been developed through a number of studies and a broad description is offered by Hjerpe [48].

The KQA is an iterative process. Its aim is to foster communication of assumptions and uncertainties. The different aspects covered by the KQA address the key issues:

- are the data fit for purpose?
- has data quality been checked?
- have all available data been used? and if not, why not?

The process offers a structured approach to addressing assumptions, uncertainties, sensitivity and consistency. These considerations are expanded upon below.

Main assumptions: their impact, potential for alternative interpretations.

Main uncertainties: uncertainties in the input data and those produced during the interpretation or modelling process, their causes, whether the uncertainties have been assessed, means to resolve and whether such resolution would improve the further assessment.

Sensitivity and data quality: how sensitive the models are to the input data, confidence in adequately high quality of the data and underlying process understanding.
Overall consistency: consistency within the biosphere description, with previous versions, relevant other models and science in general.

The Posiva approach includes recording data quality checks, ensuring transparency of process and allowing independent review of decision making.
4 UK AND INTERNATIONAL GUIDANCE ON SITE-SPECIFIC FACTORS RELEVANT TO SITE CHARACTERISATION

4.1 Setting the Scene

Within the MRWS process, site characterisation effectively begins at Stage 4. As stated in the White Paper (paras. 7.15 and 7.16):

‘Participating communities whose areas have not been screened out by sub-surface criteria and who wish to continue their involvement will be carried forward to the desk-based studies at Stage 4.

Stage 4 will involve the NDA’s delivery organisation undertaking more detailed assessments focusing on the suitability of a specific site or sites within each potential Host Community. These assessments will be mainly through desk-based studies, and will involve gathering information about the candidate communities and sites and evaluating them against the site selection criteria. The NDA’s delivery organisation will work with Community Siting Partnerships to ensure that local issues are addressed in the assessments. In parallel, Government anticipates that Partnerships will be discussing the package of measures that they would like to see implemented alongside a disposal facility to develop the community’s social and economic wellbeing.’

The process to be followed at Stage 4 has been addressed by the NDA [49] and identifies six key criteria for evaluation.

- Geological Setting
- Potential Impact on People
- Potential Impact on the Environment and Landscape
- Potential Beneficial and/or Adverse Effects on Local Socio-economic Conditions
- Requirements for Transport and Infrastructure Provision
- Cost, Timing and Ease of Implementation

In general, only pre-existing material will be used at this stage (although this does not necessarily preclude walkover ecological surveys, so that deficiencies in existing records can be remedied at a qualitative level).

Likely sources of information include OS maps, the soils maps of England and Wales, agricultural data held by MAFF at a parish level, data on locally designated land (SACs, SPAs, SSSIs etc.) and many other types of paper and electronic records. Generic land-use types representing differing geological and topographical conditions can be identified, and surface water and potential coastal influences can be considered. Therefore, by the end of Stage 4 a fairly detailed historical and current picture of the area and of potential sites within it will be available. Furthermore, the information will be spatially distributed and will require interpretation and presentation through appropriate software, e.g. in a GIS and through construction of a first-generation DEM. There will, of course, be substantial gaps, (e.g. in terms of local meteorology, unless there happens to be an existing meteorological station in the area), hydrology, hydrogeology and hydrogeochemistry. Nevertheless, the range and type of ecosystems should be well characterised and there should be no significant surprises in this discipline during Stages 5 and 6.
Quantitative field-based investigations will not be undertaken during Stage 4 of the MRWS, and the details of desk-based investigations at Stage 4 are not considered further in this report, except to note that the evaluation procedure will have to be applied consistently to all participating communities, so cannot accommodate differences in its specification, for example in the evaluation criteria to be applied, in response to individual community interests.

As the MRWS enters Stage 5 (surface investigations of areas remaining following the desk-based studies at Stage 4) a higher degree of resolution in defining ecosystems, and the inclusion of many more site-specific factors, is required. As site characterisation becomes more focused on specific areas, the accumulation of local information permits more subtle distinctions to be made at a particular site or between sites.

The White Paper (para. 7.18) states that:

“This stage will involve the NDA’s delivery organisation obtaining planning permission to undertake surface-based investigations at the remaining candidate site or sites, which would include non-intrusive seismic surveys and then later the drilling of boreholes to various depths to investigate local geology in more detail. Assuming planning permission were granted, the NDA’s delivery organisation would undertake the surface-based investigations, which could last a number of years, and carry out more detailed assessments of the sites in question. The NDA’s delivery organisation will work with Community Siting Partnerships to ensure that local issues are addressed in the assessments, and will evaluate sites against the criteria discussed below. As part of a staged authorisation process, it is envisaged that the NDA’s delivery organisation would require an authorisation from the environmental regulator before proceeding with the Stage 5 investigations.”

At Stage 5, specific sites within the area will be identified. However, because there is a need to characterise the range of ecosystems that could occur in discharge areas under current climatic conditions, this does not necessarily mean that the spatial scale of biosphere characterisation will be reduced. Thus, the range of ecosystems studied is likely to be similar to that at Stage 4. What will change is the detail with which those ecosystems can be studied. This will include quantitative studies and will likely allow detailed distinctions to be made at habitat, community and population levels. It is also at this stage that detailed hydrological, hydrogeological and hydrogeochemical studies can be undertaken. This will mean that water, energy, nutrient and trace-element balances can be compiled for various domains at this stage. Thus, at Stage 5 site-specific, quantitative biosphere models could be developed for EIA, operational safety and post-closure safety assessment purposes.

Biosphere characterisation work will continue through Stage 6 (undertaking underground operations). As stated in the White Paper (para. 7.21):

“Part of this work will involve the NDA’s delivery organisation undertaking long-term underground investigations. The aim of this work will be to confirm a site’s suitability to host a geological disposal facility that complies with safety and environmental regulatory requirements. This process will be subject to regulatory scrutiny and the NDA’s delivery organisation will have to submit specific assessments for review at agreed hold-points. If the site meets the regulatory requirements, the regulators will permit construction of a geological disposal facility to proceed at the preferred site.
Planning permission will be required for underground investigative work and construction of the geological disposal facility.”

Stage 6 thus becomes a time for refining those models, particularly the generation and interpretation of longer time-series of data, developed in Stage 5. For example, with longer time series of climatological and hydrological data, validation of distributed surface-water catchment models can be undertaken.

In principle the work undertaken during Stage 6 may be very intensive. However, it is anticipated that for the biosphere most of the site-specific information will have been gathered by the end of Stage 5 and Stage 6 will mainly involve collecting additional time-series data and monitoring the effects of underground construction (e.g. drawdown of the water table due to dewatering of the excavated facility) to augment information acquired at Stage 5.

4.2 UK Requirement for Site Characterisation

The regulatory guidance on requirements for authorisation for geological disposal facilities [50] makes clear that the developer/operator should establish an iterative approach to site investigation that uses results from site characterisation, modelling studies, design and construction to guide investigations. In particular,

“The developer/operator will need to show that the biosphere is characterised, understood and capable of analysis to the extent necessary to support the environmental safety case. This may involve consideration of, for example, topography, soils, surface water systems, flora and fauna distributions and human settlement patterns and activities. The investigation and characterisation of the biosphere should be sufficiently comprehensive to support calculations of dose during the period of authorisation and should be proportionate to the assumptions made in the environmental safety case for calculating risks after the period of authorisation.” (Para 6.4.8)

The specific link between site characterisation and establishment of the ESC is notable here, as is the implicit assumption that radiological dose calculations are a primary driver for information gathering. This is consistent with the approach adopted by SKB [22, p. 219], who state that,

“Knowledge of the area’s biota is a prerequisite for understanding and calculating the dispersal and accumulation of radionuclides in the ecosystems and in human food. Information on and monitoring of biota provide a foundation for being able to evaluate changes in the ecosystems.

The discipline [of ecosystem/biosphere characterisation] describes water conditions in lakes, seas and running waters. These parameters provide an understanding of processes in limnic and marine ecosystems (e.g. sedimentation, water currents and particle concentration) and furthermore interface with other disciplines. In dose calculations in the safety assessment, this knowledge is essential for calculating dispersal and dilution of radionuclides within the ecosystem.”

As discussed, long-term radiological dose assessments are not the only potential end use for information obtained in the DBM, but they are an important consideration within the regulatory framework.
The iterative approach to information gathering indicated above applies across the range of disciplines required to construct a SDM. In addition, possible cross-overs in impacts of separate characterisation activities should be considered. For example, biosphere characterisation and intrusive geological investigations will be undertaken in parallel during Stage 5 of the MRWS. Ideally, prior to installation of a drilling rig, a specific biosphere characterisation of the area should be conducted to inform an approach to drilling that minimises unnecessary disturbance of the site and to assess any implications that residual disturbance might have for the environmental safety case.

4.3 **International Guidance on Site Characterisation**

International standards have been developed that are applicable to geological disposal [51, 52] consistent with the basic safety standards for radiological protection [53]. The ICRP has also produced general recommendations and guidance [54, 55, 56] on disposal of solid radioactive waste, including geological disposal. Key international programmes contributing to an understanding of site characterisation requirements are reviewed below.

4.3.1 **European Commission**

The European Commission (EC) has produced guidance which sets out basic requirements for site characterisation and environmental impact assessment and for the development of geological repositories for radioactive waste [57]. Much of this guidance is rather generic in nature, but does emphasise the role of social, cultural and archaeological heritage, and that the built environment as well as the natural/semi-natural environment is of concern.

Regardless of the precise method for site selection adopted, the siting process will generally be organised in the following four stages:

- Concept and planning;
- National and area survey;
- Site characterisation;
- Site confirmation.

The initial site characterisation is distinguished by the collection of site-specific geological, hydrogeological and other environmental data, as well as by the results of research work on the performance of the engineered elements of a GDF at that location. This phase involves detailed (usually surface based) site-specific geological investigations.

It is worth noting that surface-based geological investigations fall into two categories: non-invasive (such as aeromagnetic and seismic surveys) and invasive (boreholes and associated logging and sampling). In practice, non-invasive surveys require calibration and ground-truthing through invasive work, so initial site investigation cannot be considered to be non-invasive, except in the earliest stages. Thus, site confirmation will normally involve detailed site investigations undertaken underground, with the aim of confirming that the assumptions made in developing the preliminary performance and environmental impact assessment for that site are likely to be valid.

Data requirements for site characterisation may include the following factors:

- Geological setting and geodynamic phenomena (i.e. seismic events, as well as potential intrusive and extrusive volcanism);
• Hydrogeology;
• Geochemistry;
• Use of natural resources at the site including minerals;
• Construction and engineering conditions;
• Implications for transport of wastes;
• Impacts on landscape, including impacts on plant and animal life;
• Implications for archaeological and cultural heritage;
• Current land use;
• Social impacts including impacts on population distribution, community services and infrastructure, impact on the economy and on employment.

A website has recently been developed under the EU 7th framework MoDeRn programme\(^8\) to provide “a reference framework for the development and possible implementation of monitoring activities and associated stakeholder engagement during relevant phases of the radioactive waste disposal process, i.e. during site characterisation, construction, operation and staged closure, as well as a post-closure institutional control phase”. However, to date, the available project reports do not appear to reflect activities during the site characterisation phase.

4.3.2 BIOPROTA

The links between site characterisation and the biosphere component of the assessment, including guidance on protocols for obtaining data, have been considered in the BIOPROTA Theme 3 (Site Characterisation, Experiments and Monitoring) report [25]. Experience with characterisation at particular sites is now being gathered from those who have done the work, in terms of recognition of difficult areas as well as successes. Information is being shared on how the obtained data are presented and interpreted, for the purpose of demonstrating an understanding of the site, and for use in developing scenarios for possible site evolution, and for evaluation of those scenarios via conceptual and mathematical models for site behaviour. These models can then be used to justify assumptions for assessment models that address radionuclide migration and accumulation in the biosphere and radiation exposure of humans and other biota.

The BIOPROTA report [24] states that; “taking into account site-specific data often enables the reduction of uncertainties in impact calculations”. Nevertheless, citing Sheppard [58], it is noted that site-specific transfer parameter values should not be used to the exclusion of other available data because transfer parameters are inherently variable and using a few site-specific data, which may not give a comprehensive description of the site, to the exclusion of all other data may decrease accuracy. This means that although the SDM will clearly take account of site-specific data, it should also, in producing a coherent and comprehensive description, rely on more broadly based data. These may be of very different types, e.g. compilations of transfer factor values to set site-specific values in

\(^8\) http://www.modern-fp7.eu/home/
context or information on the advance and retreat of ice sheets to aid interpretation of the local lithostratigraphy.

BIOPROTA [24] summarised biosphere site characterisation requirements as laid out in Table 1.

Table 1 Summary of BIOPROTA identified requirements for biosphere characterisation

<table>
<thead>
<tr>
<th>Component</th>
<th>Importance to Performance Assessment calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate and Atmosphere</td>
<td>Precipitation and temperature measurements are of primary importance and are required in order to calculate the water balance of the biosphere on a large scale, but also at a detailed scale to determine the soil water balance. Temperature and solar radiation may also have a bearing on agricultural practices and human activities. Given the long-term nature of potential impacts from deep disposal, it is generally considered desirable to analyse long-term time series data. Temporal variability has general relevance to the adequate characterisation of various natural events which may occur on a series of different timescales. Spatial variability may have relevance where the existence of microclimates is a possibility.</td>
</tr>
<tr>
<td>Near-surface lithostratigraphy</td>
<td>The characterisation of soil types, including texture and composition, are important factors in contributing to the development of hydrogeological models and in the consideration of future land-uses. Characterisation of the near-surface geology is also key; in particular, characterisation of the geometry, structure, composition and hydrogeologically significant structures and their properties is crucial to being able to determine model boundaries, processes and parameters. Characterisation of the geosphere-biosphere interface zone (GBIZ) is another area of crucial importance.</td>
</tr>
<tr>
<td>Topography(a)</td>
<td>Topography is considered to be of primary importance in determining the extent of surface water catchments and the potential locations of surface water features and groundwater discharges. The development of a digital elevation model (DEM) is advantageous in capturing the required topographic influences and is also a useful data source for other aspects of biosphere characterisation (e.g. geology, hydrology).</td>
</tr>
<tr>
<td>Water bodies</td>
<td>Contaminant concentrations within water bodies are important as such water bodies are often a source of water used for drinking and irrigation, and may also be a source of freshwater or marine foodstuffs. The location of water bodies may have topographic controls and may also be related to the location of the GBIZ. Chemical characterisation of the water bodies is important in supporting the development of hydrological and hydrogeological models, determining radionuclide transport and bioaccumulation parameters and other indicators.</td>
</tr>
<tr>
<td>Biota (Flora and Fauna)</td>
<td>Characterisation should be adequate to describe the current site conditions and land use, and to allow the development of models to describe the accumulation of radionuclides within flora and fauna.</td>
</tr>
<tr>
<td>Human community</td>
<td>Not considered within BIOPROTA however, some characteristics of human behaviour are relevant to biosphere characterisation (e.g. land use).</td>
</tr>
</tbody>
</table>
SKB [22] note that an area’s topography and stratigraphic sequences are important for the near-surface hydrological models that describe the dispersal of radionuclides at the surface. The stratigraphic sequence provides information on the large-scale processes that have occurred in the area, which is important as a starting point for projections of possible future changes in the area [59].

In addition to the more physical descriptions (topography, hydrogeology, soil composition etc.) and species listings (flora and fauna) consideration of habitat type and biota assemblages (from biome to local communities) will also be required.

BIOPROTA [24] also identify a sequence in data acquisition, related to the stage of site development. Prior to the initial site identification phase, the emphasis is necessarily on generic information. During site selection, where multiple sites may be compared and evaluated, an emphasis on equivalence of databases is required, ensuring that comparisons are made without avoidable bias. Following site selection and during design optimisation, a focus on site specific information will be required.

4.3.3 BIOMASS / BioMoSa

The IAEA BIOMASS (Biosphere Modelling and Assessment methods [60]) and EU BioMoSa (BIOsphere MOdels for Safety Assessment of radioactive waste disposal [61]) programmes developed a number of methodologies for recording and justifying decisions. This includes the identification of ‘reference biospheres’ (a generic set of features which allows current site characteristics to be linked to a range of potential future states) and predictive models.

The reference biospheres developed within the IAEA BIOMASS programme are deliberately simple. BIOMASS was primarily concerned with the development of reference biospheres for post-closure radiological assessment purposes [60]. These are simplified abstractions that are developed within a particular assessment context. The assessment context may range from a generic initial study to demonstrate the potential acceptability of a broadly defined disposal option through to a detailed safety assessment provided in the context of a request for permission to construct or operate a disposal facility (see Section A2.3.1 of [60]). The BIOMASS methodology assumes the site description as part of the assessment context. Thus, it is a post-closure assessment methodology that makes use of an SDM (if available) and is not a methodology for construction of a SDM. Nonetheless, reference features within the biospheres are summarised in Table 2 below (from Tables CII, GII, SII, TII, WI, BI and II of [60]) as they provide a potentially useful indication of the range of information anticipated from a DBM.
### Table 2  Summary of BIOMASS identified requirements for biosphere characterisation

<table>
<thead>
<tr>
<th>Biosphere Component</th>
<th>Primary Characteristic</th>
<th>Measurable parameters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>Climate Characteristics</td>
<td>• Temperature&lt;br&gt;• Precipitation (Rainfall/Snowfall/Occult)&lt;br&gt;• Pressure&lt;br&gt;• Wind speed and direction&lt;br&gt;• Solar radiation (hours of sunshine)&lt;br&gt;• e.g. Diurnal, Seasonal, Inter-annual, Decadal etc.&lt;br&gt;• Latitudinal&lt;br&gt;• Longitudinal&lt;br&gt;• Altitudinal&lt;br&gt;• Aspect-related</td>
<td>Precipitation (rainfall/snowfall/occult) and temperature measurements are of primary importance and are required in order to calculate the water balance of the biosphere on a large scale, but also at a detailed scale to determine the soil water balance. Temperature and solar radiation (e.g. sunshine hours) may also have a bearing on agricultural practices and human activities. Temporal variability (whether diurnal, seasonal, annual or longer-term trend analysis) has general relevance to the adequate characterisation of various natural events which may occur on a series of different timescales. Spatial variability (including topographic or altitude related variability) may have relevance where the existence of microclimates is a possibility.</td>
</tr>
<tr>
<td></td>
<td>Temporal Variability</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spatial Variability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geology</td>
<td>Lithostratigraphy&lt;br&gt;Fracture systems&lt;br&gt;Weathering&lt;br&gt;Erodability&lt;br&gt;Mineralogy</td>
<td>• Vertical and horizontal variation</td>
<td>Characterisation of the near-surface geology is key to developing models to estimate potential impact in Performance Assessment calculations.</td>
</tr>
<tr>
<td>Soil and Sediment</td>
<td>Stratification&lt;br&gt;Composition&lt;br&gt;Texture&lt;br&gt;Fracture system&lt;br&gt;Areal variation&lt;br&gt;Weathering</td>
<td>• Horizons&lt;br&gt;• Organic content, mineralogy</td>
<td>The characterisation of soil types, including texture and composition, is an important factor in contributing to the development of hydrogeological models and also in the consideration of future land-uses. Soil types also are important in determining the sorption of radionuclides on soils and hence the partitioning between solid and dissolved phases. They also influence the uptake of radionuclides by plants.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Biosphere Component</th>
<th>Primary Characteristic</th>
<th>Measurable parameters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography</td>
<td>Altitude</td>
<td>Level</td>
<td>Topography is considered to be of primary importance in determining the extent of surface-water catchments and the potential locations of surface-water features and groundwater discharges.</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>Position</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Erodability</td>
<td>Variation (global, local)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deposition rates</td>
<td>Basal characteristics e.g. permanent / ephemeral</td>
<td></td>
</tr>
<tr>
<td>Water Bodies</td>
<td>Geometry</td>
<td>Level</td>
<td>Identification of types of surface water (streams/rivers, lakes, coastal margin etc.), extent of groundwater (presence of different aquifers etc.), proximity of natural or artificial points of upwelling (e.g. wells).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Position</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Variation (global, local)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flow rate variation</td>
<td>Basal characteristics e.g. permanent / ephemeral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suspended Sediments</td>
<td>Load</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Freezing/Thaw Phenomena</td>
<td>Water body and ground freezing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrochemistry</td>
<td>Seasonal and long-term (permafrost, ice lens etc.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pH and Eh</td>
<td>Snowpack development</td>
<td></td>
</tr>
<tr>
<td>Terrestrial and</td>
<td>Net Primary Productivity</td>
<td>Major / minor anions and cations</td>
<td>Agricultural activities are of more prominence with respect to human exposure scenarios, but also harbour natural populations of relevance to non-human biota assessments. Characteristics of note include crop types and yields and animal produce. Since crops can be subject to rotational or other variability across years, characterisation should be based on past situations and likely future trends. Natural or semi-natural systems include basic descriptors (forest, shrub, moor, grassland etc.), and dependencies (e.g. land management such as drainage) or transitional status (e.g. previously cultivated land).</td>
</tr>
<tr>
<td>Aquatic Ecosystems</td>
<td></td>
<td>Organic compounds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Net Secondary Productivity</td>
<td>Colloids</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biomass / Standing Crop</td>
<td>pH and Eh</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rate at which organic material is created by photosynthesis after accounting for respiration per unit area per unit time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Net productivity of heterotrophic organisms – animals and saprobes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry weight per unit area</td>
<td></td>
</tr>
<tr>
<td>Biosphere Component</td>
<td>Primary Characteristic</td>
<td>Measurable parameters</td>
<td>Comments</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------------------</td>
<td>-----------------------</td>
<td>----------</td>
</tr>
<tr>
<td></td>
<td>Cropping</td>
<td>• Rate of removal by humans</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Population dynamics</td>
<td>• Physical structure, interception of light, water, aerosols, vapours and gases</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vegetation canopies</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plant roots</td>
<td>• Structure and distribution with depth; absorption of nutrients and water with depth</td>
<td>Fauna and flora are a primary endpoint for biosphere studies as well as intermediaries in routes through to man. Adequate characterisation is not limited to species lists and/or biodiversity measures but needs to explore population dynamics (e.g. migration and the role of transient populations as well as food web interactions). Biomass distribution (e.g. plant root distribution) can determine availability for radionuclide uptake.</td>
</tr>
<tr>
<td></td>
<td>Animal diets</td>
<td>• Composition and quantity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Animal behavioural characteristics</td>
<td>• The part of the ecosystem in which an animal forages and the time it spends foraging in different parts of the ecosystem</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chemical composition and chemical cycles</td>
<td>• Sources and sinks for major and minor nutrients and trace elements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chemical composition</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chemical cycles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Community</td>
<td>Population</td>
<td>• Age distribution</td>
<td>The local community is relevant both with respect to establishing actual or potential exposure groups and impact on the biosphere.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Density</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Diet</td>
<td></td>
</tr>
</tbody>
</table>
SKB [22] appear to have adopted a similar reference framework to develop a checklist of parameters to model surface ecosystems during the site investigation and detailed characterisation stages. They identified the following summarised components and characteristics.

- **Geology** Topography, Land uplift, Soil layers, Exposed rock
- **Hydrogeology (groundwater)** Recharge/discharge areas, Soil water and groundwater levels, Wells
- **Hydrogeology (surface water including seas)** Bottom topography, Water level, Water turnover, Volumes and salinity
- **Hydrogeology (Meteorology)** Precipitation, Runoff, Evapotranspiration
- **Hydrogeochemistry (soils and sediments)** Nutrients and major elements, Trace substances, Radionuclides, Toxic organic pollutants, Water content, Redox zone, pH, Salinity
- **Ecosystems (forest and agriculture)** Productivity, Age structure (forests), Animal husbandry (agriculture), Meat production

In addition, BIOMASS [60] identified key human activities having a primary influence on the reference biosphere components, and these are summarised in Table 3.

### Table 3  Summary of BIOMASS human activities influencing the biosphere

<table>
<thead>
<tr>
<th>Biosphere System Components</th>
<th>Human Influence on Biosphere System Components</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climate Atmosphere</strong></td>
<td>Change composition of the atmosphere (local, global scale)</td>
</tr>
<tr>
<td></td>
<td>Create a local microclimate</td>
</tr>
<tr>
<td></td>
<td>Controlled ventilation of buildings</td>
</tr>
<tr>
<td><strong>Geological Media</strong></td>
<td>Quarrying</td>
</tr>
<tr>
<td></td>
<td>Mining</td>
</tr>
<tr>
<td><strong>Soils / Sediments</strong></td>
<td>Homogenisation (ploughing / tilling)</td>
</tr>
<tr>
<td></td>
<td>Change composition (soil improvement and fertilisation, including crop residues and animal waste)</td>
</tr>
<tr>
<td></td>
<td>Transport/transformation (dredging and disposal of sediment)</td>
</tr>
<tr>
<td></td>
<td>Impermeable surfaces / artificial drainage</td>
</tr>
<tr>
<td><strong>Topography</strong></td>
<td>Alteration of erosion rates</td>
</tr>
<tr>
<td><strong>Water Bodies</strong></td>
<td>Change the physical shape and flows (damming)</td>
</tr>
<tr>
<td></td>
<td>Change the effective volume/level (artificial mixing, water abstraction)</td>
</tr>
<tr>
<td></td>
<td>Transport of water (pumping and distribution of water)</td>
</tr>
<tr>
<td></td>
<td>Change the composition (waste water discharge)</td>
</tr>
<tr>
<td><strong>Natural and Semi-Natural Ecosystems (Terrestrial &amp; Aquatic)</strong></td>
<td>Fire control (e.g. periodic burning / firebreaks)</td>
</tr>
<tr>
<td></td>
<td>Pest / weed control</td>
</tr>
<tr>
<td></td>
<td>Use for grazing</td>
</tr>
<tr>
<td></td>
<td>Hunting / fishing</td>
</tr>
<tr>
<td><strong>Managed Ecosystems (Terrestrial &amp; Aquatic)</strong></td>
<td>Planting</td>
</tr>
<tr>
<td></td>
<td>Irrigation</td>
</tr>
<tr>
<td></td>
<td>Cropping</td>
</tr>
<tr>
<td></td>
<td>Husbandry practices (e.g. seasonal relocation)</td>
</tr>
<tr>
<td></td>
<td>Feeding and watering</td>
</tr>
</tbody>
</table>

The EU BioMoSa project set out to implement the reference biosphere methodology developed in the IAEA BIOMASS programme. The study focused on the development and application of a generic biosphere tool BIOGEM (BIOsphere GEneric Model) and a comparison between BIOGEM and five site-specific biosphere models [62]. BioMoSa did
not develop new reference biospheres, but did develop databases relevant to generic modelling of reference biospheres.

4.3.4 BIOCLIM

In the longer term, changes in environmental conditions, such as sea-level rise and climate change will be relevant where post-closure ESCs are to be developed. This is not the main purpose of the SDM, but it is relevant to note that the aim of the EU BIOCLIM project was to provide a scientific basis and practical methodology for assessing the potential impacts of long-term climate change on biosphere characteristics (see, for example, [63]). Such long-term factors need to be taken into account when developing SDMs, in order to ensure that FEPs referenced within the current site description will provide a suitable base for the requirements of future safety assessments.

Work Package 4 of the BIOCLIM project [64] addressed biosphere system descriptions in terms of model requirements, in order to develop a methodology to demonstrate how biosphere systems can be represented in the long-term.

The main innovation in the methodology was the development of a method to characterize key aspects of landscape development in transitions between different future climate states. This is of little direct relevance to SDM development, although the past presence of transitional states, and the historical factors leading to their development, may be an important feature of the BDM.
5 REVIEW OF NATIONAL APPROACHES TO THE INTERPRETATION AND MODELLING OF DATA TO SUPPORT THE DEVELOPMENT OF A SITE DESCRIPTIVE MODEL FOR THE BIOSPHERE

5.1 Introduction

Worldwide, there is general agreement that the only viable long-term strategy for the storage and/or disposal of higher level, long lived radioactive wastes is in deep geological formations. Current activities in most countries are focused on the development of strategies for site selection, the development of GDF near-field engineering solutions (packaging, geological and man-made barriers etc.) and safety assessment of geological repositories. Several countries have constructed underground test and research facilities (e.g. Sweden, Finland, France). However, to date only the USA has an operating deep geological repository, the Waste Isolation Pilot Plant (WIPP), and this does not accept high level waste or spent fuel from the civil nuclear power industry. Deep geological disposal is also proposed for low and intermediate level waste at the Bruce site in Canada, and the safety case has been reviewed recently within the BIOPROTA programme ([27], see section 2.2) as part of a broader review of approaches to modelling the geosphere-biosphere interface zone.

5.2 UK

Work on deep geological disposal of radioactive waste in the UK is undertaken by the NDA. Formerly this work was undertaken by UK Nirex Ltd (Nirex). The functions of Nirex are now incorporated into the NDA, especially within the RWMD of NDA, which has the responsibility for implementing geological disposal (see Section 1.1). Work undertaken previously for Nirex is available from the NDA. The development of a strategy for deep geological disposal builds on earlier studies by Nirex and continuing generic work by the NDA [e.g. 11, 28, 65]. As of early-2013, no candidate site for a deep geological disposal facility has been identified and no site characterisation activities have been carried out.

The NDA has published a generic disposal system safety case (DSSC) to develop confidence in the safety of generic geological disposal systems suitable for a range of UK host geologies and wastes. The NDA also monitors developments in site characterisation techniques in the context of deep geological disposal, focusing on aspects of the biosphere linked to ecological, hydrogeological and geological processes. A summary of NDA and Nirex research and development programmes is presented here.

Information of relevance is also available from the programme of work undertaken for the Low Level Waste Repository (LLWR) by LLW Repository Ltd. Although the LLWR is a surface disposal facility for UK low-level radioactive waste, extensive site characterisation has been undertaken: including the collection of a large environmental data set and the development of descriptive and conceptual models, including some related to groundwater flow. Accordingly, work undertaken by LLW Repository Ltd is included in this review.

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5.2.1 Overview

The Quaternary Characterisation Programme carried out by Nirex in the Sellafield area during the 1990s included an extensive programme of near-surface (i.e. biosphere related) site characterisation and modelling work. The programme also used the body of information available from work for the existing nuclear sites at Sellafield and LLWR, and wider research on the Quaternary of West Cumbria. The emphasis was on reconstructing the Late Quaternary history of the region to inform geological and hydrogeological interpretations of the site, with a particular emphasis on characterisation of the near-surface hydrogeology [31]. These investigations were summarised in [28]. That summary includes a detailed account of the implications of the work for future SDM development. In particular, Thorne et al. [28] noted that:

"It is debatable whether characterisation of near-surface hydrogeology should be a component of the geosphere or biosphere site characterisation studies, or indeed whether a distinction between biosphere and geosphere characterisation is useful in this context. However, irrespective of its classification it needs to be undertaken. Furthermore, the near-surface hydrogeological regime is likely to remain substantially unchanged for a period of up to some tens of thousands of years or more, whereas more superficial aspects of the biosphere are likely to alter substantially on considerably shorter timescales. As dilution of a contaminated groundwater plume with recent meteoric water needs to be taken into account in post-closure safety assessment studies, quantification of the flow characteristics of the near-surface hydrogeological system is an essential element of site characterisation.

However, groundwater flow in the near-surface is only one consideration. The hydrogeochemical characteristics of this zone are also of relevance. For example, changing redox conditions can lead to the accumulation of radionuclides at particular locations, and these accumulations can subsequently be remobilised if environmental conditions change.

The Quaternary Characterisation Programme at Sellafield illustrates an approach to near-surface hydrogeological characterisation in a geologically complex environment. The Quaternary history of the area, particularly since the Last Glacial Maximum has resulted in a complex sequence of sediments that has been deformed by subsequent ice-marginal processes, so that both glacially deformed and glacially over-ridden sequences are present. The complex 3D structure of these sediments could only be inferred by a combination of invasive and non-invasive geophysical investigations coupled with a conceptual model of the depositional and deformation history of the deposits. The Nirex programme displayed this interplay of field investigations with conceptual modelling of the evolution of the site during the Late Glacial and Holocene.

Although sea levels in the vicinity of Sellafield have varied substantially since the retreat of the Late Devensian ice sheet, much of the evolution of the area has taken place close to the current coastline. This has meant that any continuity of depositional history from onshore to offshore has largely been destroyed or distorted. When combined with the practical difficulty of conducting geophysical surveys in the vicinity of the coastline, this meant that the onshore characterisation programme was conducted largely independently of the offshore programme. Even by the time that the programme was terminated, after several years of field investigations, only a few
tentative correlations could be proposed between the onshore and offshore areas. This difficulty of relating onshore to offshore sequences is likely to be a common problem at many coastal sites.

Complexities of interpretation are exacerbated by the presence of relict features following a glaciation. In particular, large bodies of buried ice can take several thousands of years to melt and can result in the formation of structures that can be misinterpreted in terms of neotectonic faulting.

In summary, the Quaternary Characterisation Programme at Sellafield emphasises that near-surface hydrogeological characterisation at a site where the Quaternary deposits are structurally complex is a resource intensive and time-consuming activity. It needs to be carefully planned from the outset, as the timescale for obtaining an understanding adequate for safety assessment purposes may be comparable to the time required for obtaining an adequate understanding of the deep hydrogeological system.

Further, in a structurally complex environment, careful consideration needs to be given to how the data will be interpreted for modelling purposes. The concept of geological and hydrogeological domains may be a useful approach for distinguishing larger-scale structural characteristics from smaller-scale (intra-domain) variability in properties.

Finally, it is noted that the Quaternary Characterization Programme at Sellafield was strongly focused on hydrogeological issues. Hydrogeochemical characterization was not given much emphasis. This probably reflects the limited amount of insight that could have been gained from such characterization, due to the predominance of recent meteoric and marine waters in the superficial deposits.

This text has been reproduced in full because it highlights a number of important points. First, there is an inevitable overlap in the geosphere/biosphere site characterisation and possibly it is better to accept the overlap than to risk either programme omitting characterisation of near-surface hydrogeology. Second, characterisation of the near-surface hydrogeology may be complex, resource-intensive and time consuming. Third, near-surface hydrogeology may be relatively stable over long time periods whereas more superficial aspects of the biosphere may alter substantially over much shorter periods.

Fourth, hydrogeochemistry also requires characterisation although past UK programmes have given relatively little attention to this area. This is not true of the SKB and Posiva programmes, which have been very good on hydrogeochemistry, with a great deal of detective work on the origin and evolution (through rock-water interactions) of various water bodies in different regions of the bedrock.

A methodology of Quaternary Domain mapping was developed to characterise the near surface (terrestrial) environment. A regional depositional model and conceptual model of the depositional and deformational history of the superficial deposits were developed [66] for the Late Quaternary. Similarly, the area was classified into seven hydrogeological domains, of similar hydrogeological behaviour, to facilitate modelling (with a focus on recharge and discharge processes).

Near-surface hydrology/hydrogeology (as the basis for biosphere radionuclide transport calculations) was modelled using the SHETRAN physically-based catchment modelling
system (developed by Newcastle University). Regional groundwater modelling was carried out using the ModFlow 3D groundwater flow model.

Currently, the NDA is developing its site characterisation programme as a means to demonstrate whether or not a site is suitable for hosting a GDF (for the specified waste types). Site characterisation supports the development of a Safety Case and engineering design for the disposal facility and provides information relevant to the undertaking of Environmental Impact Assessments. Site characterisation involves the interpretation of data and generation of SDMs and will be subject to progressive update. The generic process is illustrated in Figure 9 (from [11]).

Three key inter-related stages in the site-characterisation process are identified:

- Data acquisition;
- Data interpretation – transforming measurement data into meaningful information on properties of the site to develop a consistent understanding of the site as a whole; and
- Communication – communicate understanding obtained to others (e.g. involved in the development of the ESC, engineering design and EIA).

This process would proceed iteratively, with initial stages of interpretation identifying data gaps or uncertainties requiring further stages of data acquisition and interpretation and progressive updating of a single integrated SDM, describing the geometry, properties of the bedrock and water, and the associated interacting processes and mechanisms. The SDM is to provide the understanding of the characteristics of the site, sufficient to allow further qualitative and quantitative modelling to be undertaken as part of the development of the Environmental Safety Case.

The integrated SDM would be divided into disciplines or parts which may be either descriptive chapters or discipline-based models. The discipline-based models identified as likely to be required for UK sites comprise the following:

- Geology
- Hydrogeology
- Hydrochemistry
- Geotechnical
- Transport properties
- Thermal properties
- Biosphere

The scale and content of each discipline-based model will need to be developed according to the nature of the geological strata present. The discipline-based subdivisions, when combined together and with transfer of information between models, will provide an overall geosphere and biosphere understanding of the site.

Ongoing work by NDA into information requirements for the geosphere has also identified key types of biosphere characterisation information that should be collected in support of safety assessment work. For current biosphere conditions this includes: climate, fauna and
flora; near-surface topography, geology and geomorphology; surface hydrology and near-surface hydrogeology; surface and near-surface hydrochemistry.

**Figure 9. NDA generic site characterisation process**

From [11]
A key consideration in the process is the determination of when a sufficient level of understanding has been developed, such that any remaining uncertainties in the understanding of the site area are acceptable in terms of the intended use of the SDM developed. The establishment of a stable SDM in which the discipline-based models do not change significantly as further site characterisation information is added is one potential criterion for determining when completion of characterisation has been achieved. However, a wider overview would be required to ensure the model incorporated all information required to support subsequent design, safety and impact assessment work.

Effective data management is also identified as a key aspect of the site characterisation process. A data management system (DMS) will be developed, covering both acquired measurement data and interpreted information [67], to ensure that data are acquired in formats suitable for efficient storage, processing and dissemination.

5.2.2 Methodology

NDA studies have assessed the interface between the geosphere and biosphere, how it is conceptualised and modelled and how this affects subsequent assessment of biosphere transport and impacts [e.g. 68]. Modelling has covered from local to catchment scales.

Generic performance assessment work, including that formerly carried out by UK Nirex, has used relatively simple (1D) models (e.g. spreadsheet based), underpinned by more complex (2D and 3D) models, from which parameters, fluxes etc. have been derived. In the earlier Sellafield investigations undertaken by, or on behalf of, Nirex (e.g. [69]) for the post-closure performance of a deep geological disposal facility more detailed catchment scale modelling was used.

Recent work has recognised that different environments may require different levels of characterisation and modelling (e.g. [68] identified six generic environments).

Recognised hydrological modelling strategies include:

- Simple models based on site characterisation information (DEM, River flow, Rainfall, Meteorology etc.), e.g. a model developed by Quintessa using the GRASS GIS system [70].
- Use of more complex, integrated modelling codes, such as SHETRAN and MIKE-SHE, which require more detailed inputs but can provide more detailed transient analyses.
- Specialised (3D) groundwater flow models, such as ModFlow and FeFlow, where required.

Distributed catchment-scale modelling has been identified as a key issue, should it be required, due to the potential complexity and data requirements. This is particularly relevant for environments where spatially variable radionuclide concentrations in the biosphere would be expected.

Such physically based, distributed catchment modelling, which is possibly more relevant to biosphere characterisation and development of the SDM than to assessment studies, is also data intensive. Data requirements include:
• vegetation mapping – understanding vegetation types, correlating communities or species, estimating mass and productivity, and characterising ecosystems – through site surveys and/or remote sensing imagery;

• soil characteristics – texture, particle size, acidity, porosity (\(\phi\)) and soil water content (\(\theta\)), hydraulic conductivity (\(K\)), organic/mineral content, permeability, and other properties or topographical descriptions (such as slope);

• river flow rates – with continuous or discontinuous sampling appropriate to the accumulation of time-series data representing seasonal fluctuations due to meteorological conditions.

Soil and hydrological characterisation, and potential water table fluctuations or drawdown, will have a particular relevance during the construction phase of a facility. As noted in Section 5.2.1, hydrogeochemistry, as well as hydrology, requires characterisation: for example, to consider oxygen depletion as a function of depth.

5.2.3 Low Level Waste Repository (LLWR)

The Low Level Waste Repository (LLWR) in west Cumbria is a near-surface disposal facility for UK low level radioactive waste. Extensive site characterisation activity has been associated with the production of environmental safety cases (ESC), in 2002 and the recently submitted 2011 ESC [e.g. 71]. Work has included the collection of a large environmental data set, development of descriptive and conceptual models, numerical modelling (particularly of groundwater) and safety assessments developed using compartment model methodologies.

As part of the recent development of the 2011 ESC programme, considerable attention has been applied to improving the understanding of the geological and hydrogeological evolution of the site, including review at a number of workshops. Site geological data have been acquired from geophysical surveys, trial pits and a large number of boreholes. Both a lithostratigraphic approach [72] and, more recently, a lithofacies approach [73] have been used to represent the observed geological conditions:

• Lithostratigraphic – pertaining to a stratigraphy defined on the basis of rock type.

• Lithofacies – a lateral, mappable subdivision of a designated stratigraphic unit, distinguished from other adjacent subdivisions on the basis of noteworthy lithological characteristics.

Both approaches have employed a degree of simplification to allow units to be correlated across the site. In the 2002 post-closure safety case (PCSC), the lithostratigraphic approach subdivided the drift deposits into a succession of stratigraphic units, each of which was described as the accumulated depositional product of a specific glacial event. The 2002 geological interpretation does not delineate in detail the spatial distribution of different sediment types and the corresponding hydraulic properties of those materials.

Since 2002, a revised geological interpretation has been put forward with the aim of providing a more suitable basis for subsequent hydrogeological interpretation and modelling and the development of a 3D geological model of the site [74]. This uses a grouped, bulk lithofacies approach, which also takes into consideration the regional geological context of the site and contemporary local analogue exposures. The validity of this approach is reliant
on the assumption that sensible bulk properties can be assigned to each lithofacies package, despite the heterogeneous characteristics of each package.

Calibrated site-scale groundwater models have been developed using ModFlow, FeFlow and, for the 2011 ESC, ConnectFlow [75]. The ConnectFlow model uses the 3-D geological lithofacies model as a framework and extends over the local region, with the boundaries of the model largely defined by topographic catchment boundaries and the distribution of offshore sediments. These models have, in effect, been used as part of site characterisation to demonstrate understanding of the site. Simplified representations of transport and exposure pathways were then established in a GoldSim model for the radiological assessment.

The LLWR is located near to the coast and the ESC developed for the LLWR has included specific (and quite extensive) consideration of historic, current and future anticipated coastal development [e.g. 76, 77, 78]. Given that a GDF will be located at considerable depth, and given the site selection process, it is unlikely that coastal erosion processes will offer a challenge to site integrity. Nonetheless, biosphere characterisation for a GDF should include both consideration of proximity to coast and, where applicable, prevailing coastal evolution.

5.3 Sweden

The Swedish Nuclear Fuel and Waste Management Company (SKB\textsuperscript{10}) is responsible for the management and disposal of radioactive waste in Sweden. Publications of SKB are generally freely available from their website. Key documents have been reviewed, including recommendations by the NDA supplied contact at SKB.

SKB has investigated two potential repository sites, Forsmark and Laxemar-Simpevarp, selecting Forsmark as their preferred site. Several rounds of site characterization have been carried out, including the collection of extensive site-investigation data and modelling of the surface system. SKB’s strategy has been the same at both sites, although more comprehensive information is available for Forsmark and therefore review has focused on that site.

The Forsmark site is underlain by crystalline bedrock of Precambrian gneisses and migmatites, overlain by younger granites and sandstones. Regionally, large-scale fracture zones enclose what are described as “tectonic lenses”, within which there is less deformation. The Forsmark site lies within one of these tectonic lenses. Quaternary sediments comprise predominantly sandy glacial till. Clay soils form about one-third of the soils. The area is characterized by relatively low relief and small-scale topographic variation and lies almost entirely at less than 20 metres above sea level. The area is undergoing continuing post-glacial isostatic uplift and has only emerged from the Baltic over the last few thousand years. There is thus an emphasis on ecosystem succession during emergence from the sea that would rarely be relevant in the UK context, where rising sea levels are likely to be relevant around most of the coastline.

Forsmark is a coastal location. Lakes, wetlands and various vegetation types are present, with wetlands of significant importance for accumulation of organic matter and other

\textsuperscript{10} http://www.skb.se/
elements. In the marine environment, advective water flows are the dominant process controlling fluxes of organic matter.

The Forsmark site fits within the NDA “Higher strength rocks” type geological environment class (see Section 1.4). Table 4 summarises the techniques suggested by SKB for biosphere characterisation [79].

### Table 4  Methods for characterisation

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Land</strong></td>
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<tr>
<td>Inventory of key habits</td>
<td>Key habitats and general biotope protection</td>
</tr>
<tr>
<td>Vegetation and biotope mapping</td>
<td>Vegetation and biotope map</td>
</tr>
<tr>
<td>• Existing material</td>
<td></td>
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<tr>
<td>• Aerial photos</td>
<td></td>
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<tr>
<td>• Map interpretation</td>
<td></td>
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<tr>
<td>• Field studies</td>
<td></td>
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<tr>
<td>Forestry</td>
<td></td>
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<tr>
<td>• quantity</td>
<td></td>
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<tr>
<td>• production</td>
<td></td>
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<tr>
<td>• rotation</td>
<td></td>
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<tr>
<td>• age structure</td>
<td></td>
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<tr>
<td>Agriculture</td>
<td></td>
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<tr>
<td>• production of crops</td>
<td></td>
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<tr>
<td>Vegetation type</td>
<td></td>
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<tr>
<td>• population/production</td>
<td></td>
</tr>
<tr>
<td>• species of vascular plants, fungi, lichens, mosses and algae</td>
<td></td>
</tr>
<tr>
<td>Compilation of red-listed species</td>
<td>Red-listed species</td>
</tr>
<tr>
<td>Biomass and production</td>
<td>Hunting, allotment, felling statistics</td>
</tr>
<tr>
<td>• Existing material</td>
<td>• Species, number and occurrence</td>
</tr>
<tr>
<td>• Area assessment</td>
<td>• Biomass</td>
</tr>
<tr>
<td>• Area assessment</td>
<td>• Production</td>
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<tr>
<td>Agriculture</td>
<td></td>
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<tr>
<td>Aquatic</td>
<td></td>
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<tr>
<td>Bottom mapping</td>
<td>Vegetation zonation map</td>
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<tr>
<td>• Vegetation and animal zonations</td>
<td></td>
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<tr>
<td>• Bottom-type distribution</td>
<td></td>
</tr>
<tr>
<td>Sampling</td>
<td>Species compositions and quantity of fauna and flora</td>
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<tr>
<td>• Dip-netting</td>
<td></td>
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<tr>
<td>• Bottom samples</td>
<td></td>
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<td>• Production measurement</td>
<td></td>
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<tr>
<td>Fishing</td>
<td>Species composition</td>
</tr>
<tr>
<td>• Existing material</td>
<td>Toxic pollutants/radionuclides in fish</td>
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<tr>
<td>• Net fishing</td>
<td>Fishing licences</td>
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<tr>
<td>• Electrofishing</td>
<td>Catches</td>
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<tr>
<td>• Echo sounder</td>
<td>Professional fishermen</td>
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</tbody>
</table>

### 5.3.1 Overview

SKB defines the surface system as “the upper part of the bedrock, the Quaternary deposits and the biotic and abiotic parts of the ecosystems at the surface”. The surface system at Forsmark has been characterised by “identifying, describing and quantifying” key properties of the elements of the system that define a SDM. This includes: climate, vegetation, ecosystems, hydrology, hydrochemistry, drift deposits and soils, and land use.
During this process consideration was given to how results from modelling of the surface system are integrated and interact with modelling of the deep geosphere. For example, the interface between biosphere and deeper geosphere was considered in the evaluation of deep and shallow groundwater movement and hydrochemistry. This ensured that the hydraulic properties of the drift deposits were incorporated in groundwater modelling and the impact of infiltration on groundwater chemical composition was accounted for in hydrochemical modelling. Similarly, shallow groundwater modelling was consistent with the bedrock hydrogeological model.

Broadly, the site characterisation strategy followed the following steps:

- Develop and document individual components (topographic, regolith/geology, hydrological and near-surface hydrogeological, ecological);
- Develop an integrated site description covering all surface-system disciplines;
- Describe site-specific processes and properties important for understanding the transport of matter within and between the deep geological and surface systems;
- Perform an overall confidence assessment.

The investigation and interpretation was focused on the presence and movement of organic matter ("carbon dynamics") as a means to understand how different parts of the overall ecosystem operate and are linked. This approach has been used to produce a baseline for predictions of dispersal, transport and accumulation of radionuclides in the surface system and within and between ecosystems. It is consistent with and forms part of the methodology which has been used to calculate potential doses to humans and other biota.

The (overall) site investigations have been conducted in campaigns, punctuated by data freezes. At each data freeze, analysis and modelling has been carried out to produce an updated SDM integrating the different parts of the system. This SDM modelling generally considers the past and present only; future evolution is dealt with in subsequent safety assessment work. Several SDM versions have been produced [80, 81, 82]. The current version is referred to as SDM-Site Forsmark [83, 84]; this has two main components:

- A written synthesis summarising the current state of information on and knowledge of the site, including a description of natural processes that may affect its long-term evolution;
- A model interpreting the collected information and presenting it in a form that will facilitate use in numerical modelling and environmental impact and safety assessments.

The biosphere investigation is one part of a multi-disciplinary process to produce and licence a repository design. Attention has been paid to data integrity and quality assurance across the whole programme. Documented QA procedures have been implemented to ensure data integrity and quality assurance and to ensure relevant data are available to end users for design, modelling and assessment.

Key software employed in data management for the biosphere characterisation and modelling process include:

- SKB Site Characterization Database - Sicada
- Geographic Information System – ArcGIS SDE
- SKB model database - Simon
To facilitate integration across disciplines, and over data acquisition and modelling programmes within the biosphere assessment, a multi-disciplinary project called “SurfaceNet” was set up. This covers the disciplines of geology, soil science, hydrology, hydrogeology, water chemistry, hydrogeochemistry, oceanography, geography, limnology, ecology and radioecology.

5.3.2 Methodology

A site-specific description of the biosphere was produced by identifying and describing the key properties of the different landscape features (including current and historical land use) and ecosystems present. This was aimed at developing a constrained range of future states for consideration in subsequent assessments of radionuclide movements and impacts.

It was considered important that the whole landscape was characterised in order to produce a comprehensive descriptive model for the surface system. The key steps in this process were:

- Categorisation of the ecosystem into suitable functional units and development of a conceptual model describing stores and flows of matter;
- Collection of site-specific data to tailor the conceptual model to the specific site;
- Quantification of the stores and flows of matter for each identified functional unit;
- Description and modelling of the transfer and accumulation of matter within and between the identified functional units.

Surface hydrology, primarily vertical and horizontal movement of surface water, was considered the most important process controlling transport of matter within the environment and was studied using quantitative modelling. The functional units were therefore defined based on catchment areas. The outcome was a mass-balance model describing the transport and accumulation of matter in the surface system. The modelling process required a number of simplifying assumptions, and realistic physical and biological limits were set to constrain the range of variations requiring assessment.

SKB believe that this approach results in more accurate and precise estimations of flows and accumulations of matter, and ultimately radionuclides, in the surface system than an established alternative approach using simple transfer factors.

The Forsmark biosphere assessment (safety assessment) covers a 70,000 year ice-free period between glaciations and was based on the BIOMASS methodology [60]. The biosphere system description is a key stage in the methodology and the SDM was thus an important starting point for predictions of the future evolution of the landscape and environment. Wherever possible, site-specific parameter values were derived for the features and process affecting transport and accumulation of radionuclides, including for

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11 An important consideration in both Sweden and Finland is that there is only a slow gradation in ecosystem type from south to north. Thus, over a considerable interglacial climatic range, ecosystem types and structures, and the overall hydrological environment, do not vary markedly. Thus, land uplift is a much stronger control on ecosystem succession within the interglacial context than is climate change or climate variability. Only with the development of permafrost and ice-sheet advance does this situation change markedly.
example hydrological flows, sedimentation and resuspension rates, biomass growth and gas exchange rates.

5.3.3 **Site descriptive modelling**

A number of different modelling programs are contained within the integrated SDM.

5.3.3.1 **Digital elevation model (DEM)**

Several data sets were used to construct DEMs for the Forsmark area, including: an existing 50 metre resolution DEM from the Swedish national land survey (LMV), an SKB 10 metre resolution DEM, topographical contour maps, nautical charts from the Swedish Maritime Administration, depth soundings in lakes and the sea and point measurements of brooks and other fixed points. In addition, some “dummy depths” were incorporated to facilitate terrain modelling in areas where no data were available.

The Geostatistical Analysis and Spatial Analyst extensions within ArcGis 9 were used to interpolate the DEMs. Testing of different interpolation parameters and cross validation by substitution within the dataset was carried out, and checks were made to verify that the models would adequately fit localities with no data.

5.3.3.2 **Quaternary geology**

Soil and Quaternary geology maps were compiled from various pre-existing sources (including the Geological Survey of Sweden) and from site-specific surveys. Soils were classified according to their properties in a standard way, within eight identified land types. Where site-specific data on soils were unavailable, GIS analysis was used to interpolate the mapping, based on the detailed map of Quaternary deposits (i.e. the parent material), vegetation type and a topography-based hydrological index.

A geometrical (3D) model of the regolith in the Forsmark area with a 20 metre resolution was constructed using a GIS [85]. This was based on drilling, excavation and geophysical data and contains nine sub-domains, subdivided into seven layers along with three lake sediment lenses. In areas where regolith depth information was lacking, average depth values were used based on the conceptual stratigraphic model of the area.

5.3.3.3 **Hydrochemistry**

Along with deeper groundwater data, a very large surface hydrochemical data set has been collected for the Forsmark area, including: precipitation, streams, lakes, sea water, shallow groundwater, soil water (from soil tubes) and groundwater in private wells. The large number of parameters and data points require statistical methods to enable visualisation and to identify major patterns and anomalies (e.g. [86]).

Analyses employed have ranged from simple plots through multivariate statistical methods to multivariate models, such as the Ion Source Model. At a catchment scale, empirical measurement and mass balance approaches have been used to evaluate sources and sinks.

5.3.3.4 **Hydrological modelling**

The hydrological and hydrogeological modelling relies on a number of different site-specific data sets and generic data and has been an iterative process, linked to the site-
investigation data freezes and repeated through different model versions. This produced a site conceptual and descriptive model which was followed by quantitative flow modelling and flow path analyses, to identify groundwater discharge areas and improve the general understanding of site hydrology.

The MIKE-SHE model has been used to perform hydrological and shallow groundwater modelling [87], aimed in particular at identifying the distribution of recharge and discharge areas. For detailed modelling, the MIKE-SHE model had a no-flow boundary set at a depth of 600 m; this provided a relatively large overlap with deeper groundwater modelling (performed with the ConnectFlow model [e.g. 88]). Overall, SKB reported that they obtained good agreement with the measured groundwater levels in the Quaternary deposits, but generally simulated groundwater levels in the bedrock were too high.

It may be worth noting that the MIKE-SHE modelling identified above was undertaken with different bottom boundary condition depths depending on the issue being investigated. One general issue with groundwater modelling is that the various simulation packages available have different capabilities, e.g. surface hydrology may be explicitly included (as in MIKE-SHE), or parameterised through a prescribed boundary condition, and density dependency of flow may or may not be included. Thus, development of an overall SDM component on hydrogeology may require the employment of various tools to explore different issues followed by an interpretative synthesis of the results obtained using informed (expert) judgement.

5.3.3.5 Ecosystem models

Terrestrial ecosystem modelling focused on identifying and quantifying vegetation types considered representative with respect to areal coverage and as potential sinks for organic matter. This resulted in the identification of three locations (two conifer forests, of a type that dominate the area, and one forested wetland). The carbon balance, with respect to storage and fluxes of organic matter, was described using site-specific data whenever possible, or else appropriate literature data.

The specialised dynamic vegetation model LPJ-GUESS was used to produce site-specific regional carbon balance values for a number of representative vegetation types [89]. A 100 year period was modelled and the results validated against field-measurement-based estimates. The model could not accommodate some key types, including sea shore, wetlands and forested wetlands. In these cases, field measurements and literature data were used to construct a more empirically based model.

5.3.3.6 Marine ecosystem

Marine ecosystem modelling also focused on quantifying carbon balances, representing both stores and fluxes of organic matter. For the marine system, the study area was divided into 28 sub-basins, based on both current bathymetry and the projected outcome of continuing isostatic land uplift (for methodology see [90]).

The marine ecosystem model is in the form of a food web comprising biotic stores (primary producers and consumers), abiotic stores (particulate and dissolved matter) and fluxes of matter (primary production, respiration, consumption, sedimentation, advection and runoff). The biotic and abiotic stores represent the spatial distribution of organic matter in the model.
5.3.3.7 Uncertainty

The SDM for Forsmark is composed of a large number of sub-models, covering a wide range of disciplines, which are combined and aggregated as the SDM is built up. SKB attempts to reduce the inherent uncertainties in their models (due to the assumptions and simplifications which have to be made in their development), primarily by basing them on site-specific data wherever possible, avoiding introducing unknown uncertainty through the use of generic data. Remaining uncertainties are explicitly evaluated during development of each discipline-specific sub-model. Similarly, the assumptions made within the aggregated models are carefully considered.

5.3.3.8 Quality assurance

Controlled handling of data and workflow was considered crucial to guarantee the quality of data and model results. The aim was to ensure the calculations that produced specific results could always be reconstructed, regardless of later changes in codes or input data. Primary data from site investigation work are stored in the Sicada and GIS databases. All data are reviewed and approved by the person responsible for the activity producing it and checked by both this person and the database operator to ensure correct transfer has taken place. Data used in interpretation and modelling are then supplied only from this controlled source, with all data delivery to end users being approved and registered. Tracking and versioning systems (Trac and Subversion) are used to document modifications made to model parameter files. This methodology ensures that the data and parameters used to construct versions of models and assessments can be identified at future dates, regardless of subsequent additions to the databases and models. This also enables traceability of the basis on which decisions were made based on the state of knowledge at the time.

5.4 Finland

Posiva Oy is responsible for implementing the final disposal programme for spent nuclear fuel from Finnish nuclear power plants. Posiva has selected a coastal site, Olkiluoto as the location for a deep repository. Olkiluoto is a moderately sized island (with an approximate area of 12 km$^2$) on the Baltic Sea coast, separated from the mainland by a narrow strait. The site is located in an area of significant continuing postglacial land uplift\textsuperscript{12}.

The waste is planned to be disposed of in a KBS-3 type of repository (i.e. similar to the Swedish model), to be constructed at a depth of about 400 metres in crystalline bedrock. Extensive site investigations have been carried out; with the site, the investigation programme and assessment methodology being similar to the Swedish (SKB) situation (see above).

\textsuperscript{12} As noted in Section 5.3, with respect to site characterisation undertaken in Sweden, this means that there is an emphasis on ecosystem succession during emergence from the sea that would rarely be relevant in the UK context. With that exception, much of the site characterisation work undertaken is both relevant and represents what may be termed relevant good practice.
Posiva publishes all reports and working reports. Nearly all reports from 2006 onwards can be accessed free of charge from the Posiva website. A similar amount of information and level of detail are available as from SKB.

The Olkiluoto site fits within the NDA “Higher strength rocks” type geological environment class (see Section 1.4).

5.4.1 Overview

Posiva explicitly links the DBM to the development of their safety case through the Data Handling and Modelling sub-process [91]. In particular, Posiva states that “data are produced by Posiva’s planning, design and development processes for the EBS (Engineered Barrier System), by the site characterisation process for the geoscientific data and through the biosphere description of the Olkiluoto area” ([91], Section 1.7). The stated overall aims of the biosphere assessment in the safety case [23] are to:

- Describe the future, present, and relevant past conditions at, and prevailing processes in, the surface environment of the Olkiluoto site;
- Model the transport and fate of radionuclides hypothetically released from the repository through the geosphere to the surface environment;
- Assess possible radiological consequences to humans and other biota.

One of the key aspects to note, of relevance to the development of a DBM, is that site characterisation includes not only a description of present conditions and an understanding of past conditions, but also identifies on-going processes, emphasising the dynamic nature of the surface environment.

Significant change in the surface environment is expected over timescales comparable with the periods and timescales of releases of radionuclides (e.g. marine margins developing into terrestrial areas, lakes forming then developing into wetlands). Therefore, Posiva’s approach to biosphere assessment has been to develop a fully dynamic model for the development of the surface environment (and consequently of associated radionuclide transport and impacts).

Biosphere assessment has been conceptually divided into five main sub-processes (see Figure 10, taken from [92]):

- Biosphere description;
- Terrain and ecosystems development, via terrain and ecosystems development modelling;
- Landscape modelling;
- Radionuclide transport modelling;
- Radionuclide consequence analysis.

This study has focused on the first of these, which includes environmental characterisation and the compilation of a description of the present properties and on-going processes at the

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13 http://www.posiva.fi/
Olkiluoto site [93]. The description of the present condition of the surface environment then forms the basis of, and provides key data for, predicting the development of topography, shallow geology, hydrology, hydrogeology, hydrochemistry, hydrogeochemistry, flora and fauna at the site for future safety case assessments.

Figure 10. Schematic illustration of Posiva biosphere assessment process

From [92]

Characterisation of the Olkiluoto region has been based on extensive environmental studies undertaken over the past two decades or more [e.g. 94, 95, 96]. These studies have established information relevant to:

- Terrain, climate and surface and near-surface hydrology;
- Terrestrial populations of birds, mammals, reptiles and amphibians, insects, gastropods and other major taxonomic groupings;
- Water quality and faunal and floral assemblages (both emergent and submersed) in lakes, rivers and coastal areas around Olkiluoto;
- Effects of human interactions; and
- Comparisons with ecologically similar areas removed from the Olkiluoto region.

Data are collated to provide species lists, abundance and biomass, and, in many cases, data are sufficient to derive measures of biodiversity for the systems studied. Ecosystem descriptions include soil or sediment type and thickness, water quality, pH, Eh and organic content (as relevant to each system).

These studies have led to the compilation of site-specific data and models, such as the terrain (elevation) model [97], the land uplift model [98] and ecosystem models [93]. Based on these, forecast conditions in 2020 define the initial state for the landscape modelling, which underlies future evolution and impact assessments.

A knowledge quality assessment procedure was used as a part of the biosphere assessment process. This is an iterative process covering all activities in the biosphere assessment and in the broader safety case. It was aimed at both improving confidence in
the data and interpretations of those data, and fostering communication about assumptions and uncertainties throughout the assessment chain in a systematic and comprehensive manner.

5.4.2 Methodology

The Olkiluoto biosphere description underlies subsequent biosphere modelling, along with terrain and ecosystem development modelling. The SDMs have been quantified using site-specific data as far as possible and are then the basis for the landscape model used for radiological impact assessment (simulating radionuclide transport through and accumulation in various components of the biosphere).

The landscape model is based on “biosphere objects”. These describe continuous and reasonably homogeneous segments of the modelled area that can potentially receive radionuclides released from the repository. Each biosphere object is characterised by an ecosystem type (e.g. forest, wetland, lake, river, coast) and an associated set of parameters.

Terrain models describe the elevation and depth of the ground surface and sea bed, and are key inputs in land uplift and surface hydrological modelling.

Ecosystem models describe the processes affecting transport and accumulation of matter in the environment. The ecosystems considered are terrestrial and aquatic, a combination of both, and a shoreline system.

In order to characterise ecosystems in the Olkiluoto region, a number of long-term quadrats were established around 7-8 years ago (during Summer 2005), allowing more detailed examination of seasonal, annual or longer-term changes in vegetation cover [e.g. 99]. This information has been used to construct a number of reference ecosystems and associated reference species. A recent workshop sponsored by Posiva [100] identified nine different ecosystems to be characterised as part of the biosphere assessment contributing to the Environmental Safety Case for Olkiluoto. Five terrestrial ecosystems are currently defined, as summarised below.

- **Rock forest** – characterised by coarse mineral soil (described as rocky, young soils <500 years old, with soil <30 cm overlying bedrock). These systems will continue to develop over the next few hundred years until they mature.

- **Heath Forest** – identified as more ‘typical’ or mature forest, with a variety of different soil types (e.g. coarse, medium and fine mineral soils). Understorey coverage varies from sparse to very lush.

- **Grove** – typically these are herb-rich forests with fine-textured soil and a mixture of broadleaf and spruce trees. Decomposition of dead material is rapid and thus nutrients cycle efficiently.

- **Mire** – characterised as moist regions and the term includes all peatland sites. These tend to be very long-lived systems with examples in Finland >10,000 years old, but they can develop (e.g. through to forest systems) if the water level changes. Typically these have an organic soil with large variations in nutrient status, ground water level and dominant species.
In addition, an *agricultural system* is defined, consistent with human exposure scenarios. The characteristics of agricultural systems will be varied. At a large scale, different soil types and water retention characteristics can be used to define land-management regimes. Fine and medium soils store water better and are compatible with greater crop variety (e.g. cereal, potato, berries/fruits, beet, pasture).

For each of the terrestrial ecosystems, broad components of the system can be recognised:

- Canopy, above ground;
- Surface vegetation layer;
- Ground surface – litter;
- Soil rooting (up to 30 cm depth);
- Intermediate depth soil (30-70 cm depth);
- Deep soil (>70 cm depth).

Aquatic systems are divided, at a basic level, between soft (e.g. sandy) and hard (e.g. rocky) bottom types. Up to four types of ecosystem can be characterised, as summarised below.

- **Open freshwater** - lakes and ponds.
- **Open sea areas and coastal areas** (brackish water) – based on predicted land rise in the region, these will develop towards a freshwater environment over the next several thousand years. Both littoral and sub-littoral components are characterised.
- **Reed beds** – these form a community within the freshwater and brackish water environments. They may be considered as a separate ecosystem although recent discussions at Posiva have inclined towards incorporating them within the larger ecosystem definitions above.
- **Springs.** These might be important but are not currently well-defined. Springs may harbour many endangered and sensitive species.

The open freshwater and coastal areas are further divided into photic and aphotic areas by the water depth and both these types are further distinguished into soft and hard bottom types based on the surface sediment. As for the terrestrial systems, the key components of the aquatic systems can be identified to include:

- Water surface;
- Water body;
- Sediment surface ("active" or "fluffy" layer);
- Upper sediment layer (0 to 30 cm of "hard" sediment);
- Intermediate sediment (30 to 100 cm);
- Deep sediment (below 100 cm).

For each of the selected reference ecosystems, both terrestrial and aquatic, change will be a key factor over periods of as little as a few 100s of years.
Feedback provided by STUK\textsuperscript{14} on the 2009 Biosphere Assessment [101] indicated, among other issues, that the process for simplifying conceptual site models in order to produce mathematical models for use in assessments required greater transparency. On the positive side, STUK indicated that the knowledge quality assessments undertaken by Posiva (to evaluate the quality, applicability and key uncertainties associated with biosphere characterisation) significantly improved confidence in the assessments being undertaken.

\subsection*{5.4.3 Site descriptive modelling}

A high resolution statistical DTM of the Olkiluoto area was derived by combining existing data with uncertainty information from various sources. Thin-plate-spline interpolation was used to create a 2.5-metre resolution raster surface [97]. Potentially erroneous data values were rejected from the model by using a spatial autocorrelation method.

An overburden model (thickness and structure) for both land and sea bed was compiled from existing information, and interpolated, using expert judgement where necessary, to cover areas with no data. Surpac software\textsuperscript{15} (see Section 6.1) was used for data visualisation and interpolation. Conceptualised soil and sediment types were used and a standard stratification order was assumed.

A GIS toolbox, called UNTAMO, was developed (using ArcGIS) to compile site characterisation information and model land-uplift-driven and other changes in the biosphere. The UNTAMO toolbox is used in the biosphere assessment together with other related models, in particular the surface and near-surface hydrological model (SHYD [102]). The toolbox consists of the following main components and performs the following actions.

\begin{itemize}
  \item A land uplift module [103] is included.
  \item Surface water bodies are delineated through conventional (GIS implemented) flow accumulation analysis.
  \item Terrestrial erosion and the redistribution of surface soils is simulated by applying the USPED/RUSLE model [104]. In this approach, the local net erosion is determined by the soil type, land cover, rainfall intensity and slope analysis. For aquatic erosion and sedimentation, a fetch approach (physical exposure to wind-induced effects) was used [105].
  \item Accumulation of organic material is modelled for reed beds and wetlands. Peat growth in wetlands is simulated using the model of Clymo et al. [106].
  \item The development of terrestrial vegetation is also simulated by the UNTAMO toolbox. This is either done using Bayesian prediction based on site data (biomasses related to soil type, groundwater table and local solar conditions) [107] or by application of a simpler vegetation-type classification method.
  \item The Olkiluoto surface hydrology model [102, 108] was developed to model the movement and storage of water in the ecosystem, including horizontal and vertical
\end{itemize}

\textsuperscript{14} This feedback has been provided informally by Posiva (Hjerpe, \textit{pers. comm.}, 2011).

\textsuperscript{15} \url{www.gemcomsoftware.com}
water fluxes in the overburden and at the ground surface. A dual permeability approach was used.

- The model includes sub-models for snow accumulation and snow melt.
- Computation of interception and evapotranspiration is based on the Penman-Monteith equation.
- Simulations of subsurface flows in the shallow overburden system and in the bedrock system are based on solution of the 3D-unsaturated/saturated Richards equation.
- Flow to roadside and forest ditches and agricultural drains is calculated using a modified form of the Hooghoudt equation.
- Flow in rivers is calculated using a simplified form of the Saint Venant equations.
- Calculation of soil temperature and frost depth is carried out by solving the soil heat-balance equation.

Projecting the development of the surface environment is implemented in two modelling activities: the terrain and ecosystems development modelling (TESM) and SHYD [91]. The future terrain and ecosystems are simulated with UNTAMO and delivered as input data to the SHYD model to simulate groundwater flow and water table characteristics in detail, which is used as the groundwater head boundary condition in the deep groundwater flow modelling. The methodology adopted to date by Posiva has been to use a fully 3D surface hydrological model. An acknowledged problem with this method [109] has been that model runs (computations) are very time consuming and due to this it was not possible to do a conventional sensitivity and uncertainty analysis, i.e. by varying the input data and key parameters. Posiva therefore proposes to develop a simplified version of the model, possibly based on biosphere objects, for use in site assessments and to enable detailed sensitivity and uncertainty analysis, while still retaining valid descriptions of the key hydrological processes.

5.5 Switzerland

Nagra (the National Cooperative for the Disposal of Radioactive Waste) is responsible for the management of radioactive waste in Switzerland. The members of the Nagra Cooperative are:

- Swiss Confederation (represented by the Department of Home Affairs)
- BKW FMB Energie AG, Bern (Mühleberg NPP)
- Kernkraftwerk Gösgen-Däniken AG, Däniken (Gösgen NPP)
- Kernkraftwerk Leibstadt AG, Leibstadt (Leibstadt NPP)
- Axpo AG, Baden (Beznau I and II NPPs)
- Alpiq Suisse SA, Lausanne

Nagra has investigated several potential repository locations. This review has focused on extensive site investigations carried out to investigate the Zürcher Weinland region in northern Switzerland as a potential site for a repository located in the Opalinus Clay. The assessment process is broadly similar to the Scandinavian model (SKB, Posiva), although different software packages have been used.
The Nagra website\textsuperscript{16} contains a clear summary of the proposed waste management strategy, and provides links to research programmes in other countries. A large amount of information is available and key documents have been reviewed. However, little published information on site characterisation and site-descriptive modelling was available and much of the information which has been obtained relates primarily to the acquisition of data in support of long-term (post-closure) safety assessments.

The Zürcher Weinland/ Opalinus Clay site fits within the NDA “Lower strength sedimentary rocks” type geological environment class (see Section 1.4).

5.5.1 Overview

A comprehensive post-closure radiological safety assessment has been developed for a deep geological repository sited in the Opalinus Clay of the Zürcher Weinland region in northern Switzerland\cite{110}. Waste would be emplaced in tunnels constructed at a depth of about 650 m. The repository is designed for the disposal of:

- Spent fuel in the form of fuel assemblies;
- Vitrified high-level waste;
- Long-lived intermediate-level waste (ILW).

In seeking to develop a “systematic approach to building a safety case”, Nagra has undertaken a substantial programme of work relating to biosphere characterisation.

5.5.2 Methodology

Nagra developed its programme in accordance with (then current) internationally established principles for radioactive waste management (e.g.\cite{111}), geological disposal (e.g.\cite{51}) and radiological protection\cite{53}. (N.B. These have subsequently been in part superseded by more recent IRCP (2007) recommendations\cite{112}.)

The site assessment programme has been based on a number of assumptions, including the extrapolation of present-day climatic and surface environmental conditions unchanged into the future.

Nagra has addressed several sources of potential uncertainty within their characterisation and assessment programme:

- Scenario uncertainty (uncertainty in the broad evolution of the repository and its environment);
- Conceptual uncertainty (uncertainty in assumptions or conceptual models); and
- Parameter uncertainty (uncertainty in parameter values used in a model). Parameter uncertainty can also arise from uncertainty in the models used to interpret the raw data used to derive the parameters.

Nagra considers uncertainties related to the future development of the biosphere to be “of a different quality compared to other uncertainties”, in that they are highly speculative.

\textsuperscript{16} http://www.nagra.ch/
However, since the reference case biosphere model is characterised by the present-day climate and geomorphological conditions, this forms the basis for Nagra's biosphere site characterisation activities and six local geomorphological units were identified that are relevant to biosphere modelling:

- Lakes
- Braided rivers
- Meandering rivers
- River deltas (in lakes)
- Eroding rivers
- Wetlands

Only three geomorphological units, Eroding River, Sedimentation Area\textsuperscript{17} and Wetland, were considered relevant to their biosphere safety assessment.

For the reference case biosphere, the geomorphological units were defined to be present-day valley types existing in northern Switzerland, where discharge of deep groundwaters occurs. As discharge of deep groundwater generally occurs in valley bottoms, the focus has been on conditions in these areas. Consequently, rivers and associated gravel aquifers are the projected recipient compartment for radionuclide release from the geosphere to the biosphere (i.e. Eroding rivers type geomorphological unit). Discharges from springs at the side of a larger river valley have also been considered.

In all representations of the biosphere, five main compartments are considered: the Quaternary aquifer, a deep soil layer, a top soil layer, surface water and aquatic sediment. Nagra's biosphere assessment model is implemented using the assessment code SwiBAC\textsuperscript{[113]}. Contaminants are transported in the model by advection in the water phase, in association with mass movements of solids and by diffusion. The model assumes that the rooting zone soil is well mixed on a timescale of one year and that the near-surface aquifer can be treated as a homogenous unit. Similarly, the intermediate soil horizons between the aquifer and the rooting zone are treated as a single entity. In the aquatic environment, a distinction is made between the surface water and bed sediments. The five compartments (rooting zone soil, near surface aquifer, lower soil horizons, surface water and bed sediment) are all that is required to model the transport of contaminants within the single biosphere section.

5.5.3 Site descriptive modelling

The biosphere is conceptualised as part of a catchment system with flows of water and solids into and out of the modelled area. These flows are principally associated with bulk water movements in the aquifer and surface water. Solid material can be transported by surface water and deposition and erosion can occur at exposed surfaces. The atmosphere also exchanges airborne particulates with the environment within and outside the modelled biosphere. These processes represent the major interactions of the system, with the focus on radionuclides entering the biosphere in contaminated groundwater.

\textsuperscript{17} The term “Sedimentation Area” describes Braided rivers, Meandering rivers, and River deltas combined.
Modelled representations of the physical biosphere are produced to support this mass-balance-driven contaminant transport. Fluxes of water and solid material (transporting contaminants) are based on site characteristics.

Supporting models are used to guide the derivation of parameter values for the near field, geosphere and biosphere (including groundwater flow models, mechanistic sorption models and temperature evolution models) [114].

The FRAC3DVS code, used in the safety assessment, is relevant to site biosphere characterisation. FRAC3DVS is a general purpose 3D flow and transport model which can be used to calculate the transport of dissolved radionuclides through the geosphere. The code is described in detail in [115] and [116]. Three main model concepts are possible: continuum models, equivalent porous-medium models (EPM) and discrete fracture network models (DFN). The mathematical representation of flow and transport is based on mass balance, carried out over a representative elementary volume, using one or more homogeneous sub-regions to simulate the behaviour of a heterogeneous medium. The FRAC3DVS code has been verified by comparison with test cases, using both analytical solutions and comparison with other codes.

5.6 France

The National Radioactive Waste Management Agency (Andra) is responsible for the long-term management of all radioactive waste in France. Its responsibilities include the siting, construction, operation, closure and monitoring of repositories. Andra currently operates disposal facilities for low level waste and conducts scientific research programmes into deep geological disposal of high-level, long-lived radioactive waste (HLLL waste). A limited number of higher level (overview only) documents are available via Andra’s website18, e.g. [117]. Two geological media have been considered, clay and granite, and an underground laboratory constructed.

The Meuse/Haute-Marne underground research laboratory, located at Bure in eastern France (at a depth of 490 metres), has been used to investigate a clay host rock, the Callovo-Oxfordian clay. There is no underground research laboratory available in France for granite host rocks. However Andra has carried out studies to assess the potential of French granite formations and collaborated with national research programmes and underground laboratories in Switzerland, Belgium and Sweden for both media.

The Meuse/Haute-Marne Callovo-Oxfordian clay site fits within the NDA “Lower strength sedimentary rocks” type geological environment class (see Section 1.4) and is believed to have demonstrated long-term geological stability over more than 150 million years.

5.6.1 Overview

A research summary document, Dossier 2005 Argile, consisting of five reference knowledge documents containing all data currently available, has been produced. One volume covers the geological medium and the biosphere [118].

18 http://www.andra.fr/
Based on these data, Andra produced a three volume evaluation for a proposed repository in a clay formation:

- Proposed repository architecture and management;
- Analysis of repository evolution, considering all thermal, hydraulic, mechanical and chemical phenomena in the environment over a period of one million years [119];
- Repository safety assessment and risk analysis, in both normal and non-normal situations (including low-probability events and possible incidents) [120].

Extensive geological investigations have been carried out. The programme has concluded that the site/formation is long-term stable, with very low permeabilities, high retardation, absence of major faulting and low seismicity. In addition, there are no resources likely to be exploited in the future, and this includes low groundwater resource potential. The over-riding conclusion was that therefore very limited release of radionuclides to the environment (biosphere) is expected. This is likely to have influenced the limited emphasis on, and investigation of, the surface environment. Work appears to have focused on the engineering/near field and deep geological environment.

Topographical analysis (including erosion) and climate-change analysis (covering the past two million years and future predictions) has been carried out to evaluate possible variations in water flow over the next 500,000 to 1 million years (see Figure 8, from [118]). This primarily deals with effects on groundwater flows in the host rocks, but with consequential effects on potential discharge to the biosphere.
Dose impact studies for different scenarios were carried out based on very conservative assumptions. These required some assessment of the surface environment/biosphere, which was based on simple conceptual models (e.g. Figure 12 from [118]).
Figure 12. Conceptual model of radionuclide transfers from the geosphere to the biosphere for the Meuse/Haute-Marne site

From [118]

Thorne et al. [28] have pointed out that Andra has subsequently carried out a comprehensive assessment on the initial environmental state of the site. The results of that study will be used as the initial reference state for the future environmental monitoring of the Meuse/Haute-Marne Underground Research Laboratory (MHM URL) [121]. That initial assessment is relevant to SDM development and is complemented by a description of site characteristics that is available only in an Andra internal document (Plan General du Referentiel de Site, 2009). It is described as comprising five documents, but only four are listed in Volume 3, which was the only one provided by Andra to NDA/RWMD. Volume 3, The Natural Evolution of the Meuse/Haute-Marne Site (Chapters 26 to 34) was used by Thorne et al. [28] in their study related to site characterization and SDM development.

Volume 3 of Plan General du Referentiel de Site (2009) goes beyond site-descriptive modelling in the sense used by SKB and Posiva Oy. Rather, it combines what is known about the past evolution of the site and its current characteristics to make projections of likely future characteristics and to report those future characteristics in a form suitable for use in assessment modelling. The approaches that are adopted to climate, geomorphological, hydrogeological and ecological characterization and projection are
outlined in Thorne et al. [28] and on the basis of that review Thorne et al. provided a description of site characterisation studies, as reproduced below.

"it is clear that the baseline surveys that have been conducted at the MHM URL relate primarily to the requirements of Environmental Impact Assessment, but with a special emphasis on providing a comprehensive analysis of radioecological conditions. The subsequent environmental studies that have been undertaken give a particular emphasis to geomorphological investigations. This includes both detailed work on the past evolution of the landscape and 3D modelling projections of its future evolution over the next one million years. This emphasis on geomorphological evolution would seem to arise from two considerations:

- with a GDF located in the Callovo-Oxfordian, timescales of release of radionuclides to the near-surface environment are likely to be very long (hundreds of thousands to millions of years);
- the landscape is evolving relatively rapidly due to valley incision and this has important effects on hydrogeology, e.g. through restructuring of the drainage network.

Both the geomorphological and hydrogeological studies emphasise the importance of making projections of landscape evolution at different spatial scales. For the MHM URL these range from a regional scale that includes the whole of the Paris Basin down to a local scale of individual river valleys. The importance of integrating palaeoenvironmental data at these different scales is also clear and issues arise because of the fragmentary nature of the palaeoenvironmental record both spatially and temporally. In particular, whereas long, relatively continuous records are available regionally, local records tend to be of more limited duration.

In providing a palaeoenvironmental interpretation, it is seen as important to integrate various types of data, e.g. pollen data from lacustrine sediments and faunal assemblages from archaeological sites. In integrating these data, consideration has to be given to potential sampling biases in the different types of records.

For assessment purposes, the work is directed to using a combination of descriptive and numerical modelling strategies to interpret past and present day conditions to make projections of future environmental conditions at the site. The emphasis is on constructing future sequences of states and transitions between them. States and transitions are illustrated and described only qualitatively, and it is not clear how these descriptions will be translated into quantified information for use in assessment modelling."

The extensive studies undertaken by Andra directed to including palaeoenvironmental data in the SDM to provide a basis for geomorphological projection is worthy of note. In the 1980s and 1990s, the Nirex biosphere research programme included a substantial geomorphological component [122]. That component emphasized the need to evaluate valley incision in a UK context, so work by Andra on this topic is likely to be of relevance to the UK.

To date, no French research site in granite rocks has been identified and there has been no site characterisation work equivalent to that carried out at the Meuse/Haute-Marne site. However, the likely fractured nature of granite rocks was recognised, with consequently greater potential for earlier transport of radionuclides back to the surface/biosphere. Andra’s evaluation of granite host rocks has relied on foreign research programmes in equivalent formations, including those of Sweden and Finland.
The US Department of Energy's (DOE) administers the Waste Isolation Pilot Plant (WIPP) deep-geological nuclear repository for the disposal of US defence-related transuranic waste (i.e. intermediate level waste), located in New Mexico. WIPP is an operational repository, which began receiving waste in March 1999.

The WIPP site is situated in a semi-arid region; there is little surface water and none on or close to the disposal site. The area has been studied geologically for more than a century, with more recent study related to the development of several natural resources, in particular oil and potash. WIPP-specific investigations have been conducted from around the mid-1970s.

The disposal horizon lies within a rock salt deposit (predominantly halite, with minor components/interbeds of related salts and clastic sediments) known as the Salado Formation. This formation is regionally extensive, includes continuous beds of salt without complicated structure and there is believed to be little potential for dissolution of evaporite in the immediate vicinity of the WIPP. Waste disposal takes place at a depth of 650 m below ground surface.

Site characterisation and performance assessments have been developed by DOE. Certification for operation of the repository was granted by the US Environmental Protection Agency (EPA) based on a 1996 performance assessment (this followed four preliminary performance assessments between 1989 and 1992). Recertification is required every 5 years and has subsequently been granted in 2004 and 2009.

The WIPP site fits within the NDA "Evaporites" type geological environment class (see Section 1.4) and therefore has some relevance to the UK site identification and characterisation programme, although the semi-arid nature of the climate differs from UK conditions.

**5.7.1 Overview**

The US EPA is responsible for regulation of the WIPP, which must meet environmental performance standards set out in federal regulations covering the period when radioactive waste is being emplaced and the long-term post-closure phase. Regulations for the latter phase set out three long-term numerical performance requirements: containment requirements, individual protection requirements, and groundwater protection requirements.

The intra-continental location of the site is assumed to be a long-term stable geological and geomorphological environment. The area is semi-arid in nature, with limited surface water transport pathways. Consequently, there appears to have been little significant quantitative evaluation/modelling of the evolution of the site, area or region (i.e. nothing on the scale of that undertaken for the Scandinavian sites). These are probably more significant factors than the salt host rock, although the limited predicted release to groundwater from the host rock (and thus pathway/discharge to surface) is also obviously an important factor. Together, these factors mean that there are no releases/impacts from assessed natural evolution scenarios.

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However, the presence of economic mineral reserves (potash, oil) is a feature of this site, along with the potential for the use of salt caverns (including purpose constructed) for conventional waste disposal. This has led to a greater focus on the evaluation of human intrusion scenarios (drilling, mining) in assessing future risk/dose impacts compared with other sites.

Overall, the main focus seems to have been on repository engineering and geological barriers (e.g. the disturbed rock zone around excavations, salt creep sealing and the potential for spalling have received much study) and potential for groundwater transport (including considerable scientific and public discussion around the potential for karst features at the site).

5.7.2 Methodology

The site characterisation programme carried out prior to constructing the repository described the WIPP site geology, hydrology, climatology, air quality, ecology, and cultural and natural resources. The objectives were to:

- Explain the characteristics of the site;
- Describe background environmental quality; and
- Discuss features of the site that might be important for inclusion in a quantitative performance assessment.

The development of assessment scenarios then followed four stages:

- Identification and classification of FEPs potentially relevant to the performance of the repository and site;
- Elimination of FEPs according to well-defined screening criteria;
- Identification or formulation of scenarios relevant to the performance of the repository and site; and
- Specification of scenarios for consequence analysis.

The site characterisation information was used to develop and screen FEPs and to develop the conceptual, mathematical, and computational models to evaluate the performance of the planned repository (natural and engineered barriers) in comparison with applicable environmental performance standards. FEPs were evaluated both by DOE and by independent review groups.

FEPs were screened based on the acquired basic understanding of the geology, hydrology, and climatology of the region and site. The screening methodology followed US EPA criteria on the scope of performance assessments. The outcome of the FEP screening determined what physical processes should be modelled at the WIPP site.

Conceptual models of the WIPP disposal system were developed to simulate the interaction between the natural environment, the engineered structures and the waste. The starting point for development of the conceptual models was an understanding of the natural characteristics of the site and surrounding region, based on field data collection.

Conceptual model development principally consisted of cataloguing and qualitative description of natural environmental, climate, water and mineral resources, radiation
background, ecological and cultural aspects of the site/area/region, supplemented by straightforward quantitative assessments of relevant features (e.g. precipitation, river and groundwater flows, water balance calculations, etc.). There is no evidence of significant modelling of these aspects.

In total, 24 conceptual models were developed to describe the WIPP engineering and environment for the initial certification assessment. This also included description of plausible alternative conceptual models that were considered but not used (with explanations as to why they were not used). A Conceptual Models Peer Review Panel was used to review the proposed conceptual models and rejected alternative models (e.g. [123]).

The background natural environment (including ecology) and cultural and archaeological history were investigated (by field and documentary investigation), described and documented as part of the site characterisation. These factors were assessed to have no impact on nor be impacted by the repository. Background radiation levels were also evaluated and documented.

Site characterization and model development was undertaken as an interactive process:

- Basic site information led to initial models;
- Model sensitivity studies indicated the need for more detailed information;
- More site characterization led to improved models.

Assessment of the impacts of uncertainty in the parameters used to numerically simulate geological features and processes also led to more in-depth investigations of aspects of the natural system.

Partly to meet regulatory requirements, a system was developed to maintain detailed descriptions and histories of data collection, reduction and analysis, and records of modelling code input parameters. This was based on a system of forms and other documents which formed “records packages”. For example, the processes used in deriving modelling parameters from field and laboratory data were detailed in Data Records Packages supporting the conceptual models and derived parameters. The initial certification assessment contained approximately 1,600 parameters. The first recertification (2004) contained approximately 1,700 parameters and the most recent recertification (2009) a further 90 new parameters and 15 modified parameters.

5.7.3 Site descriptive modelling

Studies addressing near-surface geology and hydrology at and near the WIPP site have focused on evaluation of processes (e.g. [124]). For example, much attention has been paid to evaluation of the potential for evaporite dissolution within the Rustler Formation. Site characterisation studies have consisted primarily of “conventional” field studies and conceptual/deterministic (i.e. non-probabilistic) interpretations, correlations and basic water balance calculations.

There is some discussion of near-surface and surface hydrology. In particular, investigation of how the hydrological setting of the vicinity of the WIPP site has changed over the last 600,000 years, from a setting which has included deposition and actively eroding streams, to a relatively stable environment (from approximately 350,000 years ago).
All software employed was either bespoke, written for DOE by itself or by its contractors, or was openly available public domain software. No software requiring a licence was used. Modelling codes employed are reviewed in [125], although most of this concerns performance and impact assessment. Site characterisation modelling is discussed according to its role in supporting performance assessment.

Some of these codes are specific to the WIPP (and similar) salt rock/brine environment. Some could have wider application; however, the interconnected nature of the code sequence (e.g. requiring specific input/output formats) may make this impractical. Some key codes employed are listed below, although not all are equally relevant to characterisation of the biosphere.

**CAMDAT** is a database used by many constituent codes employed in the WIPP code sequence to hold both scenario set up and output data.

**Bragflo** is a program used to study two-phase (brine and gas), three-dimensional isothermal fluid flow in porous media. It has been developed specifically for use in assessing the performance of the WIPP, particularly the flow behaviour in the immediate vicinity of the repository, and is of limited relevance to biosphere characterisation.

**SECOFL2D and SECOTP2D** codes perform groundwater transport and release to the accessible environment, including single or multiple component radionuclide transport in fractured or granular aquifers. Fractured porous media are represented using a dual porosity model.

The DOE replaced the SECOFL2D flow code used in the initial performance assessment with ModFlow-2000, used with the parameter estimation code, PEST. (This combination was judged by the US EPA to be a significant improvement over the old code sequence).

**ModFlow-2000**, Version 1.6, is an acquired code used to solve both steady state and transient groundwater flow problems. The ModFlow groundwater software was developed by the US Geological Survey and has been continually upgraded since the first release in 1988. ModFlow numerically solves the three-dimensional ground-water flow equation for a porous medium using a finite-difference method. ModFlow is designed to be modular in that different functionalities such as wells, rivers, evapotranspiration, etc. can be added as modules to the basic groundwater flow solutions.

**PEST** is an acquired code that can perform parameter estimation and optimisation for any mathematical model. In the WIPP programme it was used in conjunction with the ModFlow-2000 groundwater flow model. PEST is freely available via the internet[^20].

The statistical codes, **PCCSRC, POSTLHS and STEPWISE** were used to evaluate parameter importance based on the correlation between input parameters and corresponding model output.

Other, more widely employed software (known as “acquired codes” within the WIPP programme) have also been used. These are not described here.

5.8 USA - Yucca Mountain

A geological repository for spent nuclear fuel from the civil nuclear power industry and other high level waste, including from defence programmes, was planned at the Yucca Mountain site. The US government has subsequently proposed to cancel this project and it is effectively on hold while political and legal challenges and a review of options for disposal of high level waste in the US proceed. However, a substantial safety assessment programme, including site characterisation and impact assessment, leading to a licence application, was completed.

Archived documents can be obtained from the US DOE Office of Civilian Radioactive Waste Management\(^{21}\). Documents were previously also available from the Licensing Support Network (LSN). Although the LSN website is no longer supported directly, much of the information can be accessed via the US Nuclear Regulatory Commission (US NRC\(^{22}\)). Documents from this source are not all in a download friendly form. The biosphere modelling undertaken in support of the Yucca Mountain project was also reviewed extensively under an international programme sponsored by the IAEA [126, 127].

The site is located in southern Nevada in the western United States. The area lies within the southern Great Basin, an arid/semi-arid, sparsely populated region. Yucca Mountain consists of a series of north–south-trending ridges, approximately 40 km long and reaching an elevation of 1,500 m to 1,900 m above sea level, 300 m to 450 m above the surrounding land.

Yucca Mountain is composed of layered welded and non-welded volcanic tuffs, underlain by older carbonate rocks. Superficial deposits in the area include thin to absent unconsolidated sediment over bedrock, unconsolidated sediment fans and debris-flow deposits along the base of hill slopes and valley sides and windblown deposits [128]. The planned repository would have been constructed in the volcanic strata (tuff), at least 200 m below the ground surface and 160 m above the water table.

The Yucca Mountain site fits within the broad description of the NDA “Lower strength sedimentary rocks” type geological environment class (see Section 1.4). However, the site is characterised by an unsaturated zone hundreds of metres deep and the repository was to be situated in that unsaturated zone in a mixture of lithophysal and non-lithophysal tuffs [129]. Such an environment is not known to be present in the UK.

5.8.1 Overview

The main site characterization programme was conducted (by US DOE) between 1988 and 2001, along with pre-existing information leading to the Yucca Mountain Site Description [130]. There have been some subsequent further site characterisation activities but of limited extent.

A four step strategy, called “strategy for issue resolution” was used to define the information needed to address the principal regulatory requirements and develop (and document) the site characterisation process:

\(^{21}\) [http://www.energy.gov/environment/ocrwm.htm](http://www.energy.gov/environment/ocrwm.htm)

• Develop a preliminary licensing strategy;
• Identify performance measures;
• Identify information needs;
• Develop testing strategies to produce the needed information.

This was aimed at both determining the site’s suitability for development of the planned repository and subsequently obtaining licensing.

A FEP-based process was employed (see previous discussion), with conceptual models produced and developed based on the compilation of site investigation and characterisation data. Expert judgement ("elicitation") was also employed in the process, for example to develop estimates of probabilities and consequences.

The Yucca Mountain Site Description report ([130]) summarises the results of an extensive site investigation and characterisation process. This was predominantly based on project specific investigation programmes, but also used some other (pre-existing) data for the area and generic information. The focus was on: geology and geomorphology, conditions and processes affecting radionuclide transport, climate (past, present and future), unsaturated zone hydrology and saturated zone hydrology.

It should be noted that some of the data collection techniques and their interpretation were challenged in contentions submitted to the US NRC and accepted as needing to be addressed (see [131] and [132] for details and references to the submissions).

There appears to have been little modelling associated with the construction of the site description. For the most part, data were compiled and interpreted into conceptual models and associated parameters using straightforward methodologies. Analysis and calculation associated with derivation of parameters (such as infiltration and recharge rates, saturated and unsaturated permeabilities, interpretation of test results etc.) appears to have used established scientific methods, although there was a lot of debate on the approach adopted for infiltration modelling [132].

Considerable attention was focused on investigating the movement of water in the thick unsaturated zone in which the repository would be developed, including model development and testing. More than 450 deep and shallow boreholes were drilled, with cores and water samples collected, to characterize geological and hydrological features and properties. Geochemical and isotopic studies were conducted to characterize unsaturated and saturated zone flow and transport, and to provide the basis for developing models to support performance assessment. The geomorphological setting was investigated to support evaluation of future landscape development. Meteorological monitoring and modelling, as well as biological and ecological investigations, were also performed.

Hydrological and hydrogeological studies developed an understanding of the surface water and groundwater flow systems, for the unsaturated zone and the saturated zone. Stream flow, infiltration and recharge rates were also studied, particularly with respect to estimating recharge contributions to the saturated zone system. Both in-situ and laboratory methods were employed [133] to measure a range of properties, including bulk density, particle density, porosity, volumetric water content, saturation, water potential, saturated hydraulic conductivity, and moisture-characteristic curves (see also [134], and the review by Thorne [132]).
Unsaturated zone studies were conducted. These were primarily aimed at understanding seepage (percolation) from the surface into the repository and the transport of radionuclides from the repository to the saturated zone, rather than the near-surface (biosphere zone) system. Studies included field and laboratory tests. Infiltration studies collected information to characterize infiltration rates for different soils, rock and geomorphological areas. Various laboratory and field techniques were used, including neutron soil moisture measurements in boreholes, infiltrometer tests and soil mapping. Six small watersheds were instrumented to record run-on/runoff and evapotranspiration rates.

Geomorphological investigations including evaluation of upland and hill slope erosion rates. Cation-ratio dating, C-14 and cosmogenic nuclide dating were used to calculate long-term feature development and erosion and removal rates for surficial material.

A long term meteorological monitoring programme was undertaken to establish local and regional conditions and extreme weather phenomena. Data collection included temperature, barometric pressure, humidity, wind direction, wind speed, cloud cover, rainfall amount, duration, and intensity. Climate studies looked at past, present and evaluated future states. This included study of various palaeo-climate indicators, including preserved records of flora, fauna and indicators of discharge sites and water table elevations [134, 135].

5.8.2 Methodology

For the purposes of Yucca Mountain site characterisation and performance assessment, the biosphere was defined as the total ecosystem, including organisms, climate, soil, surface waters, and air. The concept of a reference biosphere was employed, referring to a representation of the environment inhabited by a hypothetical receptor, the reasonably maximally exposed individual. The present-day characteristics and population of the local (Amargosa Valley) area were used to describe the reference biosphere and the pathways by which radionuclides released into the environment could reach the receptor [136]. This appears to have been focused on the human population/impacts (e.g. surveys assessing the consumption of locally produced foods and well water).

A primary output of the site characterisation programme was the biosphere component of the total system performance assessment model[23].

5.8.3 Site descriptive modelling

Some key codes employed are listed below:

ArcGIS (Version 9.1 Desktop) was used for geographical data visualization and basic spatial analysis, and was also used for visualization of model output.

ArcGIS was used in the estimation of potentiometric surfaces using automated interpolation techniques. It was used as a geodatabase to store and manipulate data from various

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23 The performance assessment method employed is heavily constrained by regulation relating to location, groundwater abstraction, diet etc. of the Reasonably Maximally Exposed Individual (RMEI) and this may, in turn, have acted to limit some aspects of the biosphere characterisation.
sources, including regional water level data, spring and surface water mapping and recharge/discharge area maps [137].

Schlumberger-GeoQuest's CPS-3 gridding and contouring software system was used to interpolate and map data throughout the study area. Interpolation employed a convergent gridding algorithm that utilizes a trend surface method to develop a series of successively more refined surfaces that honour all input data over a number of converging passes. The resulting surfaces exactly match the input data, comply with user-specified breaklines and interpolate surface trends in areas where data are absent.

ASHPLUME [138] is a non-commercial model that solves diffusive transport (by atmospheric turbulence and wind) of particles distributed in a column (plume). A version of this code (ASHPLUME_DLL_LA) was used to predict sediment thicknesses deposited from historic volcanic eruptions in areas where field data were unavailable [139].

A three-dimensional unsaturated zone flow model (and several sub-models, including transport, temperature, gas flow, and geochemistry) was developed to simulate flow fields in the unsaturated zone (UZ) [140]. This model described fracture-fracture, matrix-matrix, and fracture-matrix liquid flow rates, their spatial distributions and the distribution of moisture conditions in the UZ system at different scales and under a variety of climatic conditions. This modelling was aimed at evaluating water infiltration, percolation and seepage and radionuclide transport away from the repository.

The TOUGH2 family of codes (TOUGH2, iTOUGH2, T2R3D, and TOUGHREACT) was used because of their generalized capabilities in handling UZ flow and transport in both porous and fractured rock. The following codes were employed.

- TOUGH2 (v 1.4, 1.6) Used to simulate three-dimensional UZ flow and to conduct model calibrations, for three-dimensional gas flow and for geothermal calibrations.
- T2R3D (v 1.4) Used in transport simulations, tracer transport travel-time estimates and modelling pore-water chemistry.
- TOUGHREACT (v 3.0) Used to conduct calcite studies.
- iTOUGH2 (v 4.0, 5.0) Used for modelling fault tests and fault property calibration.

These are custom codes produced “in-house” or for the project (e.g. by Lawrence Berkeley National Laboratory).

In addition, a range of standard commercial software was used in support of model development, data processing and visualisation. Key codes used were:

Surfer (Version 6.01, Golden Software) was used for visualizing model validation results in the context of published data.

Matlab (release 11) was used for generation of synthetic ash plume data sets based on simple equations.

OriginPro 7.5 was used for data visualization and generation of basic statistics.

Tecplot 360 software was used for visualization and grid processing.
5.9 Canada

The Nuclear Waste Management Organization (NWMO), established by Ontario Power Generation Inc., Hydro-Québec and New Brunswick Power Corporation, is responsible for the long-term management of Canada’s spent nuclear fuel.

Canada is currently undertaking a site selection process to identify a location for the proposed construction of a deep geological repository for disposal of high level radioactive waste. NWMO compared three methods for the management of high level radioactive waste: deep geological disposal, centralized storage above or below ground, and long-term storage at nuclear sites. A form of deep geological disposal, within a flexible development programme and incorporating retrievability, called Adaptive Phased Management (APM) was recommended and was approved by the Canadian government in 2007.

The open site selection process is based on voluntarism but is focused in four provinces already involved in the nuclear industry (Ontario, Quebec, New Brunswick and Saskatchewan). The ongoing preliminary planning activity is developing designs for repositories in both crystalline and sedimentary rock formations. A final site selection decision appears to be some way off and consequently no relevant site investigation and modelling work has yet been undertaken.

The development of a deep geological repository (DGR) for low and intermediate level operational and decommissioning waste from Canadian nuclear power plants (excluding spent fuel) is further advanced. A site near the existing Bruce nuclear site in Kincardine, Ontario, on the east shore of Lake Huron, is currently being investigated by Ontario Power Generation (OPG).

The Bruce disposal facility DGR is proposed to be located in low permeability limestone, beneath a 200m thick layer of low permeability shale at a depth of approximately 680m. Superficial deposits comprise sands and gravels and glacial till of variable thickness (1-20 m) and lateral extent. The current planned date for the DGR to be operational is 2018.

The area has relatively low relief and the site is located within the tectonically stable interior of the North American continent, has remained stable through past tectonic events, climate change and ice ages and is expected to remain stable for at least the next few million years. The climate is cool temperate, with annual precipitation of around 860 mm/yr. Lake Huron is the dominant surface water feature. There are no major rivers in the vicinity but several small streams discharge into Lake Huron. Land use in the region is mainly agricultural.

The Bruce site is discussed further in this report. A moderate number of technical/overview reports are available\(^\text{24}\), and a description of the biosphere system relevant to a post-closure safety assessment is presented in [141]. Data relevant to the present-day temperate biosphere conditions are presented in [142]. In general, however, there is little apparent detail on environmental/biosphere characterisation methodologies other than in the limited context of post-closure safety assessments.

The Bruce site fits within the NDA “Lower strength sedimentary rocks” type geological environment class (see Section 1.4).

\(^{24}\) [http://www.nwmo.ca/](http://www.nwmo.ca/)
5.9.1 Overview

Following the development of a Geoscientific Site Characterisation Plan, initial investigations focused on characterisation of the deep geosphere, with seismic studies and deep borehole drilling. A key aspect of the DGR Safety Case is the integrity and long-term stability of the sedimentary sequence over timeframes of 100,000 years and beyond. An initial Environmental Impact Statement and Preliminary Safety Report has recently been submitted for regulatory review [143].

The target sedimentary host formations at the Bruce site are considered to be a long term geologically stable environment and to be hydrogeologically isolated from the surface environment. In addition, there are no known commercially viable resources (such as oil and gas reserves) in the area. Due to these factors, the focus of site characterisation and safety assessment has been on the geosphere and near field, despite the relatively long (100,000 years and beyond) timeframe of the assessment.

An upper permeable fresh water carbonate aquifer forms the interface between geosphere and biosphere. There is both municipal and domestic use of groundwater supplies, primarily from the shallow bedrock groundwater system (30-100 m). With respect to surface systems, shallow geosphere and biosphere, there has been a focus on long-term climate change, in particular glaciation events. The region has seen a prolonged period of cyclic glacial and peri-glacial conditions during the latter half of the Pleistocene (at least 9 glacial events with a typical 115,000 year cycle and maximum ice-sheet thicknesses around 2.5 km) [144].

A preliminary post-closure radiological safety assessment was carried out (e.g. [145]), primarily based on site-specific information obtained from a Geotechnical Feasibility Study [146]. These studies have since been updated [141, 142]. A systematic safety assessment methodology has been used. This is intended to represent international best practice for safety assessments of radioactive waste repositories and is based on the International Atomic Energy Agency’s ISAM (Improving Long Term Safety Assessment Methodologies for Near Surface Radioactive Waste Disposal Facilities) methodology [52].

5.9.2 Methodology

Scenario development of future evolution of the repository and its surrounding environment was aimed at identifying general themes, rather than undertaking detailed simulations of projected change.

Environmental assessment and, consequently, characterization was focused on the components of the environment that may be affected by the DGR and was based on current environmental components and historical conditions where necessary to fully establish baseline conditions. The list of biosphere parameters considered is presented in [142] as:

- surface water parameters, such as surface run-off, infiltration, stream flows, lake exchange rates and irrigation rates;
- soil and sediment parameters, such as densities, porosities, depths and sorption coefficients;
- atmospheric parameters, such as dust and aerosol concentrations;
- plant parameters, such as crop yields and concentration factors; and
- animal parameters, such as stocking densities, ingestion rates and transfer factors.
The specific parameter values have been derived from compilation and review of existing information and the results from the multi-year field programmes that have been conducted. For the purposes of assessment modelling, a number of assumptions are also presented in [142] when field data are contradictory or incomplete.

### 5.9.3 Site descriptive modelling

Some key codes employed are listed below:

The **FRAC3DVS** code [147] was used to produce 3-dimensional numerical simulations of the groundwater flow system within crystalline and sedimentary rocks for a 20,000 km² regional domain. These studies (by the University of Waterloo) formed part of assessment of groundwater flow system dynamics during the Quaternary.

The **University of Toronto Glacial Systems Model** was employed to construct a suite of equally plausible models of the glaciation-deglaciation process in order to explore the range of surface conditions that could develop at Bruce site (including boundary conditions for hydrogeological modelling) [148].

### 5.10 Germany

The German Company for the Construction and Operation of Waste Repositories (DBE) is responsible for the design, construction and operation of German repositories for radioactive waste. A geological repository for all types of radioactive waste is planned in the Gorleben salt dome.

Very limited information is publicly available from the German radioactive waste management programme on relevant (biosphere/surface environment) investigations.

#### 5.10.1 Overview

Investigation activities at Gorleben were halted in 2000, under a moratorium for a minimum of three and a maximum of ten years. In 2009, the German government announced that the investigations would resume. However, no further information has been published to date.

The current waste management strategy foresees decentralised interim storage at the power plant sites, although there are centralised storage facilities at Ahaus and Gorleben. Radioactive waste will ultimately be disposed of in geological repositories. At present, DBE maintains an exploration mine at Gorleben and manages the Konrad mine in Salzgitter. A construction licence has been granted by the Environment Ministry of Lower Saxony for a geological repository for waste with low heat production in the former Konrad iron ore mine. Following the decision of the Federal Government in 2007 to use the Konrad mine as a repository, work on converting the facility has now been initiated.

DBE is also responsible for the former repository for LLW and ILW in Morsleben (ERAM), which is currently being backfilled and closure is planned in 2013/14.

#### 5.10.2 Methodology

No relevant work has been found to be available.
5.10.3 Site descriptive modelling

The only site descriptive modelling identified from the open literature relates to the development of atmospheric dispersion models, notably for particle dispersion\textsuperscript{25}. This is of little relevance to biosphere characterisation.

\textsuperscript{25} http://www.bfs.de/en/ion/anthropg/artm_modell.html
6 REVIEW OF APPROACHES EMPLOYED IN OTHER SECTORS

Whilst the formal development of SDMs may not be required, all large projects will have generic requirements to assess impacts to the environment and local populations. Environmental Impact Assessment (EIA) is routinely required for larger projects in developed countries, and this process drives the majority of environmental investigation and characterisation activity in other industrial and resource sectors. Timescales over which any environmental impacts may become apparent will be shorter than are required to be considered in radioactive waste disposal programmes (major impacts may occur during the construction phase or operational lifetime) but the requirement to characterise the environment in order to enable EIA should involve comparable processes across sectors.

Biosphere modelling may be undertaken on a range of scales for different purposes. Very local models (quantitative or qualitative) may be produced to support small-scale conservation works. At the other extreme, the US National Aeronautics and Space Administration (NASA) sponsors global ecosystem modelling\(^\text{26}\) as part of a strategy to better understand the impacts of greenhouse gases and climate change.

The various models are directed to answering different questions. Different models have different levels of detail, different degrees of accuracy, and different temporal or spatial scales. Some are used for retrospective analyses (to analyse what has happened – e.g. for determining compliance with annual radiation dose limits) or for prospective analyses (to project what may happen – e.g. for demonstrating compliance with licensing requirements).

The review presented here is a brief overview of interpretation and modelling activities that have been undertaken in support of site characterisation programmes in other sectors, which may be applicable to a UK based radioactive waste management site characterisation programme. Typically, EIAs for these examples require environmental baselines to be established, but these are generally restricted to the collection and compilation of monitoring and survey data. Overall, there is very little information on site characterisation methods in publicly available documents, with published material tending to focus on higher level outcomes (e.g. the results of environmental impact assessments).

In general, the approaches to developing SDMs implemented by SKB and Posiva (and reviewed above) and being considered by NDA/RWMD are already considerably in advance of those used in other sectors. Nonetheless, a broad overview of approaches to characterising the biosphere as a component of site characterisation in those other sectors is presented below.

6.1 Mining (including uranium tailings management)

The same range of potential environmental impacts exists as for other resource and infrastructure projects of similar size, with the potential for large volume release of hazardous materials (especially tailings and other processing wastes). This brings a similar requirement for EIA and thus site characterisation (e.g. see World Bank guidance [149], which indicates what should be in EIA and what impacts should be assessed). There appears to be a focus on operational and short-term impacts (including the local environment and human population) and, not surprisingly, on isolation of materials from the

\[^\text{26}\] http://geo.arc.nasa.gov/sge/casa/index.html
biosphere (rather than characterisation of the biosphere *per se*), as well as on rehabilitation of abandoned mines. The post-operations long-term legacy is also acknowledged.

No internationally funded or internationally coordinated programme addressing biosphere characterisation requirements associated with conventional (e.g. coal, iron and other metal) mining or quarrying has been identified. Nonetheless, a number of studies of relevance to biosphere characterisation have been undertaken.

For example, studies have been undertaken at the Tono mine and the Kamaishi mine in Japan [150]. The Tono mine includes the most extensive uranium deposit in Japan, and the Kamaishi mine is one of the largest iron mines in Japan. The Tono mine is the site for studies on sedimentary rocks and the Kamaishi mine for studies on crystalline rocks. Studies on the geosphere environment have been undertaken to build an information base on the safe disposal of high-level radioactive waste in deep geological formations. However, there does not appear to be a relevant study of the surface environment/biosphere.

More extensive biosphere-related studies have been identified with respect to uranium mining (including remediation of abandoned uranium mines). Much of this relates to water management and the remediation of contaminated water associated with site restoration activities (see, for example, [151]), but other biosphere interactions are also considered, e.g. characterisation of deep soil microbial communities [152].

The importance of obtaining baseline data for site characterisation prior to commencing mining activities has been emphasised by IAEA [153]. The guidance is relatively high level and recommends obtaining information relating to meteorology, geology, surface hydrology, sub-surface hydrology, soil types, local flora and fauna and current agricultural activities as part of preparing an EIA.

The software code Surpac was developed from the mining industry, where it is well established and widely employed, and performs geo-databasing, geological modelling, geostatistics and 3D modelling functions. It supports various common database, GIS and CAD (Computer Aided Design) data and file formats. It has been used by Posiva to develop a model of overburden thickness and structure.

The Spatial Analysis and Decision Assistance code, SADA, includes integrated modules for visualisation, geospatial analysis, statistical analysis, human health risk assessment, ecological risk assessment, cost/benefit analysis, sampling design, and decision analysis. Although not developed specifically for use in the mining industry, it offers capabilities of relevance to characterising a contaminated site, assessing risk, determining the location of future samples, and when designing remedial action. This software is described in more detail in Section 7.4.2 with respect to its potential applicability within SDM development. However, it is noted that as ‘freeware’ QA qualification may be required in order to ensure its robustness.

No additional sector-specific biosphere characterisation methodologies that could be applicable to a UK-based waste management site characterisation programme were identified during this review of mining sector activity.

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27 [www.gemcomsoftware.com](http://www.gemcomsoftware.com)
The sector generally has a requirement for both geological investigation and water management, with associated geological, hydrological and groundwater modelling. Specialist software tools aimed at mine design and geological modelling are more likely to be relevant to geosphere characterisation but could also have application to aspects of biosphere characterisation. For example, the mining-industry derived Surpac software package (see Section 6.1) was used by Posiva for visualisation and interpolation of shallow geology (overburden) for the Olkiluoto site (see Section 5.4.3).

6.2 Dams

Potential large impacts on the environment (changes to ecology, impact on human population) means that impact assessments are required for large dam projects. Documentation is available from several international agencies: The International Commission On Large Dams (ICOLD)\(^{28}\), The International Energy Agency (IEA)\(^{29}\), The World Commission on Dams (WCD)\(^{30}\); and The World Bank\(^{31}\).

For example, World Bank Operational Directives \([149]\) indicate broadly what should be covered by EIA and what impacts should be assessed. EIAs are likely to consider a range of impacts comparable to those of a GDF: including on climate, geology and soils (from the point of view of construction), flora and fauna, human population/habits/land use. Timescales over which impacts are considered are shorter, covering direct construction and operational impacts and future impacts on timescales of a human lifetime.

Guidance is also available from the Environment Agency on scoping the environmental impacts of hydroelectric projects \([154]\). This sets out broadly what should be covered by an EIA, but is focused on short- to medium-term impacts.

A number of software codes have been identified relating to impact assessment following dam failure\(^{32,33}\) or modelling hydraulic requirements for water distribution\(^{34}\), however these are clearly not applicable to DBM or SDM development. More general software codes such as Surfer (see Section 7.1.2), SHE (see Section 7.2.1) or MIKE BASIN (see Section 7.2.2) are relevant to pre-construction terrain modelling, contour mapping, 3D surface mapping, volumetric calculations, catchment flow and simulation of river channel development caused by changes to the hydraulic regime.

No additional sector-specific biosphere characterisation methodologies or tools that could be applicable to a UK-based waste management site characterisation programme were identified during this review of large dam projects.

\(^{28}\) http://www.icold-cigb.net

\(^{29}\) www.iea.org

\(^{30}\) http://www.dams.org

\(^{31}\) http://www.worldbank.org


\(^{33}\) https://www.preventivestrategies.net/public/news_article.cfm?newsId=7205

\(^{34}\) http://www.gibb.co.za/SERVICESECTORS/DamsHydropowerandUndergroundWorks.aspx
6.3 Oil and gas

Much of the environmental characterisation and modelling undertaken by the oil and gas industry is for the purposes of demonstrating potential impacts arising from drilling operations or discharges to the seabed or to land. A similar range of potential impacts (resulting from operational activities and contaminant releases) and receptors exists as for other industrial sectors, depending on location and environment. Therefore, an EIA/EIS is commonly required (many EIA/EIS reports could be cited, essentially one for each project conducted over the past two decades or so, statements presented here [155, 156, 157, 158, 159] are considered typical of the many that have been identified). Procedures look similar to other comparable industries/activities, with a focus on establishing environmental baselines [160] and potential short-term effects (presumably long-term impacts will also need to be considered although no long term environmental assessments have been identified here).

No additional sector-specific biosphere characterisation methodologies that could be applicable to a UK-based waste management site characterisation programme were identified during this review of the oil and gas industry. Software tools developed within the industry will generally be more relevant to geosphere characterisation, but a few have specific application to aspects of the biosphere characterisation [e.g. 161, 162]. The DRASTIC model of the US EPA [163] evaluates aquifer vulnerability using Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity. The Schlumberger-GeoQuest's CPS-3 is a gridding and contouring software system that can be used to interpolate spatial data. CPS-3 is a general-purpose mapping system that contains a wide range of gridding algorithms, common statistical utilities, mapping and contouring and volumetric calculations. CPS-3 is most widely employed in the oil industry but was used by the Yucca Mountain Program to interpolate and map data throughout the study area and interpolate surface trends in areas where data were absent.

6.4 Carbon capture and sequestration

The geological storage of CO$_2$ in deep permeable rock formations is the only method of carbon capture and sequestration (CCS) that has been applied on a commercial scale to date (e.g. [164, 165]). Operationally, these projects tend to have a close relationship to oil and gas industry methods and environmental assessment requirements are likely to be similar. However, reported site investigation and characterisation activities are primarily focused on reservoir characterisation and other aspects of the deep geology, and as such are likely to be of more relevance to geosphere characterisation. Surface (biosphere zone) monitoring carried out is aimed at leak detection (gas/atmospheric and groundwater monitoring).

Clearly, much of the modelling associated with the carbon capture industry relates to the kinetics of CO$_2$ reactions with solid and liquid phases of a variety of sorptive materials. However, there is also considerable reliance on understanding the evolution of methane, carbon dioxide, nitrous oxide, and chlorofluorocarbons from materials and processes, and their subsequent atmospheric dispersion. Increasing interest in the ability of forests and

other biosphere systems to sequester carbon has also led to an emphasis on carbon transport through soils, peatlands and vegetation. However, there appears to be little of relevance regarding environmental/surface (biosphere) characterisation or modelling.

Environment Agency guidance on scoping the environmental impacts of carbon capture and storage is available [166]. This sets out broadly what should be covered by an EIA, but is focused on short-term impacts. Specifically, the Environment Agency note that (and require information relevant to the risks from):

3.5 Surface water hydrology can be affected by the additional abstraction requirements of the capture plant, leading to reductions in the river water flow.

3.6 Surface water quality could be affected during the pre-operation/construction phase through discharges from pipeline testing, earthworks and accidental spillage. During the operation phase surface water could be affected by wastewater discharges from capture plant activities and cooling. The receiving environment could potentially be polluted during the operation phase by suspended solids from site runoff, and through disturbance to contaminated land and accidental spillage and leaks of substances used in the capture process onsite. Surface water may also be affected by all activities in the CCS chain through a potential leak of CO$_2$, causing surface water acidification.

3.7 Groundwater hydrology can be affected through the construction and physical presence of the pipeline and capture plant. This could divert the course of groundwater flow, potentially having implications for surface water and aquatic ecology.

3.8 Groundwater quality could be affected in the event that leaks and spills that may occur onsite were allowed to seep into the ground and infiltrate into the groundwater. In an abnormal release of CO$_2$ from the transport system or storage site during operation or post closure, the groundwater could become acidified, which could lead to leaching of trace metals from surrounding matrix. Injection of CO$_2$ into the storage formation could lead to the displacement of brines, which can pollute groundwater on contact.

No reference to specific data acquisition techniques, site or biosphere descriptions or interpretive modelling approaches are described.

Further guidance is available from DECC relating to site characterisation requirements$^{36}$. These relate almost exclusively to geological and hydrogeological characterisation and contain reference to monitoring that may be required to ensure no unacceptable impact on other nearby activities.

It is anticipated that many of the surface geology, hydrology, hydrogeology and biosphere tools identified in Section 7 will be of relevance to biosphere characterisation for the pre-construction phase of CCS applications, but no sector-specific biosphere characterisation methodologies or tools that could be applicable to a UK-based waste management

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$^{36}$ http://www.google.co.uk/#hl=en&sclient=psy-ab&q=model+carbon+capture+site+characterisation&oq=model+carbon+capture+site+characterisation&gs_l=hp.12...1612.13220.0.15206.42.41.0.1.1.1.6.1756.10647.0[28][5][1][8-2.40.0...0...1c.1.8.psy-ab.6g3Ftx2p7M&pbx=1&bav=on.2,or_r_qf.&bvm=bv.44770516,d.d2k&fp=298109f27689c78d&bih=989&bih=532
biosphere characterisation programme were identified during this review of carbon capture and sequestration projects.

6.5 Waste Disposal (Landfill)

Article 4 of the European Union Waste Framework Directive (2006/12/EC) requires that waste shall be “disposed of without endangering human health and without using processes or methods which could harm the environment”. In turn, this requires that the environment is sufficiently well characterised that measures of potential harm can be assessed. The parameters to be measured and the substances to be analysed, as well as the frequency of measuring, are typically laid out in the permit document. Whilst broader biosphere measures may be introduced, such monitoring is typically related to the quality of surface and groundwaters and air quality (chemicals, dusts, microbes).

The Environment Agency presents a data acquisition and modelling strategy [167]; although the focus for health risk assessment is based on direct measurement. Modelling of risks to groundwater from landfill leachate may be undertaken using the LandSim code [168, 169, 170] or other groundwater modelling packages such as MIKE SHE, ModFlow, ConnectFlow, FeFlow (described in Section 7.2.2 to 7.2.5) and GoldSim (described in Section 7.4.5). In the context of landfill assessments, LandSim offers the advantages of many default options allowing both generic and site-specific assessments to be undertaken.

Norwegian regulations concerning the landfilling of waste specifically make provision for site-specific risk assessments, including both geological/hydrological assessments and biosphere impact assessments37. However, guidance for associated biosphere characterisation has not been identified to date.

No additional sector-specific biosphere characterisation methodologies or tools that could be applicable to a UK-based waste management site characterisation programme were identified during this review of the non-radiological waste disposal industry.

6.6 Food Quality and Agriculture

Over many years, the UK Food Standards Agency, and its predecessor body the Ministry of Agriculture Fisheries and Food, sponsored development of SPADE - a model for the transport of contaminants in terrestrial foodchains - in order to be able to assess potential impacts on food quality of routine or accidental releases to the atmosphere [e.g. 171, 172]. This has been replaced subsequently by mathematical models implemented in AMBER and used in PRISM (see Sections 7.4.3 and 7.4.5 for a fuller description of PRISM and the model platform AMBER). In many respects, e.g. representation of soils, characterisation of plant growth, correlation of soil sorption and root uptake, the models are radically different from those in SPADE.

The structure of, and parameter values within, the generic soil-plant model is documented in Walke et al. [173, 174] (see also [175, 176] for a verification report and user guide). The conceptual approach introduces a number of features of relevance to characterisation of the vegetation component of the biosphere, notably changes in various components of plant

37 http://www.klif.no/artikkel____38633.aspx. This site presents an unofficial translation of regulations relating to protection against pollution and concerning waste (the Pollution Control Act).
biomass with season, distinction between leaf components relevant to stomatal uptake and time-dependent root distributions throughout the soil profile.

Current versions of the code and supporting database [e.g. 174] are primarily of interest in defining site-specific parameters that need to be characterised to support radionuclide transport modelling, and the model does not otherwise lend itself to SDM development.

A generalised soil erosion tool developed on behalf of the US Department of Agriculture, USPED/RUSLE [104], may have some limited applicability to the development of a DBM/SDM as it identifies both soil loss as a function of rainfall and the concept of the maximum annual soil loss that can be tolerated whilst maintaining site stability. A more detailed discussion is presented in Section 7.3.1.

6.7 Conclusions

All major projects within the European Union, and in many other countries or projects with international funding, will be required to assess impacts to the environment and local populations. Furthermore, requirements to assess impacts from industry sectors such as mining, energy and waste disposal may be expected to have some overlap with the requirements for site characterisation within the radioactive waste management and disposal sector. However, this review suggests that whilst the approaches adopted within other industry sectors are fit-for-purpose, there is little that is innovative or immediately evident that it should be adopted within the RWMD site characterisation programme.
7 TOOLS EMPLOYED IN DATA PROCESSING, INTERPRETATION AND MODELLING

There are a large number of tools available for data processing and interpretation and for modelling of geosphere-biosphere systems. For the most part, the lowest level of detail on approaches to processing of raw field-collected data has proved difficult to obtain, i.e. at the level of processing such as pressure transducer output to give borehole or stream water level data. However, particularly with modern instrumentation, this could be considered a functional part of field monitoring activities, likely to be completed by consultants/contractors as a routine part of data acquisition activities and following established industry standard practice or vendor-specified procedures. This would fit with proposed NDA data management procedures, where data collector/provider consultants/contractors would be responsible for providing qualified higher-level data to the NDA database system [e.g. 67]. Nonetheless, this does not rule out that methods of sampling, of in-situ field analysis, or of transport of samples for laboratory analysis, will result in data of differing quality, and this may need to be taken into account when developing an SDM. A good example is the five-level classification scheme for hydrochemistry data used by SKB. All the data are stored on the database, but differently qualified subsets may be used for various purposes. Similarly, in the Yucca Mountain Project, results for all the groundwater samples are stored, but those that may have been subject to microbiological alteration are flagged.

Accepting that this lowest level of interpretation can be set aside (with due consideration of data quality as noted above), further care is needed in defining the break point at which data processing becomes an integral part of the SDM. For example, if paired measurements of soil water content and matric potential are made for a soil sample taken from the site, is the input to the SDM these paired measurements or a relationship between them (e.g. expressed in terms of the coefficients of a Van Genuchten soil water retention curve [see, e.g. 177])?

At whatever level the break point is set, it seems likely that a hierarchy of interpretative models will be used to develop the SDM.

Models may represent systems at a number of levels 0D (point-scale, like the soil water retention curve mentioned above), 1D, 2D, 3D or 4D (models of time-series data acquired in 3D), with varying degrees of complexity to represent the system components (e.g. ‘soil’ or ‘organic soil’, ‘inorganic soil’, ‘soil water’; with or without specific depth representations and alignment to rooting profiles). Many of the models available have been developed for the purpose of assessing dose (to man or biota).

A distinction may also be made between presentational models and interpretative models. Presentational models are used to display spatially and/or temporally distributed datasets to allow the user to visualise the data in relation to each other. GIS systems are often used for this, allowing 2D and 3D spatially distributed datasets to be displayed and examined. Time-series data can also be represented (e.g. by inset displays at specific locations in the model or by sequences of 2D or 3D displays representing the evolution of the system). Presentational models may be used to examine input data sets provided to the SDM or data sets resulting from the application of interpretative models.

It is also worth noting that considerable skill is required in selecting the most appropriate type of presentational model. A familiar approach is to display the surfaces of volumes in a projection of a 3D space. Figure 13, taken from SKB [23], shows this approach.
Figure 13. 3-D visualisation of deformation zones and fracture domains

From [23]. Deformation zones are coloured by the hydraulic conductivity within the zones and drawn as volumes to show their assigned hydraulic width. The depth dependency is clearly apparent. The effect of conditioning to a measurement was to extrapolate the conditioned value over the entire length of the deformation zone laterally, but not more than 100 m vertically.

More abstract representations can also be used. Thus, for example, Figure 14 shows how sparse hydrochemical data can be displayed on a 3D plot. This approach avoids overinterpretation of the data as would occur, for example, if they were used to generate concentration contours in 3D.

Figure 14. Display of point-scale data illustrating Cl concentrations and their lateral and vertical distribution, obtained from various boreholes

From [23]. SE-NW view of the Forsmark area showing the main surface features such as lakes and coastline; the borehole names and sample locations are shown.
Interpretative models may be the direct result of computations (e.g. 3D flow fields obtained from a hydrogeological model), but they can also include an expert judgement component that uses the data to develop an overall conceptual system model. Figure 15 shows a 2D vertical hydrogeochemical model that respects the data, but that is generalised and abstracted.

**Figure 15. 2D Vertical Hydrogeochemical Model**

From [23]. WNW-ESE 2D cross-section through the central part of the candidate area showing the groundwater types and their properties (salinity, origin, major reactions and redox conditions). The footwall (FFM01 and FFM02) and hanging wall (FFM03) bedrock segments are indicated, separated by the gently dipping deformation zones ZFMA2 and ZFMF1 (abbreviated A2 and F1), and the steeply dipping deformation zone ZFMNE0065.

Visualisation tools are important for SDM development and GIS systems are generally appropriate for displaying multi-layered biosphere data. One issue that has to be considered with such tools or related software is how inconsistencies between different datasets are to be resolved. This is exemplified in the construction of Digital Elevation Models (DEMs) where chart and map data may be combined with local field survey or remote sensing (e.g. LIDAR) data. The various datasets will have different levels of vertical resolution and will likely have been collected over different (and often overlapping) areas. Similar issues arise with the construction of 3D lithostratigraphic models where different types of data (ground-penetrating radar, electromagnetic survey, seismic survey, trial pit and borehole) may need to be integrated.

In other cases, the environmental transport and distribution of the radionuclides may be the primary focus of interest, and the model may give greater emphasis to relevant processes and pathways. A large number of research tools have been developed in support of field
and laboratory investigations. These are not addressed further in the following commentary.

The following presents a brief description of some of the most commonly used tools (whether available commercially, developed for specific applications or freely available via web-based downloads). Considerations in the application of such tools include their accuracy and resolution, the level of site-characterisation information that is required, or can be accommodated, and other input and output requirements. Additionally, the interoperability of tools, their availability and the degree of bespoke development involved are potential issues associated with their use.

7.1 General tools

7.1.1 Geographical Information Systems (GIS)

ArcGIS is a very widely employed modern GIS system which is developed by Esri. ArcGIS provides a framework providing geodatabase, spatial processing and analysis and visualisation functions. A wide range of ready-to-use tools is available, including fairly sophisticated data processing and analysis tools through a range of add-on packages. It also provides the ability to build custom scripts, models, and integrated workflows. ArcGIS supports a wide range of data formats and contains tools to create and administer databases, define data schemes, manage metadata and maintain database integrity.

A freely distributed viewer application, ArcGIS Explorer, is also available.

ArcGIS has been used within the SKB, Posiva and Yucca Mountain projects for various data manipulation, geographical data and model output visualization and basic spatial analysis (interpolation) purposes. Other GIS systems are available, most notably MapInfo, which is developed by Pitney Bowes and provides a similar range of tools and functions to ArcGIS. MapInfo appears to have been focused increasingly on business intelligence type applications recently, but does still provide environmental/science based tools. It has not been used, in a prominent way, in any of the national programmes reviewed.

GRASS is an open source GIS providing 2D and 3D data management, spatial modelling and visualization of many types of data. It is released under a Public License and runs on many computer platforms. Originally produced by the US Army Construction Engineering Research Laboratories in 1982, GRASS continues to be developed and is used by academic, commercial and government agencies. GRASS now has both a command line and windows interface and contains over 350 programs and tools for data management and processing.

38 http://www.esri.com/software/arcgis/index.html
40 http://www.pbinsight.com/products/location-intelligence/applications/mapping-analytical/mapinfo-professional/
41 http://grass.fbk.eu/intro/general.php
7.1.2 Other tools

Golden Software's Surfer is a 3D surface modelling, contouring and visualization package\(^42\). Surfer is used extensively for terrain modelling, surface analysis, contour mapping, 3D surface mapping, volumetric calculations and visualization. Surfer provides a range of data interpolation and gridding methods, with detailed control over gridding parameters, filtering, smoothing, geostatistics etc. Surfer has many capabilities in common with GIS, including support for a wide range of real world coordinate systems in recent versions. Surfer (Version 6.01) was used for visualizing model validation results by the Yucca Mountain Program.

MATLAB is a high-level technical mathematical computing language and interactive environment for algorithm development, data visualization, data analysis, and numerical computation\(^43\). It provides functions for linear algebra, statistics, Fourier analysis, filtering, optimization, and numerical integration. There are also 2D and 3D graphics functions for visualizing data and tools for building custom graphical user interfaces. Matlab is well established and provides more detailed and rigorous mathematical analysis than common office software.

PEST is a parameter estimation program that can be used with other models to calibrate parameters quickly using a set of known observations\(^44\). PEST can adjust model parameters and/or input data so that the discrepancies between model-generated numbers and corresponding measurements are minimised. It does this by taking control of the model execution and running it as many times as is necessary in order to determine this optimal set of parameters. Links to PEST are now built in to the interfaces to some widely employed modelling packages, such as ModFlow and FeFlow. PEST is freely available via the internet.

7.2 Hydrological tools

7.2.1 SHETRAN

In the 1980's the Système Hydrologique Européen (SHE) model was developed as a hydrological modelling system for water flow in river catchments by a consortium of three European organizations: the Institute of Hydrology (UK), SOGREAH (France) and the Danish Hydrological Institute (Denmark) \(^178\). Its successors are MIKE SHE (DHI) and SHETRAN (School of Civil Engineering and Geosciences, Newcastle University).

The SHE model was renamed SHETRAN by Newcastle University, after the introduction of the sediment and solute TRANsport component \(^179\). Since then it has undergone further improvements. The biggest change was the introduction of a fully 3-dimensional subsurface or variably saturated subsurface (VSS) component. Recent changes have focused on making the model more user friendly with the introduction of a graphical user interface \(^180\). This includes the automatic generation of river channels from a digital elevation model (DEM) so that a catchment simulation can be set up rapidly. The plan area

\(^42\)\text{http://www.goldensoftware.com/products/surfer/surfer.shtml}
\(^43\)\text{http://www.mathworks.co.uk/products/matlab/index.html}
\(^44\)\text{http://www.pesthomepage.org/}
of the catchment in SHETRAN is usually in the range of one to a few thousand square kilometres and the vertical depth of the subsurface domain is usually less than 100m.

Newcastle University has established a website in support of SHETRAN. The main components and processes represented within SHETRAN are tabulated below.

### Table 5  SHETRAN Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water flow</strong></td>
<td>Canopy interception of rainfall;</td>
</tr>
<tr>
<td></td>
<td>Evaporation and transpiration;</td>
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<tr>
<td></td>
<td>Infiltration to subsurface;</td>
</tr>
<tr>
<td></td>
<td>Surface runoff (overland, overbank, and in channels);</td>
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<tr>
<td></td>
<td>Snowpack development and snowmelt;</td>
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<tr>
<td></td>
<td>Storage and 3D flow in variably saturated sub-surface;</td>
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<tr>
<td></td>
<td>Combinations of confined, unconfined, and perched aquifers;</td>
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<tr>
<td></td>
<td>Transfers between subsurface water and river water;</td>
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<tr>
<td></td>
<td>Ground-water seepage discharge;</td>
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<tr>
<td></td>
<td>Well abstraction;</td>
</tr>
<tr>
<td></td>
<td>River augmentation and abstraction;</td>
</tr>
<tr>
<td></td>
<td>Irrigation.</td>
</tr>
<tr>
<td><strong>Sediment transport</strong></td>
<td>Erosion by raindrop and leaf drip impact and overland flow;</td>
</tr>
<tr>
<td></td>
<td>Deposition and storage of sediments on the ground surface;</td>
</tr>
<tr>
<td></td>
<td>Total-load convection with overland flow;</td>
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<tr>
<td></td>
<td>Overbank transport;</td>
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<tr>
<td></td>
<td>Erosion of river beds and banks;</td>
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<tr>
<td></td>
<td>Deposition on river beds;</td>
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<tr>
<td></td>
<td>Down-channel advection;</td>
</tr>
<tr>
<td></td>
<td>Infiltration of fine sediments into a river bed.</td>
</tr>
<tr>
<td><strong>Solute transport</strong></td>
<td>3D advection with water flow;</td>
</tr>
<tr>
<td></td>
<td>Advection with sediments;</td>
</tr>
<tr>
<td></td>
<td>Dispersion;</td>
</tr>
<tr>
<td></td>
<td>Adsorption to soils, rocks, and sediments;</td>
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<tr>
<td></td>
<td>Two-region mobile/immobile effects in soils and rocks;</td>
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<tr>
<td></td>
<td>Radioactive decay and decay chains;</td>
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<tr>
<td></td>
<td>Deposition from atmosphere;</td>
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<tr>
<td></td>
<td>Point or distributed surface or subsurface sources;</td>
</tr>
<tr>
<td></td>
<td>Erosion of contaminated soils;</td>
</tr>
<tr>
<td></td>
<td>Deposition of contaminated sediments;</td>
</tr>
<tr>
<td></td>
<td>Plant uptake and recycling (simple representation only);</td>
</tr>
<tr>
<td></td>
<td>Exchanges between river water and river bed.</td>
</tr>
</tbody>
</table>

Downloadable versions of SHETRAN are available free of charge (although registration is required) from the website. The downloadable version does not contain all of the most recent modifications and additions to the code. Notably, the downloadable version does not include the recent extension of the contaminant component to represent nitrogen transformations in soils, embedding of a two-dimensional analytical solution to represent groundwater flows near abstraction wells or particle-tracking codes for mapping groundwater protection zones.

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45  [http://research.ncl.ac.uk/shetran/](http://research.ncl.ac.uk/shetran/)
A number of case studies, and full documentation for the downloadable version of the code, are available from the website.

A variant version of the modelling system is also available that includes ice-formation and melting in the surface-water system as well as ground-freezing effects. This variant includes full 3-D heat transport calculations.

7.2.2 The MIKE Suite of Codes

The MIKE suite of codes has been developed by DHI, a Danish company. The codes have been established over a number of decades. Some, such as MIKE SHE, have their origins in international collaborative programmes. DHI report a range of case studies and relevant applications of their software on their website. Software from DHI is available commercially and includes the following water resources management tools.

1. MIKE 11 and MIKE FLOOD: provide 1D and 2D river modelling capabilities, including flood analysis.
2. MIKE 21C and MIKE BASIN: simulate developments in the river bed and channels caused by changes in the hydraulic regime. Simulated processes include bank erosion, scouring and shoaling brought about by activities such as construction and dredging or seasonal fluctuations in flows. MIKE BASIN is a multi-purpose, GIS-based river basin simulation package.
3. MIKE SHE: integrated modelling of groundwater, surface water, recharge and evapotranspiration processes.

Other software developed specifically for coastal and marine systems includes MIKE 21, which provides 2D simulation of physical, chemical and biological processes in coastal or marine areas. MIKE 3 offers 3D representations. MIKE Animator is a digital video production studio, which turns MIKE 21 and MIKE 3 model results into 3D video presentations.

Many of the MIKE codes are downloadable on a commercial basis, and a full description of the codes, capabilities, user-support resources and a catalogues of services, are available from the DHI software website.

MIKE3 has been used by SKB (Sweden) for the hydrodynamic and ecosystem modelling of the sea, including radionuclide dispersal, and MIKE11 has been used for modelling rivers. The MIKE suite of codes and SHETRAN have been compared for RWMD [181].

7.2.3 ModFlow

The ModFlow groundwater software was developed by the US Geological Survey (USGS) and has been continually upgraded since the first release in 1984. ModFlow numerically solves the three-dimensional ground-water flow equation for a porous medium using a

47 http://www.dhisoftware.com/
48 http://water.usgs.gov/nrp/gwsoftware/modflow.html
finite-difference method. The code can be used for both steady state and transient groundwater flow problems.

ModFlow is designed to be modular, in that different functionalities such as wells, rivers, evapotranspiration, etc. can be added as modules to the basic groundwater flow solutions. The unsaturated zone and variable density fluids can be modelled. Associated contaminant transport codes can provide radioactive decay chain modelling (e.g. MT3D99).

ModFlow is public domain software and is freely available from the website of the USGS, who continue to develop it. In addition, several commercial GUI interfaces to the ModFlow models are available, of which the most widely employed are Visual ModFlow, Groundwater Vistas and GMS. All of these support the range of ModFlow modules and provide a range of pre- and post-processing and visualisation tools. GMS also contains a finite element groundwater model, FemWater.

7.2.4 FeFlow

FeFlow is a software package for modelling fluid flow and transport of dissolved constituents and/or heat transport processes in the subsurface. FeFlow was originally developed by Wasy which is now a part of DHI, who continue to develop the code.

FeFlow is capable of solving a variety of non-linear groundwater flow and transport problems, including various representations of unsaturated groundwater flow and transport, and coupled thermal-hydro-chemical models. FeFlow is able to represent chemical reactions amongst transported contaminants, including radioactive decay chains and solid-phase and liquid-phase interactions.

FeFlow contains pre- and post-processing functionality and an efficient simulation engine. A graphical interface provides easy access to the extensive modelling and post-processing options within a completely integrated system. It includes a public programming interface for user code.

7.2.5 ConnectFlow

ConnectFlow is a groundwater modelling suite that integrates a continuum porous medium module (called NAMMU) and a discrete fracture network module (called NAPSAC). ConnectFlow can model groundwater flow and transport, including radionuclide species, in both fractured and porous media on a variety of scales. Steady-state and transient constant-density groundwater flow can be modelled, along with advective transport based on a particle tracking approach.

ConnectFlow has been developed by Serco Assurance (and previously by AEA Technology) over the last 15 years. It is more suited to modelling of the deep

49 http://www.swstechnology.com/groundwater-software/groundwater-modeling/visual-modflow
50 http://www.groundwater-vistas.com/
51 http://www.aquaveo.com/gms
52 http://mikebydhi.com/Products/GroundWater/FEFLOW.aspx
53 http://www.connectflow.com/
geosphere/groundwater flow system, lacking the tools for detailed simulation of the near-surface environment and has been used by SKB (Sweden) for deep groundwater modelling.

7.2.6 Other codes

SKB (Sweden) have used some other codes for hydrological and groundwater modelling:

**PCRaster-POLFLOW** was used to model surface hydrology, coupled advection and decay solute transport and surface water/groundwater discharge to the sea, applied within a GIS framework.

PCRaster is a raster GIS-based system developed at the faculty of Geographical Sciences of Utrecht University, the Netherlands. The system permits the integration of environmental process modelling functions with GIS functions and databasing. POLFLOW is a catchment-scale hydrologic modelling approach. SKB also used ArcGIS to perform some pre-processing of data for use with this model.

**PHAST** has been used to model groundwater transport and retardation in different geological and discharge conditions.

PHAST is a 3-dimensional, reactive-transport simulator that is available for Windows and Linux, developed within the USGS. PHAST simulates multicomponent, reactive solute transport in three-dimensional saturated groundwater flow systems, with capabilities to model a wide range of equilibrium and kinetic geochemical reactions. The flow and transport calculations are restricted to constant fluid density and constant temperature. The geochemical reactions are simulated with the geochemical model PHREEQC, which is embedded in PHAST. PHAST is more suited to deep geosphere modelling than to the representation of near-surface systems.

Several specialised groundwater flow codes were produced within the WIPP site assessment programme, e.g. BRAGFLO, SECOFL2D and SECOTP2D (see discussion under WIPP section in this report). They could be applicable to relevant situations at other sites and may still be available (whether they are still actively supported is unknown). However, it is likely that their functionality is available in some of the other codes discussed in this section, which are readily available and known to be actively supported.

NWMO used the **FRAC3DVS** code (developed by the University of Waterloo, Canada) for 3-dimensional numerical simulations of the groundwater flow system at the Bruce site. These studies formed part of assessment of groundwater flow system dynamics during the Quaternary.

FRAC3DVS is a 3-D finite-element model for steady state/transient, variably-saturated flow and advective-dispersive solute transport in porous or discretely-fractured porous media, including arbitrary combinations of porous, discretely fractured and dual porosity media. Other FRAC3DVS capabilities include modelling unsaturated moisture movement, non-reactive and reactive chemical species and decay chain processes for radionuclides.

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54 [http://pcraster.geo.uu.nl/](http://pcraster.geo.uu.nl/)
7.3 Geomorphological and Hydrogeomorphological Models

7.3.1 Geomorphological modelling

Fish et al. [183] have developed empirical and process-based approaches to cliff erosion in the context of predicting long-term changes in the Cumbrian coastline for post-closure safety assessments for the LLWR. Although such predictive modelling is outside of the scope of this report, the conceptual geomorphological space/time framework adopted in the development of the conceptual coastal-change projection model incorporates elements which may be of relevance to the BDM.

- **Space**: geomorphological variation of the [cliff behaviour units] CBUs from St Bees Head to the Esk Estuary that have been specified in terms of their geomorphology, sedimentology and paraglacial inheritance.

- **Process**: provides functional models for the development of the coastline accounting for the paraglacial inheritance from previous geological / climate conditions, and assessment tools to quantitatively model the evolution of the open coast, barrier beach and estuary CBUs accounting for forcing and resistance to change. Assessment tools comprise an empirically based cliff recession model, the process-based SCAPE model and an estuary evolution model.

- **Forcing and resistance to change**: considers climate-change forcing cases and shoreline resistance to change, based on hinterland landforms, materials and sediment budget.

- **Response**: develops projections of coastal change for the open coast, barriers and estuaries over defined future time periods.

A more generalised terrestrial soil erosion tool, USPED/RUSLE [104], has been developed by Michigan State University, based on data first established on behalf of the US Department of Agriculture, Agricultural Research Service. USPED/RUSLE is an online erosion modelling tool⁵⁶ that allows estimation of:

\[ A = R \times K \times L \times S \times C \times P \]

Where
- \( A = \) estimated average soil loss in tons per acre per year
- \( R = \) rainfall-runoff erosivity factor
- \( K = \) soil erodibility factor
- \( L = \) slope length factor
- \( S = \) slope steepness factor
- \( C = \) cover-management factor
- \( P = \) support practice factor

Another factor for soils is called the "T value" which stands for "Tolerable Soil Loss." It is not directly used in the RUSLE equation, but is often used along with RUSLE for conservation planning. Soil loss tolerance (T) is the maximum amount of soil loss in tons

⁵⁶ [www.iwr.msu.edu/rusle/](www.iwr.msu.edu/rusle/)
per acre per year that can be tolerated and still permit a high level of crop productivity to be sustained economically and indefinitely.

7.3.2 Hydrogeomorphological modelling

The development and application of hydrogeochemical models is discussed [23]. There SKB notes that:

“As a result of the extensive site bedrock investigations in Sweden and Finland it is perceived that the hydrogeochemical evolution of fracture groundwater results from advective mixing and water-rock interactions driven by past and present changes in the climate … . Many of the evaluation and modelling steps used within ChemNet are focused on differentiating these effects by using alternative modelling approaches. Mixing modelling focuses on tracing the origin of the groundwater, whereas reaction modelling focuses on understanding the interaction between oxic/anoxic groundwaters and the bedrock and, for example, the mediating role microbial activity may play.

For modelling purposes, different approaches can be used leading to quite different descriptions of the system. For example, when applying end-member mixing models, the choices of end members are crucial for the description of both mixing and reactions. This does not necessarily mean that some models are correct and some models are not. It is more a question of choosing the most suitable model available for describing the part of the system that is to be addressed, and also to focus on the time period of interest. All epochs and all parts of the system can never be described with high resolution using the same model; usually several models are required as well as different sets of end members and starting prerequisites.”

The computer codes that were used in the hydrogeochemical evaluation are listed below.

- PHREEQC: Code for calculations of chemical equilibrium, reaction simulation, advective transport and inverse modelling. The thermodynamic data base WATEQ4F, distributed with the PHREEQC code was utilised with some modifications.
- M3: Mixing and mass balance calculation program.
- CORE2D: Coupled hydrochemical/hydrogeological modelling code.
- OpenDX: 3D visualisation (IBM Open Visual environment, OpenDX).

Studies of fracture fillings, composition of the porewater in the bedrock and groundwater residence times are important information for the site description. During the explorative analyses of the groundwaters, it became apparent that a subdivision of the sampled groundwaters into four major groundwater types would facilitate the description and interpretation of the figures and diagrams. The major water types distinguished are: Fresh, Brackish Marine, Brackish Non-marine and Saline Non-marine. Because of the lack of deep groundwater hydrochemical data, the brackish and saline non-marine groundwaters were combined. In addition, two groundwater types were included to accommodate important mixing processes resulting from anthropogenic and natural processes: a) a near-surface ‘Mixed Brackish’ type mainly comprising fresh and brackish marine groundwaters,
and b) a deeper ‘Transition Zone’ type comprising degrees of mixing between brackish marine and brackish to saline non-marine groundwaters.

7.4 Biosphere tools

Many of the tools described in this section are used mostly in assessment of the biosphere, however, they can also be applied in the context of interpretation and interpretive modelling and hence are included in this report.

7.4.1 UNTAMO-GIS toolbox

Posiva (Finland) has developed various site-characterisation information and modelling tools for the biosphere in their UNTAMO GIS toolbox (developed within ArcGIS):

- Surface and near-surface hydrological model (SNSH) [102, 108];
- Accumulation of organic material and peat growth model [106];
- Statistical digital terrain model [96].

UNTAMO was developed for simulating land uplift, or other changes in the biosphere, and the Olkiluoto surface hydrological model uses raster files created by the UNTAMO-toolbox as model input data.

7.4.2 SADA

Developed for the United States Environmental Protection Agency and the United States Nuclear Regulatory Commission, the Spatial Analysis and Decision Assistance code, SADA is free software\(^57\). The tools within the SADA model include integrated modules for visualisation, geospatial analysis, statistical analysis, human health risk assessment, ecological risk assessment, cost/benefit analysis, sampling design, and decision analysis. The capabilities of SADA can be used independently or collectively to address site-specific concerns when characterising a contaminated site, assessing risk, determining the location of future samples, and when designing remedial action.

Although primarily developed for non-radioactive contaminants, SADA can be applied to radioactive contamination for basic screening tier assessments by inclusion of biota concentration guidelines (BCG’s) (i.e. predicted no-effects media concentrations).

SADA is described as “an evolving freeware product” and errors in the coding have been identified. Although the most recent updates to the code have rectified the issues previously identified, as with all freeware which is developmental, some user difficulties may be encountered.

The visualization techniques in SADA are simple to use, easy to understand, and facilitate the data exploration, modelling and decision analysis components present in SADA. A number of functions are available that will be recognizable to GIS analysts and introduce

\(^{57}\) A freeware version is available from [http://www.tiem.utk.edu/~sada/index.shtml](http://www.tiem.utk.edu/~sada/index.shtml). SADA is developed in the Institute for Environmental Modelling at the University of Tennessee.
beginners to GIS tools. SADA can be applied to a wide range of applications where spatially distributed information plays a role.

SADA provides a number of methods for the exploration of spatial data in two or three dimensions. Two-dimensional information is presented as simple xy plots or as GIS-rich mappings. Three-dimensional information is presented in two ways: by 2-D slices (layers) or by 3-D volume. The 3-D volume approach does not depend on any layering scheme and shows all depths at once. The volume view can be customized with a variety of features that allow the user to better characterize contamination at depth.

In order to allow data visualization with respect to site characteristics, SADA can accept map layers from a Geographic Information System (GIS) saved in a Data eXchange Format (DXF), Shape File Format (shp) or as a variety of raster formats including JPEG, GIF, and TIFF.

SADA can also input to site sampling designs.

Although it appears that SADA may be aligned to the needs of SDM development, QA qualification would be an important issue since the SDM will underpin site assessments.

7.4.3 SKB biosphere characterisation models

SKB (Sweden) has developed and used a range of other models over recent years, including Ecolego, PANDORA, Tensit and LPJ-GUESS.

LPJ-GUESS [184] is a modular framework for modelling the dynamics of ecosystem structure and functioning from small/local to global scales and at varying levels of process detail. The framework incorporates process-based representations of plant physiology and ecosystem biogeochemistry, which may be represented at various levels of abstraction. It can be used to assess vegetation/ecosystem effects on air quality and climate change.

LPJ-GUESS was developed from the BIOME3 family of models by Lund University, Sweden [58]. Development appears to have been active up to present and the model has been applied widely in European-based projects, also to other parts of the world, with recent publications evident [e.g. 185].

An educational version is available for free download from the website; other users are requested to contact the developers.

Studsvik developed the codes BIOPATH and PRISM in the context of site clean-up. BIOPATH and PRISM were also used in the SKB preliminary safety assessment for the planned deep repository for long-lived low-level and intermediate-level waste in Sweden [186, 187], but these codes are now generally superseded by the more recent models outlined above.

[58] http://www.nateko.lu.se/lpj-guess/lpj_guess_main.html
7.4.4 Hydrodynamic and oceanographic models

Posiva [108] has reported that the Olkiluoto surface hydrological model is a 3D-model that is used to study the water balance components on Olkiluoto Island and to evaluate the effect of the ONKALO underground research laboratory[59], constructed at Olkiluoto, on groundwater levels in overburden soils and in shallow bedrock drillholes [102, 188]. In the model, overburden and bedrock are combined into one single numerical solution and the overburden-bedrock interface can be seen as the layer where hydraulic properties change from soil values to bedrock data. The model links unsaturated and saturated soil water in the overburden and groundwater in bedrock into one continuous pressure system. Horizontal and vertical fluxes can be obtained as output values. Moreover, flux at the interface between overburden and bedrock - recharge to bedrock or discharge out of bedrock - can be calculated since the location of the first bedrock node in the vertical direction can be obtained from bedrock elevation data.

A so-called SVAT (Soil-Vegetation-Atmosphere-Transfer) model was developed to analyse the different water and energy balance components of the Forest Intensive Monitoring Plots [189]. The SVAT model is an extension to the Olkiluoto surface hydrological model. The SVAT model utilizes the soil water models available in the Olkiluoto surface hydrology model. In the SVAT model, the soil profile can be divided up to 30 layers and both vertical and horizontal water fluxes are computed.

Hydrological processes that are quantified in the Olkiluoto SVAT model of forest stands include precipitation, interception, evaporation, transpiration, snow accumulation and melt, soil- and ground-water movement, overland flow, horizontal subsurface flow and flow to forest ditches.

The surface hydrology model calculates horizontal and vertical water fluxes in a 3D grid but various types of spatial and temporal simplifications - conceptualizations - of the complete model have been programmed in such a way that model results can be used in estimating the water fluxes for spatially extensive biosphere objects.

Posiva [93] has also reported that the fate of sediments transported by the rivers Eurajoki and Lapinjoki to offshore Olkiluoto is studied using a numerical 3D hydrodynamic model [190], however, the report is available only in Finnish.

7.4.5 Other codes

Although of limited use in the context of developing an SDM, reference may be made to the UK Environment Agency tool to assess Natura 2000 sites for compliance with the EC Habitats Directive in England and Wales [191] and the principles and guidance for an initial prospective assessment of public doses following a release of activity to the environment [192, 193]. These tools may illustrate site-specific parameters that need to be characterised to support radionuclide transport modelling, but do not otherwise lend themselves to SDM development.

59 http://www.posiva.fi/en/research_development/onkalo/
60 This has also been largely superseded by the ERICA assessment tool: https://wiki.ceh.ac.uk/display/rpemain/Workshop+reports
PC-CREAM [194] is a tool for performing radiological impact assessments of routine and continuous discharges of radionuclides to the environment. It allows some, limited, representation of the local environment, but is not primarily a site characterisation tool. PC CREAM is commercially available from the UK Health Protection Agency61.

The AMBER software platform has been applied to biosphere assessments for deep geological radioactive waste disposal facilities (e.g. [72, 195, 196, 197]). AMBER is a flexible software tool that allows the user to build their own dynamic compartmental models to represent the migration and fate of contaminants in a system, for example in the surface and sub-surface environment. It is a model platform, rather than a bespoke simulation package. Consequently, AMBER may be used to represent site characteristics, although it is primarily used as an assessment tool. A free demonstration version of AMBER (version 5.5) is available to download from the online support website62. This version has restricted functionality but does allow case studies to be run. A web-hosted version of the AMBER model code, Wham!, has also been developed by Quintessa.

GoldSim is another general-purpose dynamic probabilistic simulation software package. It can be used in many applications and has been used extensively in radioactive waste management programmes [e.g. 198, 199]. It has also been applied within the recent RWMD generic post-closure safety assessment for a GDF [e.g. 200]. GoldSim is a hybrid of several simulation approaches, combining an extension of system dynamics with some aspects of discrete event simulation, and embedding the dynamic simulation engine within a Monte Carlo simulation framework. Since the structure of a model is not predetermined by use of GoldSim, essentially any level of site characterisation can be used to construct a model of radionuclide transport to and through the biosphere, at varying levels of complexity. GoldSim is available commercially, but a free version (GoldSim Player) is downloadable63, with restricted functionality.

Finally, the RESRAD family of computer codes was developed by the Environmental Science Division of the US Argonne National Laboratory to provide a dose assessment tool contributing to the provision of guidelines for clean-up of radiologically contaminated sites. RESRAD has been widely used in the United States. It allows investigation of different pathways for transport of radionuclides through the environment and includes limited ability to modify parameters. As noted for other assessment tools, this may provide an indication of parameters considered to be of relevance for site characterisation, but does not otherwise lend itself directly to developing an SDM. RESRAD is freely available to download64.

7.5 Discussion

A number of the codes developed and described above are generic software platforms rather than specific system models. Both GoldSim and GIS systems fall into this category.

61 https://www.hpa-radiationservices.org.uk/pccream
62 http://www.quintessa-online.com. The most recent version of AMBER available under licence is version 5.6.
63 http://www.goldsim.com
64 http://web.ead.anl.gov/resrad/home2/
Such software platforms allow both geosphere and biosphere aspects to be considered and therefore have advantages where the geosphere-biosphere interface is of concern.

GoldSim has built-in capabilities for modelling a range of different systems (e.g. hydrological) and can also handle radionuclide transport (e.g. through inclusion of radioactive decay and in-growth of daughter radionuclides) and offers default parameters in a number of instances, allowing model development to be started from a relatively low platform of user knowledge or of specific site characterisation information. At the same time, the platform allows considerable refinement as both user capability and site characterisation information develops.

GIS systems also provide generic platforms for data manipulation and modelling and are widely employed for database, data and model output visualisation, spatial modelling and interpolation. These systems can be used for geo-environmental data management, providing input in required formats to other modelling packages, and as a framework within which to implement various mathematical model schemes (e.g. Posiva’s UNTAMO toolbox, developed in ArcGIS). ArcGIS seems to be the most widely employed GIS in this context. The open source GRASS system may also still be worth consideration where the development of bespoke tools/models is being considered.

It is noted that the RWMD Biosphere Status report [24] specifically makes mention of the GoldSim, MIKE SHE and SHETRAN packages, and uses interaction matrices (although this is in the context of developing a conceptual model for post-closure assessments).

Some programmes have used a range of more or less bespoke software codes for specific purposes. This appears to be particularly the case within the US programmes. While this approach may enable the development of models tailored to the needs of the programme, and the physical and regulatory environment, satisfactory verification of the codes employed may be more difficult to establish.

Software tools developed primarily in other industries may be applicable for specific purposes in radioactive waste management programmes. The Surpac and CPS-3 codes for example have been employed in site-descriptive modelling applications (by Posiva and the Yucca Mountain Project, respectively).
8 AREAS OF RESOURCE VULNERABILITY

Resource requirements, and hence the potential for vulnerability of supply, can be considered in four separate areas: data acquisition, processing, modelling, and interpretation. In addition, some specialist requirements may arise as a result of site-specific conditions.

There are numerous commercial consultancies and academic institutions in the UK and abroad that can potentially provide research and investigative services in relevant areas. Many of the developers of key software packages identified can also offer related consultancy services which go beyond simple support of their software. For example Schlumberger (Visual ModFlow), ESI (Groundwater Vistas), DHI (MIKE SHE, FeFlow), Amec (ConnectFlow).

Support may be available from other national repository development organisations. SKB notably offers consultancy services.

A key question is the extent to which the available skill sets match the actual needs of the industry. We have therefore focused this evaluation on identifying potential bottlenecks (i.e. key skills shortages / lack of specialist tools and services) in the process of delivering the identified site characterisation programme requirements.

8.1 Data acquisition and processing

It seems unlikely that basic measurement and interpretation skills can be regarded as vulnerable. Hydrology, meteorology, ecology etc. are all widespread disciplines. It seems equally unlikely that basic measurement tools can be regarded as vulnerable. Tools such as satellite mapping (for climate, geology etc.) are supported by much larger programmes. Collecting information relating to topography, soil or sediment type, species distribution etc. requires quite basic equipment.

Specialist equipment e.g. borehole drilling rigs and subsurface mapping equipment, are available in the UK though there may be limited availability at any one specific time, causing a temporary delay or setback in the characterisation programme.

Another rate limiting (but not vulnerable) area of characterisation is the requirement for experimental data to support or determine site-specific characteristics (e.g. soil Kd values and plant concentration factors for important elements). These typically take time to commission and complete, and therefore could cause a temporary delay.

8.2 Modelling and interpretation

The only discipline that may become skills limited appears to relate to modelling and, more specifically, to the support of a single specialist model or application. Conceptual modelling is rarely rate limiting and the development of interaction matrices is a widespread approach with many international precedents and established workshop procedures. Generic uptake and transfer modelling to describe the environmental distribution and accumulation of radionuclides is widespread and many of the model platforms are distributed widely on a commercial basis. A rate limiting factor may be the requirement for iterative model development, but this represents a workflow issue rather than a potential area of expertise vulnerability.
8.3 Variation in geological environment

At this stage there are no obvious vulnerabilities related to the geological environments that could potentially be characterised in the UK. The range of modelling tools available would appear to be capable of dealing with a sufficient range of environments as to cover any credible UK situation, at least to a basic extent. The possibility of complications due to unique, site-specific factors remains. However, more detailed consideration of such issues would need to be undertaken once a potential host site has been identified. Similarly, there are no obvious difficulties with the availability of suitably skilled and experienced practitioners at this point. Further consideration may be required once a potential host site has been identified.

8.4 Multi-disciplinary team building

Although each of the individual skills areas is unlikely to be at risk, SDM development is a multi-disciplinary activity that involves a substantial team of field and modelling experts. Recruiting and integrating such a team may be an important rate limiting step in initiating SDM development, so this needs to be planned well in advance.

Furthermore, the team, once established, needs to be maintained for an extended period. This matter was commented on by Thorne et al. [28] who drew the following conclusions.

"Biosphere characterisation necessarily integrates contributions from ecology, soil science, hydrology, hydrogeology, hydrogeochemistry, geomorphology, and aspects of sociological and demographic studies. This multi-disciplinary basis means that careful consideration needs to be given to the development of an integrated biosphere characterisation team and to the maintenance of that team through the period of site characterisation.

It must be recognized that the characterization of the biosphere at a specific site will require a multi-year programme. Both overseas and UK experience indicates that a period of around seven years is required. This involves an initial baseline survey (including a radiological survey), time-series monitoring (e.g. of meteorological and hydrological characteristics), and additional focused surveys on topics identified as important to the various users of the site characterization data."
9 SUMMARY AND CONCLUSIONS

9.1 Summary

The key objectives of this review were to provide RWMD with an authoritative account for the biosphere discipline of:

- The processes and tools that have been used in international radioactive waste management programmes for processing, interpreting and modelling biosphere data acquired through site characterisation;

- Any additional processes and tools that are used in other sectors for processing, interpreting and modelling biosphere data acquired through site characterisation that may be applicable to a UK-based waste management site characterisation programme;

- The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in the UK;

- The extent to which the required resources may vary in response to variations in the geological environment at the site(s) in the UK that are being characterised; and

- The identification of any gaps in available resources to support a UK-based site characterisation programme.

This has been achieved through review and evaluation of programmes adopted in the UK and internationally, from the radiological assessment community and other sectors, for the characterisation of the biosphere on a site-specific basis.

The radioactive waste management programmes, relating to geological disposal, of Sweden, Finland, Switzerland, France, the U.S.A., Canada and Germany have been reviewed. The volume and detail of information available from each varied, with particularly useful information obtained from the Scandinavian programmes. In contrast, the detail available from the French programme was more limited and very little relevant information was available from the German programme, mainly due to less site characterisation work having been carried out here. The environments under investigation were, in general, more relevant to the potential UK situation in the other European programmes than in the North American programmes. Of the individual programmes reviewed, the approaches developed by SKB and Posiva Oy form a suitable template for a UK programme (subject to variations appropriate to the specific environments being considered, e.g. giving less emphasis to land uplift and more to erosion at coastal sites).

The review of other sectors has provided less useful information.

The tools and methodologies identified as potentially relevant to a site characterisation programme have been summarised, including consideration of their availability. The availability of key practitioners and potential gaps in resources has also been considered. The potential variation in required resources due to variations in geological environment in the UK has received less discussion. Based on the information available and range of potential environments in the UK, this issue will require more detailed consideration when a potential host site has been identified. The overall conclusion is that there is a suitable range of resources (tools and practitioners) available to support a credible UK site characterisation programme.
9.2 Site characterisation and modelling

This review has identified two key aims of site characterisation and modelling:

1. to identify what is there now; and
2. to predict what could be there in the future.

Although the SDM is limited to the first of these two aims, in some cases an evaluation of how an environment has developed historically can help both to understand the present conditions and how they may develop in the future.

While this review was aimed at identifying site characterisation methods, it is important to bear in mind that, within the context of the national repository programmes reviewed, site characterisation forms the basis for impact assessments as part of a safety case. To this end it must take into account the associated requirements of the impact assessment process and models in order to obtain sufficient understanding that can estimate the range of likely future impacts on man and biota over timescales of 10,000 years or more.

Key elements of the overall approach common to the programmes reviewed are:

- Breakdown of the biosphere/environment into functional units and evaluation of parameters in required/key areas, i.e. landscape, hydrology, etc.
- The iterative nature of characterisation and modelling.
- Quality Assurance – data and database integrity, data control, checking and sign-off.

Site characterisation models build an understanding of the system. They are more complex than impact assessment models, which have necessarily to be simplified representations of the environment due to the large-scale and long-term nature of the assessments required to be undertaken. This extra complexity and associated data collection, processing and modelling are required in order to adequately understand the physical and ecological aspects of the site and its likely future development.

In order to manage this scale and complexity, site characterisation should proceed in a structured way, with interpretation and modelling contributing to it, e.g. as set out below.

1. Determining the site-characterisation requirements: Based on dialogue with all relevant end users of the SDM.
2. Gathering and recording data: Data gathering by a range of well-established methods, with data recorded in a geo-referenced form (e.g. GIS).
3. Statistical analysis, visualisation and exploration of data: Presenting data in such a way as to identify clearly data that are measured and data that are inferred.
4. Development of a site conceptual model: Based on multi-disciplinary interpretation of the gathered data to identify important site characteristics, including spatial extrapolation between measured data points. Initially the conceptual model will include a mix of quantified information (e.g. topography and land use characteristics) and descriptive aspects (describing features and processes in a site-specific manner but not numerically parameterised). Such a conceptual model will be spatially distributed and aspects of it will often be best expressed through 2D and 3D ‘cartoons’ showing how the structure and operation of the system are conceived.
5. Development of numerical models: The purpose of developing numerical models here is not initially to support assessment calculations, but to build and demonstrate understanding of the processes that are relevant to the needs of all end users. This may prompt further characterisation in order to populate the numerical models with parameter values. A typical example might be demonstration that modelled groundwater heads or surface water flows, given measured or assumed values for porosity, aquifer geometry, effective rainfall, etc., match measured values. This may prompt the need for further characterisation measurements to resolve conflicts between models and reality. This is where the complex codes, such as 3 dimensional hydrogeological codes, chemical speciation codes, etc., come into play. A feature of the codes used here is that they are generally mechanistic in nature, i.e. they seek to represent the actual physical and chemical processes that are occurring.

A key issue, which may differ from programme to programme, is where the interface between characterisation and impact assessment takes place, or indeed whether there is a formal interface at all. Most commonly this would be considered to occur between the beginning of (5) and the beginning of (6). The translation of detailed site characterisation models into simplified assessment models will tend to be easier to achieve for more physically structured aspects of the environment, like hydrology/hydrogeology, than for ecosystem/ecology aspects. The way this is achieved and potential associated requirements on site characterisation and modelling (e.g. range of data collected, form of output) may require explicit consideration.

6. Simplified descriptions for assessment: Having developed very detailed models (usually of specific sub-systems within the site conceptual model) in order to confirm that characterisation has resulted in a self-consistent description of the real features of the site, simplified descriptions, probably linking a number of sub-systems, will generally be developed for use in assessment modelling. These represent processes by abstractions, such as transfer rates between compartments, which may be derived from the more complex numerical models mentioned above.

It has been emphasised that data acquisition and management must be subject to adequate quality control to ensure confidence in site characterisation. Careful management will be required to deal with the volume of information expected to be (continually) collected during a typical site characterisation process.

The iterative nature of the site characterisation, data collection and modelling process has also been noted: the approach involves initial conceptual models guiding site data collection, with review and assessment to revise the conceptual models and identify key interactions (for example, as in the Swedish and Finnish programmes). The process adopted must enable both the development of authoritative site characterisation models (and impact assessments) and rigorous traceability and reproducibility.

As much of the work is expected to be carried out by sub-contractors to the NDA, control of data / database quality should extend to sub-contractors, i.e. a system of oversight to ensure that data are collected, processed and maintained correctly before hand-over to the NDA.
The biosphere component of the SDM will never be simply an integrated numerical model of the whole near-surface and surface system. Rather, it will comprise a mix of descriptive models, numerical models and interpreted data that together provide a comprehensive account of the biosphere. Thus, the process of assessment model development involves abstraction of the essential elements from this mix to provide first a conceptual model for assessment purposes (this is where FEP analysis and interaction matrices can play an important role) and then to develop a numerical model (informed in terms of equations and parameter values by the numerical models and interpreted data in the SDM).

In the early stages, it may be that the SDM includes no numerical models, but solely comprises descriptive models and interpreted data. This does not preclude the development of conceptual and numerical assessment models. Indeed, this has often been done in the past, where compartmental models of the biosphere have been parameterized directly using observational data.

The principle of voluntarism is an important aspect of the Managing Radioactive Waste Safely (MRWS) programme site selection process. The outcome of the site characterisation process, and the science underlying it, must support this and demonstrate confidence to the host community and other key stakeholders that the potential disposal facility site is adequately understood. This is not easily done and it is not clear that any waste management programme has yet fully achieved this. The principal problem is that the description of the SDM tends to become extremely lengthy and technical. How to provide a more accessible version of a SDM that conveys the key information and uncertainties, but without over-simplifying the issues, is a matter that will require careful consideration.

9.3 Other site characterisation programmes

The Swedish and Finnish geological disposal programmes are well planned and managed (and well explained/documented) and appear to follow what would be recognised as up-to-date international best practice. They represent the most advanced, recently developed examples available and share similar (surface) environmental conditions to those that may be encountered at some potential UK sites. They are also (fairly openly) collaborative, with both other national and with international research programmes. These programmes could therefore be recommended as offering useful examples to inform the development of a UK site characterisation programme.

In addition, in order to determine an appropriate degree of site investigation and modelling, it will be important to be clear before proceeding as to (among other things):

- The regulatory framework – what standards of protection are required to be met and over what timescale; and
- The broad site surface environment, which will determine the degree of attention required to be paid to future site development. In particular, potential changes due to isostacy, eustacy, anticipated glaciations and other possible climate change and landscape evolution effects need to be taken into account.

The US approach appears to have involved much less focus on the surface environment, and modelling of future evolution. This is partly due to the nature of the environments (semi-arid, with limited surface water systems) and the long-term stable conditions, but the
regulatory requirements also constrain the RMEI and reference biosphere (see Section 5.8.2), limiting the degree and range of future impact assessment required for compliance.

International research programmes, both directly associated with radioactive waste disposal and other more general programmes can also offer valuable guidance. These are another form of collaboration and, indeed, most of the national geological disposal programmes reviewed have drawn on and/or participated in such research programmes (e.g. BIOMASS, BIOCLIM and BIOPROTA).

Other industry sectors would appear to have little novel to offer a UK geological disposal programme. The level and scope (especially timescales) required to be addressed by other sectors generally fall well short of those required in radioactive waste disposal. Consequently, site characterisation and environmental (impact) assessment activities tend to be straightforward and are effectively already covered by established practice as demonstrated in the national programmes reviewed.
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GLOSSARY

**Andra**  The organisation responsible for waste management and the development and operation of disposal facilities in France.

**barrier**  A physical or chemical means of preventing or inhibiting the movement of radionuclides.

**biosphere**  Regions of the earth’s surface and atmosphere normally inhabited by living organisms.

**closure**  The administrative and technical actions that have to be taken to put a disposal facility in its intended final state after the completion of waste emplacement.

**Committee on Radioactive Waste Management (CoRWM)**  CoRWM was set up in 2003 to provide independent advice to Government on the long-term management of the UK’s solid higher activity radioactive waste. In October 2007, CoRWM was reconstituted with revised Terms of Reference and new membership. The Committee will provide independent scrutiny and advice to UK Government and devolved administration Ministers on the long-term radioactive waste management programme, including storage and disposal. Further information available at [www.corwm.org.uk](http://www.corwm.org.uk).

**decommissioning**  The process whereby a nuclear facility, at the end of its economic life, is taken permanently out of service and its site made available for other purposes. The term ‘site clean-up’ is sometimes used to describe the work undertaken to make the site available for other purposes.

**Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE)**  The German Service Company for the Construction and Operation of Waste Repositories; the organisation responsible for waste management and the development and operation of disposal facilities in Germany.

**devolved administrations**  Collective term for the Scottish Executive, Welsh Assembly Government and in Northern Ireland, the Department of the Environment.

**disposal**  In the context of solid waste, disposal is the emplacement of waste in a suitable facility without intent to retrieve it at a later date; retrieval may be possible but, if intended, the appropriate term is storage.

**disposal facility (for solid radioactive waste)**  An engineered facility for the disposal of solid radioactive wastes.

**disposal system**  All the aspects of the waste, the disposal facility and its surroundings that affect the radiological impact.

**disposal vault**  Underground opening where ILW or LLW waste packages are emplaced.

**Environment Agency (EA)**  The environmental regulator for England and Wales. The Agency’s role is the enforcement of specified laws and regulations aimed at protecting the environment, in the context of sustainable development, predominantly by authorising and controlling radioactive discharges and waste disposal to air, water (surface water, groundwater) and land. The Environment Agency also regulates nuclear sites under the Environmental Permitting Regulations and issues consents for non-radioactive discharges.
**Environmental Safety Case (ESC)** The collection of arguments, provided by the developer or operator of a disposal facility, that seeks to demonstrate that the required standard of environmental safety is achieved.

**Evaporate / Evaporite** The generic term for a geological environment created by the evaporation of water from a salt bearing solution to form a solid structure.

**far field** The geosphere surrounding a GDF, comprising the surrounding geological strata, at a distance such that the GDF can be, for modelling purposes, considered a single entity.

**geological disposal** A long-term management option involving the emplacement of radioactive waste in an engineered underground geological disposal facility or repository, where the geology (rock structure) provides a barrier against the escape of radioactivity and there is no intention to retrieve the waste once the facility is closed.

**geological disposal facility (GDF)** An engineered underground facility for the disposal of solid radioactive wastes.

**geosphere** The rock surrounding a GDF that is located below the depth affected by normal human activities and is therefore not considered to be part of the biosphere.

**groundwater** Water located beneath the earth’s surface in rock pores and fractures.

**half-life** The time taken for the activity of a given amount of a radioactive substance to decay to half of its initial value. Each radionuclide has a unique half-life.

**Health and Safety Executive (HSE)** A statutory body whose role is the enforcement of work related health and safety law. HSE is the licensing authority for nuclear installations. The Nuclear Safety Directorate of HSE formerly exercised this delegated authority through the Nuclear Installations Inspectorate (NII) who were responsible for regulating the nuclear, radiological and industrial safety of UK nuclear installations under the Nuclear Installations Act 1965 (NIA 65). This role has now passed to the Office for Nuclear Regulation (ONR).

**higher activity radioactive waste** Generally used to include the following categories of radioactive waste: low level waste not suitable for near-surface disposal, intermediate level waste and high level waste.

**higher strength rock** Typically crystalline igneous and metamorphic rocks or geologically older sedimentary rocks where any fluid movement is predominantly through discontinuities.

**high level waste (HLW)** Radioactive wastes in which the temperature may rise significantly as a result of their radioactivity, so this factor has to be taken into account in the design of storage or disposal facilities.

**intermediate level waste (ILW)** Radioactive wastes exceeding the upper activity boundaries for LLW but which do not need heat to be taken into account in the design of storage or disposal facilities.

**International Atomic Energy Agency (IAEA)** The IAEA is the world’s centre of cooperation in the nuclear field. It was set up as the world’s "Atoms for Peace" organization in 1957 within the United Nations family. The Agency works with its Member States and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies.
International Commission on Radiological Protection (ICRP) An international advisory body founded in 1928 providing recommendations and guidance on radiation protection. ICRP recommendations normally form the basis for EU and UK radiation protection standards.

lower strength sedimentary rock Typically geologically ‘young’ sedimentary rocks where any fluid movement is predominantly through the rock matrix.

low level waste (LLW) Defined in the UK as “radioactive waste having a radioactive content not exceeding 4 gigabecquerels per tonne (GBq/te) of alpha or 12 GBq/te of beta/gamma activity”.

Low Level Waste Repository (LLWR) The UK national facility for the near-surface disposal of solid LLW, located near to the village of Drigg in Cumbria.

Managing Radioactive Waste Safely (MRWS) A phrase covering the whole process of public consultation, work by CoRWM, and subsequent actions by Government, to identify and implement the option, or combination of options, for the long-term management of the UK’s higher activity radioactive waste.

Nagra The National Cooperative for the Disposal of Radioactive Waste; the organisation responsible for waste management in Switzerland.

near field The engineered barrier system (including the wasteform, waste containers, buffer materials, backfill, and seals), as well as the host rock within which the GDF is situated, to whatever distance the properties of the host rock have been affected by the presence of a GDF.

Nirex (United Kingdom Nirex Limited) An organisation that no longer exists that was owned jointly by Department for the Environment, Food and Rural Affairs and the Department for Trade and Industry. Its objectives were, in support of Government policy, to develop and advise on safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials in the United Kingdom. The Government’s response to Committee on Radioactive Waste Management in October 2006 initiated the incorporation of Nirex functions into the NDA, a process which was completed in March 2007.

Nuclear Decommissioning Authority (NDA) The NDA is the implementing organisation, responsible for planning and delivering the GDF. The NDA was set up on 1 April 2005, under the Energy Act 2004. It is a non-departmental public body with designated responsibility for managing the liabilities at specific sites. These sites are operated under contract by site licensee companies. The NDA has a statutory requirement under the Energy Act 2004, to publish and consult on its Strategy and Annual Plans, which have to be agreed by the Secretary of State and Scottish Ministers.

Nuclear Waste Management Organization (NWMO) The organisation responsible for the long-term management of Canada’s used nuclear fuel.

operational period (of a disposal facility) The period during which a disposal facility is used for its intended purpose, up until closure.

performance assessment Assessment of the performance of a system or sub-system and its implications for protection and safety at an authorised facility.
**permeability** A measure of the rate at which a gas or a liquid moves under a pressure gradient through a porous material.

**porosity** The ratio of the aggregate volume of interstices of a porous medium to the total volume of that medium.

**Posiva Oy** The organisation responsible for waste management and the development and operation of disposal facilities in Finland.

**post-closure period (of a disposal facility)** The period following sealing and closure of a facility and the removal of active institutional controls.

**radioactive waste** Any material contaminated by or incorporating radioactivity above certain thresholds defined in legislation, and for which no further use is envisaged, is known as radioactive waste.

**Radioactive Waste Management Directorate (RWMD)** The NDA Directorate established to design and build an effective delivery organisation to implement a safe, sustainable, publicly acceptable geological disposal programme. It is envisaged that this directorate will become a wholly owned subsidiary company of the NDA. Ultimately, it will evolve under the NDA into the organisation responsible for the delivery of the GDF. Ownership of this organisation can then be opened up to competition, in due course, in line with other NDA sites.

**retardation** A feature of a component of a GDF that contributes to safety. The engineered barriers and host geological environment provide retardation of radionuclides through physical and chemical processes that reduce the concentration of contaminants or their rate of release from the barrier. Retardation processes may result in effective containment of the radionuclides if they would only be released through the barriers after the time at which they and their daughters have decayed to negligible levels.

**retrievability** A feature of the design of a GDF that enables the waste to be withdrawn, even after the disposal vaults have been backfilled.

**safety cases** A ‘safety case’ is the written documentation demonstrating that risks associated with a site, a plant, part of a plant or a plant modification are as low as reasonably practicable and that the relevant standards have been met. Safety cases for licensable activities at nuclear sites are required as licence conditions under NIA65.

**site characterisation** Detailed surface and subsurface investigations and activities at a site to determine the radiological conditions at the site or to evaluate candidate disposal sites to obtain information to determine the suitability of the site for a repository and to evaluate the long term performance of a repository at the site.

**sorption** The interaction of an atom, molecule or particle with the solid surface at a solid–solution or a solid–gas interface. Used in the context of radionuclide migration to describe the interaction of radionuclides in pore- or groundwater with soil or host rock, and of radionuclides in surface water bodies with suspended and bed sediments.

**stakeholders** People or organisations, having a particular knowledge of, interest in, or that might be affected by, radioactive waste, examples being the waste producers and owners, waste regulators, non-Governmental organisations and local communities and authorities.
storage The emplacement of waste in a suitable facility with the intent to retrieve it at a later date.

*Svensk Kärnbränslehantering AB (SKB)* The organisation responsible for waste management and the development and operation of disposal facilities in Sweden.

voluntarism An approach in which communities “express an interest” in participating in the process that would ultimately provide the site for a geological disposal facility. Initially a community would be expressing an interest in finding out more about what hosting such a facility would involve. In the latter stages, there would be more detailed discussion of plans and potential impacts.