GDF

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Roadmap towards a Biosphere Characterisation Programme in Support of a UK Geological Disposal Facility

Contractor Report

March 2022

Nuclear Waste Services

Preface

Radioactive Waste Management (RWM) carries out research in support of geological disposal of the UK's higher activity radioactive waste. The work presented in this report forms part of our biosphere research programme and was carried out by Quintessa on our behalf. The work has been reviewed by RWM and by two independent peer reviewers. RWM accepts the data and conclusions in this report.

This work was originally contracted by Radioactive Waste Management (RWM). On 31 January 2022, RWM joined with Low Level Waste Repository and the Nuclear Decommissioning Authority's (NDA) Integrated Waste Management Programme, and is now part of a single organisation, called Nuclear Waste Services, within the NDA group.

Roadmap towards a Biosphere Characterisation Programme in Support of a UK Geological Disposal Facility

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This report has been prepared by Quintessa Limited under contract to Radioactive Waste Management Limited (RWM), now part of Nuclear Waste Services (NWS). The report has been reviewed by NWS, but the views expressed and conclusions drawn are those of the authors and do not necessarily represent those of the NWS.

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Summary

Nuclear Waste Services (NWS) is developing a site characterisation programme to support evaluation of the potential for sites to meet the safety requirements for a Geological Disposal Facility (GDF) for the UK's higher active radioactive wastes. Such a programme includes characterisation of the surface/near-surface environment (biosphere).

This report describes main topics of interest for a biosphere characterisation programme and presents an illustrative biosphere characterisation roadmap including proposals for future tasks. The roadmap contains a strategic plan with major tasks, links and deliveries to other programme functions. The illustrative biosphere characterisation roadmap provides a framework for more detailed planning.

The report emphasises the need to integrate both the planning and execution of biosphere characterisation with other parts of the GDF programme. Major 'end user' needs for the information and understanding delivered by biosphere characterisation are discussed and put into an overall programme context where safety and environmental assessments are in focus. A general strategy is suggested that builds on system understanding and uses the Site Descriptive Model (SDM) as a central and integrating function within which the biosphere site characterisation tasks sit.

The recommendations presented in the report draw on experience and lessons learnt from other projects, including other national programmes for geological disposal of radioactive wastes. An integrated and holistic system understanding approach is proposed where the biosphere part of the site characterisation is linked to the geosphere, and programme functions within NWS use a common system understanding reflected in a synthesised site descriptive model. The review of biosphere characterisation undertaken in other projects is included as an appendix.

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Contents

1 Introduction

Nuclear Waste Services (NWS) is developing a site characterisation programme to support evaluation of the potential for sites to meet the safety requirements for a Geological Disposal Facility (GDF) for the UK's higher active radioactive wastes (RWM, 2016a). The objective of site characterisation is to provide the information on the geoscientific, environmental and socioeconomic conditions at one or more sites throughout all stages of the development and implementation of geological disposal, needed for the development of the GDF design, safety case and environmental assessments (Thorne et al., 2011).

Biosphere characterisation is an integral part of the overall process of site characterisation (BIOPROTA, 2006). It provides understanding of near-surface lithostratigraphy, hydrology, climate, human populations, distribution and abundance of animal and plant species, and aspects of sociological and demographic studies. Understanding of the biosphere then informs multiple aspects of a GDF programme, including:

- Environmental Impact Assessment (EIA), required for the Development Consent Order under the Planning Act 2008 for both (i) the site investigations, and (ii) construction of a GDF;
- providing context and constraints for design and construction; and
- informing operational and post-closure safety assessments.

Biosphere characterisation requires a multi-disciplinary team that should be maintained over a multi-year characterisation programme. Similar or closely related information from biosphere characterisation is needed to inform the different components of a GDF programme.

This report draws on experience gained nationally and internationally to help identify information requirements from biosphere characterisation, as well as overlaps and interfaces in the demands from different elements of a GDF programme. This understanding is then used to outline an illustrative 'roadmap' (e.g. strategical planning with main goals and tasks) for biosphere characterisation as input to NWS's forward planning.

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1.1 Context and Structure of the Report

Current plans and a programme towards implementing geological disposal in the UK are available via the 'Working in Partnership' website[1].

National Geological Screening has been undertaken to summarise existing information about the geology of England, Wales and Northern Ireland that would be relevant to the safe disposal of higher-activity radioactive waste. The results of the National Geological Screening are available[2] and provide input to individuals and organisations to consider opening discussions with NWS regarding potential to host a GDF.

Figure 1 illustrates the process of working in partnership with communities to support site selection, along with associated timescales (RWM, 2020a). After establishment of working groups, site evaluation work will be carried out to begin to narrow the area where the geology and potential site conditions could be considered in detail. Information will initially be gathered through non-intrusive investigations, for example, surveys and assessments of ecology, seismic surveys and air borne physics, transport, noise, air quality may be commissioned, amongst other topics (RWM, 2020b).

Figure 1: Process of working with communities in support of site selection for a GDF, from RWM (2020a).

Discussions, non-intrusive investigations and initial site evaluations could take around five years. If there is continuing interest from the community and NWS in pursuing siting at a particular location, then deep investigatory boreholes will need to be drilled to carry out further testing of the geological conditions at depth. The detailed characterisation and technical work associated with the borehole drilling phase could take around 10-15 years (RWM 2020a).

[1] https://www.workinginpartnership.org.uk/
[2] https://www.gov.uk/guidance/about-national-geological-screening-ngs

A preferred site for further underground investigations, construction and operation of a GDF will be selected based on comparative evaluations following the deep borehole investigation phase. NWS will work in partnership with communities throughout, and a right to withdraw from the process will be maintained through to selection of a preferred site, which will include a test of public support. NWS will also need to obtain approval from the Secretary of State for (i) selection of sites for borehole investigations, and (ii) selection of a preferred site.

Both establishment of deep investigatory boreholes and development of a GDF are classed as nationally significant infrastructure projects (NSIP). The requirement for deep borehole investigations and the GDF are described in a National Policy Statement (BEIS, 2019), along with detailed planning guidance explaining how development consent applications will be examined. The National Policy Statement explains how the process will be regulated under the planning (under the Planning Inspectorate and Secretary of State), environmental permitting (under the Environment Agency) and nuclear site licensing (under the Office for Nuclear Regulation).

Characterisation of both the surface and subsurface environment has a key role to play throughout the process. Although this report focuses on biosphere characterisation, it is emphasised that the biosphere forms an integral part of the overall system that needs to be considered in assessments. The report is structured around key demands placed on biosphere understanding, notably:

- ▲ EIA requirements in support of planning consent (Section 2); and
- ▲ Safety assessments in support of Office for Nuclear Regulation (ONR) site licencing, and Environment Agency (EA) permitting requirements during operation and demonstrating long-term (post-closure) safety (Section 3).

Other considerations relating to biosphere site characterisation and understanding are discussed in Section 4, including the relationship between characterisation and Site Descriptive Models (SDMs), on-going monitoring, design/construction and programme integration.

An illustrative roadmap for biosphere characterisation is then presented and discussed in Section 5.

References are provided at the end of the main text, along with a glossary of key terms.

Appendix A summarises understanding gained from a review of biosphere characterisation undertaken in support of other relevant projects in other countries.

1.2 System Understanding

During early phases of a GDF development programme, a general strategy for developing and maintaining site understanding must be determined. A lesson learnt from other national programmes, e.g. Andersson et al. (2013), and described in International Atomic Energy Agency (IAEA) guidelines/requirements (IAEA, 2011), is the importance of conceptualising, planning and assessing a GDF and its surrounding environment as a system with interacting units. This system constitutes the designed parts, the geosphere and the biosphere. A biosphere characterisation roadmap should, therefore, be an integral part of the overall site characterisation, and links between system components should be identified in a conceptual site model. In this report the terms "site characterisation" and "site descriptive modelling" are used if the issue discussed is not specific to the biosphere. The use of a common conceptual system model provides a good starting point in identifying previously undetermined site-specific features, properties and processes. It also enables a stepwise enhancement of site understanding, or the SDM, to be used as "one model for all end users" and will help to optimise the site characterisation programme. Other benefits of a system understanding strategy would be:

- to foster a scientific culture characterised by curiosity and high ambitions;
- development and maintenance of high scientific competence in the programme and an integrated overall programme strategy;
- integration between disciplines, including between the bedrock and surface system, e.g. hydrogeochemistry and biogeochemistry, geology and pedology, hydrogeology and hydrology/weather, bedrock and topography geometry, geosphere radionuclide transport and biosphere radionuclide transport plus dose modelling;
- to facilitate the development of a knowledge management system and establishing a common site information synthesis through a SDM that is supported by discipline-specific models and reports;
- to establish a common general site investigation plan, which should build on a requirement management system, including safety arguments, and be used as an early support to an iteratively developing safety case; and
- to support arguments about expected impact on fundamental safety and environmental protection objectives using a graded approach (IAEA, 2012).

Lessons learnt from other on-going programmes (see Appendix A for a summarised compilation of programme descriptions) show the importance of constructing system understanding in a way that can be used to argue for the safety performance of the system, by showing scientifically supported confidence in system functions and processes. In Figure 2, an example of a biosphere dose assessment strategy is shown that builds on on-going international collaborations since the 1990s (IAEA, 2003; IAEA, 2021). Note the central placement of system understanding that includes overall site characterisation, and the information flow between the assessment steps and system understanding. Site descriptive modelling builds that system understanding, drawing on site characterisation, and can support the development of generic FEP lists[3], and/or development of site-specific FEP lists used in support of safety assessment studies.

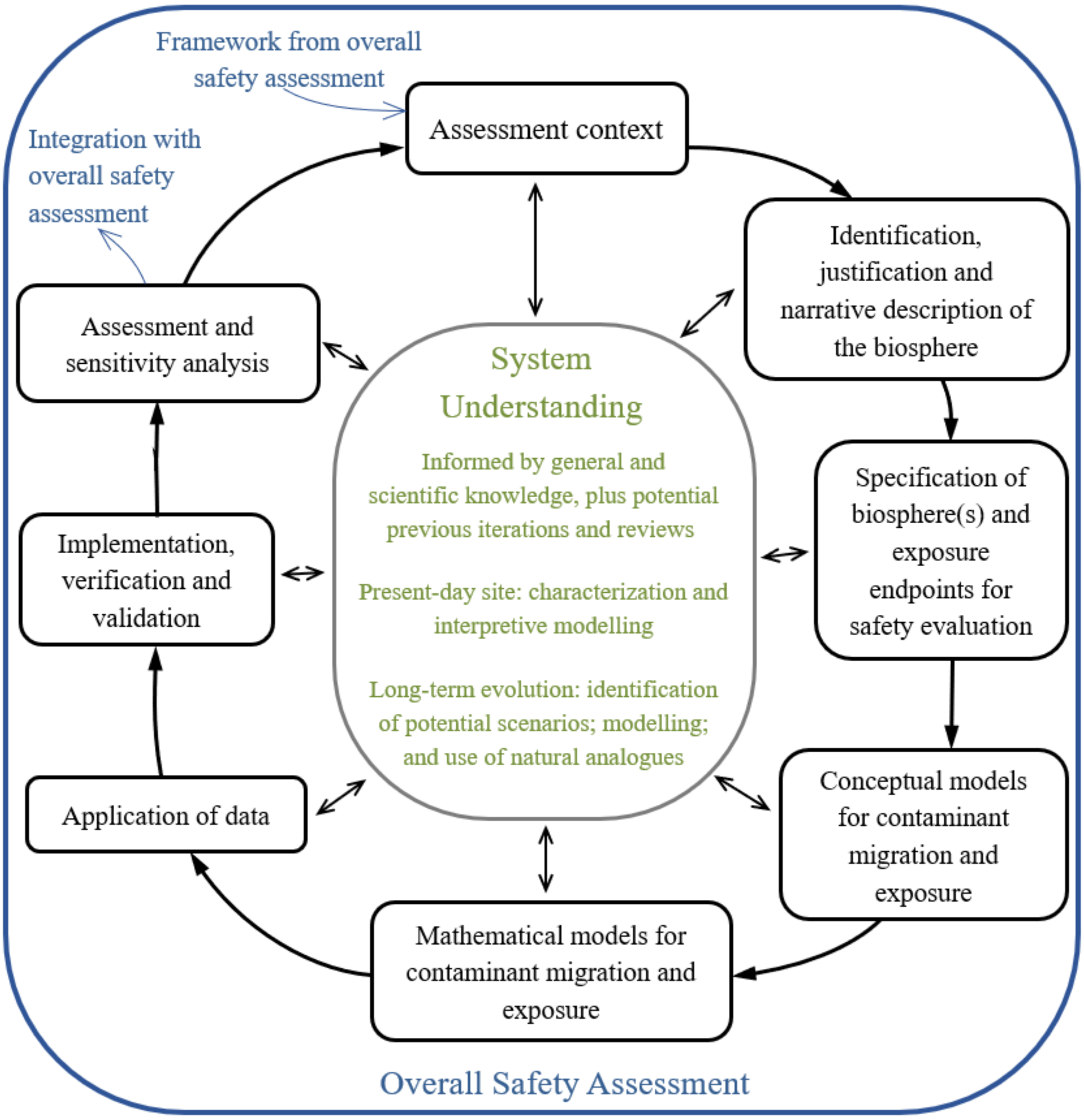

Figure 2: Suggested methodological workflow for biosphere dose assessment. Illustrating the central role of system understanding in support to all assessment steps. Draft report of Working Group 6 of the IAEA programme on Modelling and

[3] FEP lists are sets of 'features, events and processes' used in support of safety assessment studies to help build confidence that nothing of potential important to the performance of the system and safety has been overlooked; see https://www.oecd-nea.org/fepdb

Dose Assessment for Radiological Impact Assessment (MODARIA) Phase II, IAEA (2021).

1.3 Biosphere Data and Site Investigations

Site characterisation constitutes two main activities, site investigations that produce data and the interpretation of data into descriptions and models that characterise the site. A well-designed site investigation plan with a "system understanding" focus is essential to support assessments, not only for long-term safety, but also to support assessment of environmental impact during investigations, construction, and operations. There is also a need to suggest practical measures to counteract or "replace" disturbed or modified environments. To support this, an understanding of site-specific ecosystem properties, functions and processes is essential. Typically maps, field surveys and installations are used to gain spatial and temporal knowledge of physical properties and the chemical composition of vegetation, soils, sediments, animal populations and endangered species, hydrology, groundwater levels, weather and human behaviour/land-use. Together with topography/bathymetry and ecosystem delineations, a good basis for impact assessments can be achieved that serves as input to all end-users such as safety assessment, environmental assessments, and GDF design/construction.

In Figure 3, a typical site characterisation structure from on-going and advanced national programmes is exemplified, see Lindborg et al. (2021), SKB (2008, 2015), and Posiva (2012) for examples on details and linkages to end user needs. It should be noted that the biosphere component of the characterisation (highlighted in red in Figure 3) is integrated into a common task and that many investigation and modelling disciplines have strong links between the geosphere and biosphere. The important message here is that this integration should not only be seen in planning documents, but rather as an implemented strategy when conducting investigations and modelling activities. Examples of this are that when drilling deep core boreholes, it is important to make sure that the upper part of the bedrock/soil also is characterised, and when using borehole data to produce hydrogeological models, make sure that a hydrological model describing the surface/upper bedrock/soils is included, or that overlapping model domains are used consistently and in a way that is supported by results from both disciplines. By this strategy, a common conceptual understanding is produced using multiple lines of evidence.

A major part of constructing a site characterisation roadmap is to help ensure that the site investigations are conducted in a way that addresses the demands of end users (see Section 1.1). A stepwise approach, that uses the formal information requirements for the GDF programme to move forward into the next stage, is recommended. This implies that the site characterisation plan is a living document that uses the latest site information together with the identified information demands from the various end users to plan for future investigations. Therefore, the goals and requirements for the present stage should be the main basis for planning, but with a view also to longer-term goals and requirements. However, some site information will take time to collect. One example is parameters or processes for which time series are required to develop understanding and quantification. This means that, from the outset, the site investigation planning must take time lags into account. Another aspect is the time needed for planning and the integration of topics into an operational investigation programme that can be executed. The Swedish example in Appendix A.5 shows that this can be a two-year task for a group that includes members from all relevant programme functions and disciplines.

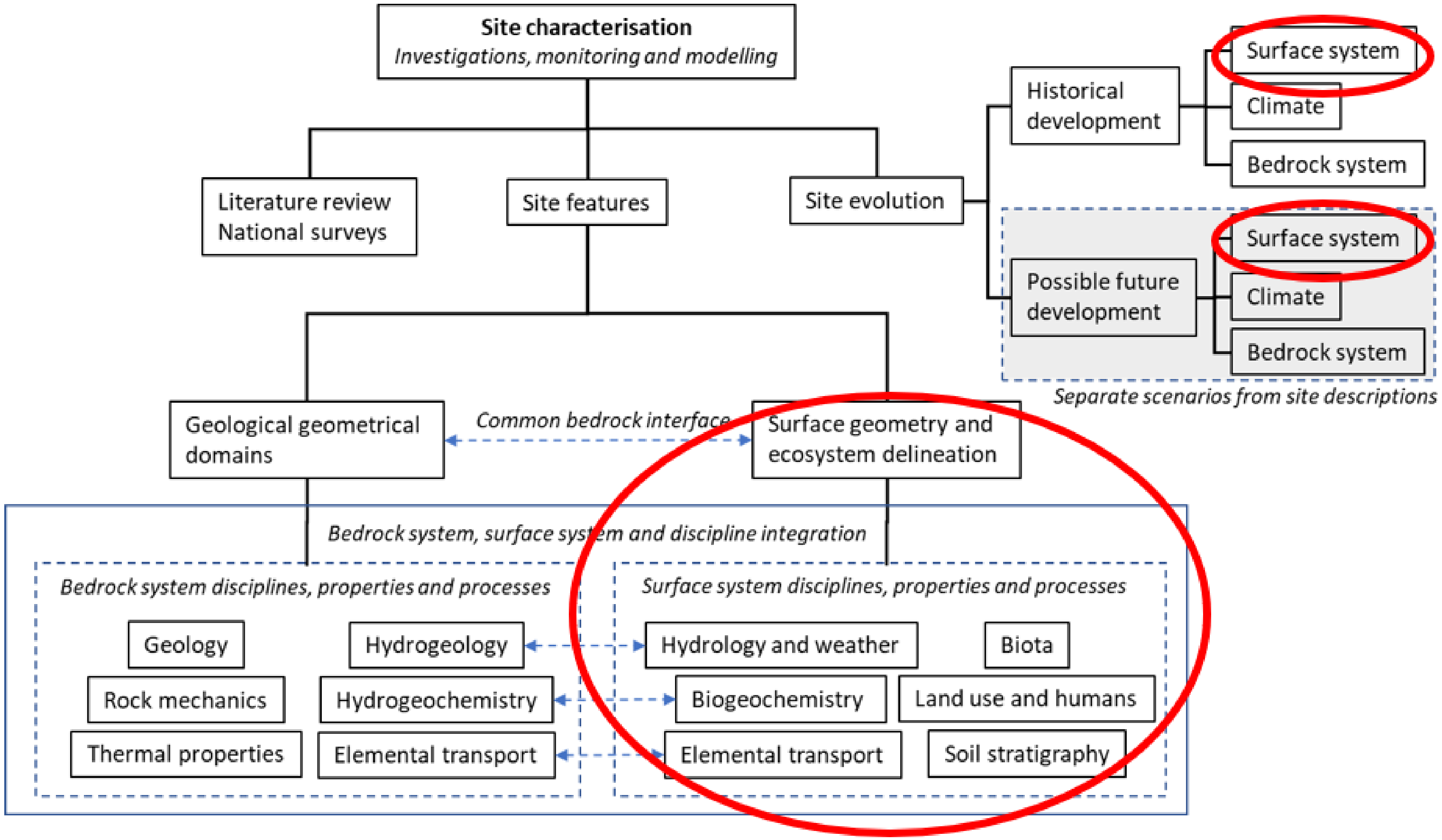

Figure 3: Site characterisation structure showing the total natural system with typical scientific disciplines in a radiological waste management programme. Biosphere components of the site characterisation are highlighted in red. Site characterisation disciplines with a strong need for integration are shown with blue arrows. Adjusted illustration from Lindborg et al. (2021).

2 Environmental Impact Assessment (EIA)

EIA is the term used to describe the formalised process of gathering baseline data and assessing the potential effects of implementing the construction and operation of a development, such as the GDF, in a particular location. The primary aim of EIA is to protect the environment by ensuring that a decision maker, when deciding whether to grant consent for a project that is likely to have significant effects on the environment, does so in the full knowledge of the likely significant effects, and takes this into account in the decision-making process[4]. The Infrastructure Planning (Environmental Impact Assessment) Regulations 2017 (2017 EIA Regulations) set out the procedure for identifying those projects which should be subject to EIA, and for assessing, consulting and coming to a decision on those projects which are likely to have significant environmental effects. The aim of EIA is also to ensure that the public are given early and effective opportunities to participate in the decision-making process.

To consider, characterise and quantify the potential effects, multiple specialist studies across a wide range of topics are undertaken to take account of potentially significant positive and negative effects, including those that are direct, indirect, secondary, cumulative, short-, medium- and long-term, permanent and temporary, as well as the consequences of future changes that may occur in the baseline environment, such as climatic change.

The baseline conditions set out in the EIA are often used as the starting point for defining the biosphere conditions adopted in both the operational and post-closure safety assessments. Here the term "baseline" refers to conditions existing before development against which subsequent changes can be referenced.

Ultimately, achieving the appropriate consents to drill geotechnical boreholes and develop the GDF will be reliant upon the thoroughness of the EIA process, including stakeholder and public consultation, throughout the characterisation and assessment of the biosphere. Consequently, EIA forms an integral component to the biosphere characterisation roadmap as illustrated in Section 5 of this report.

2.1 EIA Process and Consenting Regime for the GDF

The legal framework for EIAs conducted in relation to NSIPs in England and Wales is set out in the 2017 EIA Regulations. There is potential for the GDF project to also fall

[4] https://www.gov.uk/guidance/environmental-impact-assessment

under the purview of the Marine Works (Environmental Impact Assessment) Regulations 2007 (as amended).

The Planning Act 2008 and National Policy Statement (BEIS, 2019) are explicit in identifying development relating to a radioactive waste geological disposal facility as a NSIP.

Given the scale and national importance of the GDF, it will be considered a NSIP (BEIS, 2019) requiring a positive decision and issue of a Development Consent Order (DCO) from the relevant Secretary of State (SoS), giving the necessary approval to construct and operate. This decision milestone will be preceded by the detailed examination of the DCO application documentation by the Planning Inspectorate (PINS), as defined in the Planning Act 2008, the Infrastructure Planning (Environmental Impact Assessment) Regulations 2017 (the 2017 EIA Regulations), and the Marine Works (Environmental Impact Assessment) Regulations 2007 (as amended).

It is understood from NWS (and consistent with BEIS, 2019) that the process of identifying a preferred site for the GDF will involve the sinking of deep geotechnical boreholes to evaluate underlying geological conditions at two potential host community locations, and that this phase of work will also be considered NSIP in its own right and subject to the same consenting regime as the final host site selected for the installation of the GDF.

As such, the expectation is that EIAs will be required for the individual applications for DCOs for (i) the geotechnical borehole evaluations, and (ii) the selected and fully designed GDF site, with Environmental Statements (ESs) being prepared for (i) and (ii) as part of discrete application documentation packages submitted to PINS for detailed examination.

This section of the report, in particular, includes several acronyms. They are defined on first use and also defined in the glossary at the end of the report.

2.2 DCO Application Timeline to Decision

Each DCO application has a fixed timeline from application submission to DCO decision as set out in the Planning Act 2008 and illustrated in Figure 4. This shows that a DCO decision issued by the relevant SoS can take between 12 and 14 months to achieve, excluding any post-decision legal challenge, from receipt by PINS of the DCO application documentation.

As described above, the DCO application documentation submitted to PINS will include an Environmental Statement detailing the results of the EIA. Consequently, the pre-application phase (the first box in Figure 4) could take several years to complete, to allow for detailed design work and for baseline environmental data to be scoped, collected, analysed and assessed, for consultations with key stakeholders to be held, and to hear and take account of the views and opinions of the public and interested parties.

An indicative timeline for the GDF project from evaluation to construction is provided in Table 1.

The route to obtaining a DCO is process driven and the typical EIA stages (screening, scoping and impact assessment) interact with this process as shown in the flow diagram in Figure 5.

The subsequent sub-sections explain how the EIA and DCO processes will fit into the GDF programme.

Table 1: Indicative timescale for the GDF project from evaluation to construction.

Timescale	Activity
~2 years	Establishment of community partnerships and initial non-intrusive investigations, monitoring and modelling commences at several potential GDF host communities.
~3 years	Potential GDF host communities are narrowed down to a few potential sites. Detailed design of geotechnical evaluation boreholes. EIAs focussed on geotechnical borehole evaluations at two host communities. Preliminary Environmental Information Reports (PEIRs) prepared. Key stakeholder and public consultations. Environmental Statements prepared. DCO application documentation submitted to PINS for geotechnical evaluation boreholes at two sites.
~2 years	DCO examination period. PINS issue recommendation to relevant SoS. SoS decision.
~10-15 years	On the basis DCO obtained, geotechnical boreholes sunk at two sites. Results inform decision-making process on preferred host site for GDF. Site selection for GDF completed.
~5 years	Detailed design of the GDF at preferred host site. Detailed biosphere assessments and EIA undertaken at preferred host site. PEIR prepared. Key stakeholder and public consultations. Environmental Statement prepared. DCO application documentation submitted to PINS for the GDF.
~ 2 years	DCO examination period. PINS issue recommendation to relevant SoS. SoS decision.
	On the basis DCO obtained, construction of GDF commences.

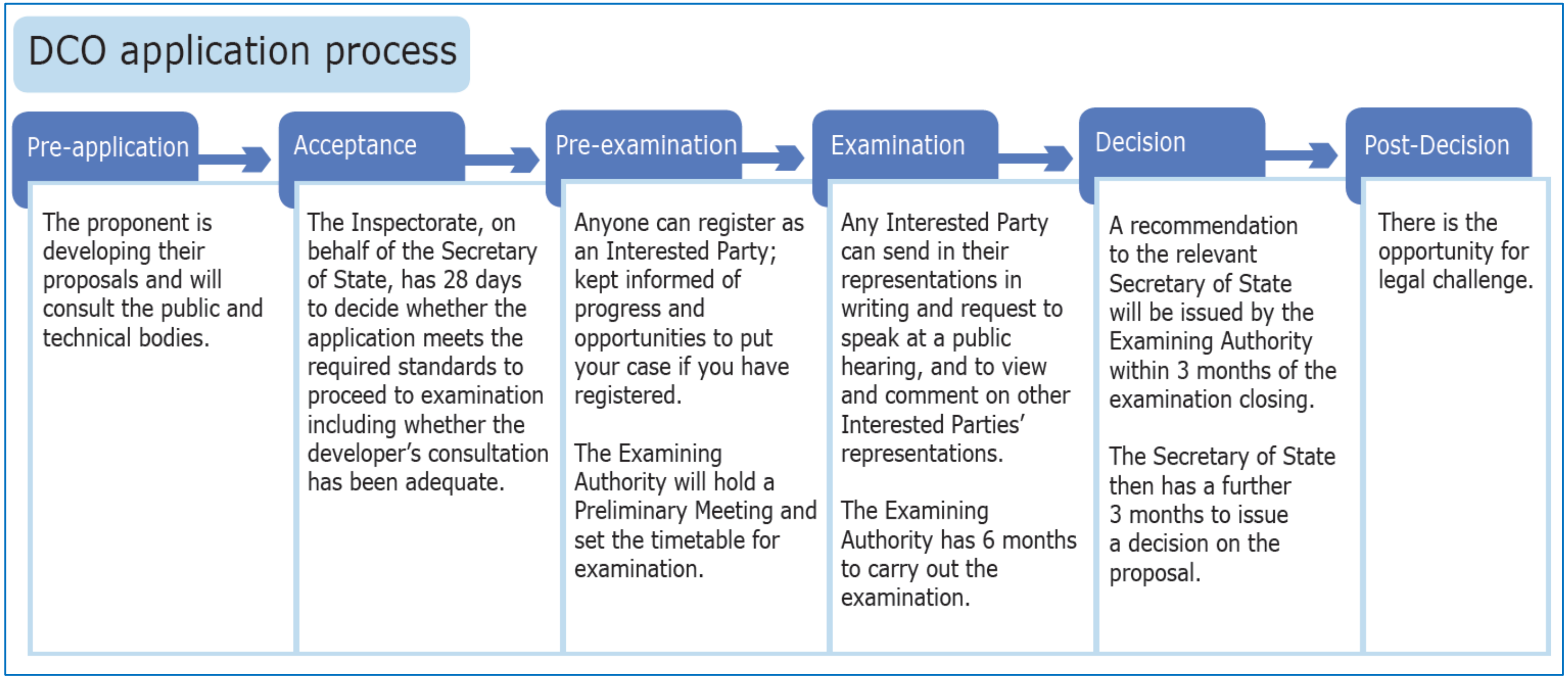

Figure 4: Decision-making process flow diagram following receipt of a DCO application. Source: The Planning Inspectorate, Advice Note 8[5].

[5] https://infrastructure.planninginspectorate.gov.uk/legislation-and-advice/advice-notes/

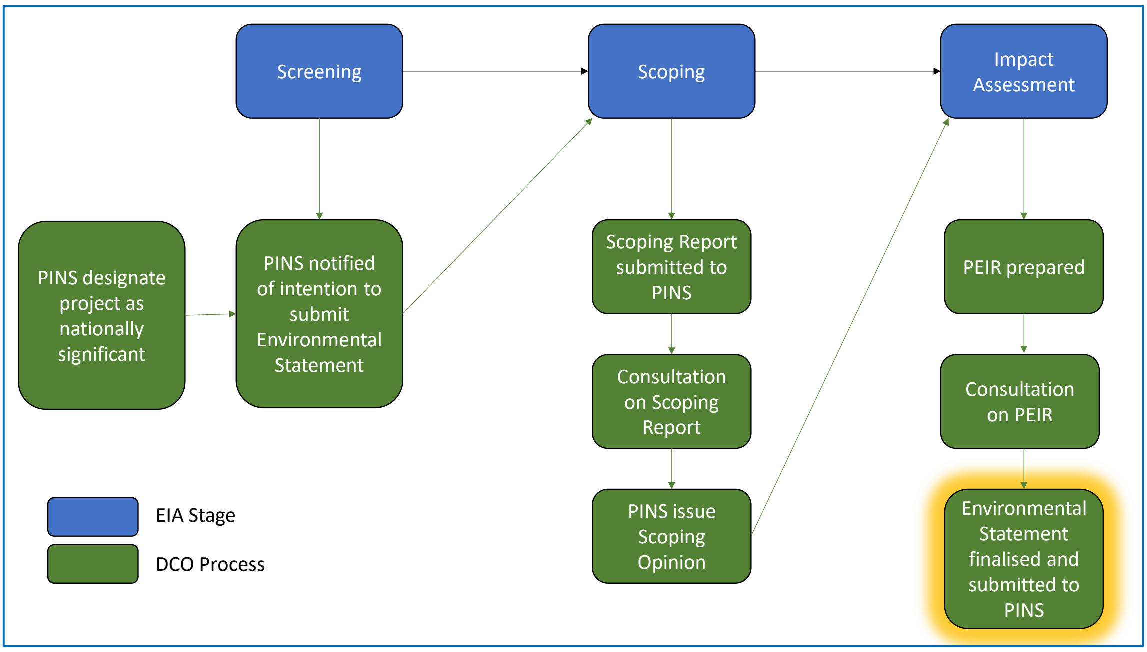

Figure 5: Flow diagram illustrating how the Development Consent Order and Environmental Impact Assessment processes interact.

2.3 Site Selection, Optioneering and Assessment of Alternatives

During the pre-application consultation and within the EIA deliverables it will be explained why the selected site for the GDF has been chosen over alternative sites. In order to assist the site selection and decision-making process, the biosphere at the potential host sites can be characterised at a high-level, predominantly through desk studies. The potential host community areas will initially be defined by their geographic location (e.g. Local Authority (LA) boundary) and by defined parameters for the suitability of a community to host the GDF (e.g. coastal zone, access, topography).

2.4 Screening and Scoping the EIA

Throughout the pre-application process for the GDF, PINS will focus attention on any data gaps, lack of detail, uncertainties, and the thoroughness of consultation with key stakeholders and the public. Projects can be delayed or pushed back if PINS consider greater detail or dialogue is needed.

Agreeing the scope of the EIAs with relevant bodies early and in advance of commencing any studies will allow third parties to express any immediate views, issues and concerns relating to the GDF project, which may become dominant themes for consideration within the EIAs. The use of an "Issues Log" can be helpful to document all correspondence and to track how each point raised has been dealt with, particularly if these result in adjustments and/or design changes for any GDF components.

Scoping for EIA is the process of describing and agreeing with relevant key stakeholders, such matters as:

- which topics/sub-topics are to be scoped in and out of the assessment;
- the coverage and duration of baseline data capture and monitoring;
- the extent of study areas;
- which modelling parameters will be used and what standards will be adopted; and
- any limitations in baseline studies and impact assessments.

Potential considerations for the GDF

The GDF site selection process will affect how EIAs are conducted and how biosphere baseline data is collected, including the timing of such studies; examples are given below.

- Defining project boundaries, parameters, and site layout at an early stage, so that the scope and limitations of the EIA approach can be agreed with key stakeholders.
- Where more than one potential location for the GDF is being considered, it may be appropriate to undertake "EIA Screening and Scoping" studies for each of the shortlisted options.
- If the construction date of the GDF project component for which a DCO is being sought is likely to be several years from when the EIA baseline field data collection is undertaken, this may become a constraint to key stakeholder acceptance. For example, baseline data is considered to have a "shelf life" for certain topics (e.g. ecology survey data normally needs refreshing after two years; air quality uses monitoring data and models to determine baseline, opening year and future year predictions derived from traffic modelling data from the project's transport consultants). The conduct of multiple seasons of field data acquisition may be required.

The outcome of the "EIA Scoping and Screening" process will be the publication of an "EIA Scoping Report", documenting the consultation undertaken to date, and detailing the proposed level of baseline study and impact assessment to be undertaken by technical discipline. The "EIA Scoping Report" is submitted to PINS, who will then review and consult on this and issue an "EIA Scoping Response", setting out any changes considered necessary to the scope of the EIA.

2.5 Establishing the EIA Baseline Situation

The selected locations of the potential host communities and the siting of the GDF components (e.g. geotechnical boreholes and onshore/inshore components of the main build) will form the basis of establishing study areas and the EIA baseline situation through a combination of desk studies, modelling and field-data collection.

Characterisation of the baseline situation will include establishing background concentrations of radionuclides and non-radiological pollutants, as well as the natural background dose rate. These provide a basis against which potential impacts can be assessed, as well as context and a point of reference for assessment modelling (see Section 3.2).

Proximity to and potential environmental impacts covering a range of factors will influence decision makers and key stakeholders and effect the outcomes of the EIA. Those factors include proximity to and potential effects on:

- international and nationally designated areas and individual assets (see examples in Table 2);
- people and the environment (e.g. risks of emissions/nuisances/changes to the water environment) (see examples in Table 3); and
- people's employment, businesses and health (see examples in Table 4).

When characterising socio-economic baseline conditions (included in Table 4), then the extent of the off-site emergency planning zone will be an important consideration. This is discussed further in Section 4.3.

Table 2: Examples when considering potential effects on international and nationally designated areas and individual assets in the context of EIAs.

Category	Examples
Ecology/Biodiversity	▲ Habitats and species: e.g. marine flora and fauna, protected species, migratory and coastal birds. ▲ Mapping and characterisation of regional/national/international designations: e.g. Marine Conservation Zones, Special Protection Areas, Special Areas of Conservation, Ramsar sites, National/Local Nature Reserves, Sites of Special Scientific Interest (SSSIs). ▲ Net loss/gain calculations will be a key factor and any commitments to biodiversity offsetting and % net gain will need careful consideration; final site selection and what it comprises in terms of existing biodiversity value will be decisive.
Landscape/Seascape	▲ Mapping and characterisation of regional/national/international designations: e.g. National Parks, Areas of Outstanding Natural Beauty, National Trails. ▲ Mapping of nearby residential properties, photography from key viewpoints, creation of Zones of Theoretical Visibility models, in order to consider the existing visual amenity for local residential properties, visual amenity, and the potential effects with the inclusion of the project (e.g. through modelling and 3D visualisations).
Cultural Heritage/Archaeology	▲ Archaeological sites (known and potential) and built heritage assets. ▲ Mapping and characterisation of regional/national/international designations: e.g. World Heritage Sites, Scheduled Monuments, Protected Wrecks, Listed Buildings, Registered Parks and Gardens. ▲ The wider setting extents of heritage landscapes and designated assets.

Table 3: Examples when considering potential effects on people and the environment in the context of EIAs.

Category	Examples
Air Quality	▲ Mapping of nearby residential properties and ecological sites to include in the modelling as sensitive receptors (e.g. from construction generated dust, vehicle emissions). ▲ Establishing through modelling if there is any potential worsening effect on sensitive receptors in the future with the inclusion of the project. ▲ Determining if the project's activities (construction and operation) contribute any potential exceedance of the Air Quality Standards.
Noise and Vibration	▲ Mapping of nearby residential properties and ecological sites to include in the modelling as sensitive receptors (e.g. from construction and operation generated noise and vibrations from equipment, borehole and foundation drilling, vehicles).
Access and Transport	▲ Mapping the local road network, building a traffic model, collecting data to establish existing and future traffic flows, which can then consider the effect of the project's proposals on the network (e.g. increases in traffic volumes, effects on non-motorised users, equestrians and local businesses, new roads, road closures, footpath diversions, public transport, accessibility for local community).
Water, Drainage and Flood Risk	▲ Mapping of all drainage components such as catchments, surface watercourses, flow data, water quality, groundwater levels, local drainage network, to include in the modelling, which can then consider the effect of the project's proposals on the water environment, people's property and homes (e.g. groundwater protection, surface water run-off rates, pollution hazard control, flooding risks, sustainable drainage, and sea-level-rise resilience, including future climate change factors).

Table 4: Examples when considering potential effects on employment, businesses and health in the context of EIAs.

Category	Examples
Human Health	▲ Obtaining data on the predicted numbers of employees and activities to be undertaken during the construction and operation of the GDF which can then be used to consider the effect of the project's proposals on human health.
Socio-Economics	▲ Mapping of the existing situation, which can then allow a consideration of the effect of the project's proposals on the local economy in the host community (e.g. positives: local employment (construction and operation), infrastructure improvements, community investment, apprenticeships, training, supply chain and proximity advantages to other businesses; negatives: loss of livelihood, compulsory purchase, property devaluation, site security restrictions on access, disadvantages to other businesses).

2.6 EIA Topics/Sub-topics, Baseline, Impact Assessment and Mitigation

In order to characterise the biosphere, a team of specialists will collect baseline data, assess potential impacts, and devise appropriate levels of mitigation. With an eye on the end deliverables for the DCO submissions, as well as the suite of stakeholder and public consultations, this section provides NWS with a guide on the anticipated structure of the EIAs required for the GDF. This section does not elaborate on which topics are relevant for a borehole drilling application and which would be relevant for a GDF application: most would be expected to be included in all EIAs.

The list of EIA topics and sub-topics included in the Table of Contents for the published Environmental Statements for the GDF will be agreed during scoping and may include:

- air quality (including dust);
- noise and vibration;
- protection of human health and the environment;
- surface water resources, drainage, and flood risk;
- climate change factors and project resilience;
- hydrogeology, including groundwater, geology and soils;
- ecology and biodiversity (including terrestrial and marine);
- cultural heritage and archaeology;
- landscape and visual amenity (including lighting);
- sustainability, resource use, and waste management;
- access and transport;
- socio-economics and land use;
- major risks and accidents assessment; and
- cumulative effects assessment.

Each topic/sub-topic of the EIA will describe the baseline situation, defining “zone(s) of influence” that will determine each topic/sub-topic’s study area. These study areas will be unique to each topic/sub-topic and could be at the local, regional, national and/or international level. Each topic/sub-topic will identify its “sensitive receptors” and will typically ascribe a value to these using pre-defined criteria (“sensitive receptors” could include, for example: people, protected species, habitats, watercourses, archaeological sites, groundwater).

The impact assessment stage of the EIA considers the potential effects of the GDF project arising from all phases (construction, operation, and closure) on all "sensitive receptors" identified in the baselines, taking account of the project's embedded design components. Each topic/sub-topic uses published EIA guidance or accepted criteria, previously described and agreed at scoping, to attribute a significance of effect value to each "sensitive receptor" based upon the predicted impact of the project arising from each phase of activity (construction, operation, and closure).

Strategies to help reduce, mitigate and manage potentially significant adverse effects on each "sensitive receptor" are then provided, often following dialogue with key stakeholders, and an overall residual effect value is determined.

2.7 Preliminary Environmental Information Report, Statement of Community Consultation and Pre-application Consultation

The outcome from the impact assessment stage is a PEIR, detailing all the results from the baseline studies, anticipated levels of impact per technical discipline, mitigation proposals, and residual effects. Submission of the PEIR to PINS then follows and the PEIR is included with project information issued in the formal pre-application consultation stage (Figure 5). A "Statement of Community Consultation" (SoCC) is prepared setting out the proposed consultation process for the GDF. The outcome, following the Pre-application Consultation, is the publication of a "Consultation Report" detailing meeting attendances, a compilation and assessment of responses received and the considered replies from the proponent's team to comments/issues raised.

2.8 Updated EIA and Environmental Statement

The final stages of the EIA process through to examination by PINS is explained below and highlights the level of potential reworking of the GDF biosphere characterisation assessments that may be necessary prior to formal submission.

The design of GDF project components may be adjusted to take account of recommended changes, alternative layouts, different approaches, addressing areas of concern/issues raised during consultation with key stakeholders and the public. The EIA process is iterative and evolves as new data becomes available or changes are made.

Such changes may have a bearing on the EIA outcomes, so the EIA (impact assessment and mitigation strategy components) are updated, as necessary. If the changes are substantive, this could involve new modelling and may affect the timing of formal submission to PINS.

Once the EIA has been modified, the end product is a finalised "Environmental Statement" (ES); an updated version of the PEIR following the consultation phase. This forms part of the package of information submitted to PINS for formal Examination (Figure 4).

The Examination period then follows. PINS will consider the submission and issue clarification questions to the team. If the project is approved by the SoS following the PINS's recommendation, a Development Consent Order (DCO) is issued, allowing compulsory acquisition powers of land/property and construction to commence once the statutory challenge period has closed out.

2.9 Environmental Mitigation and Management Plans

The implementation strategies for reducing effects take the form of mitigation and management plans (per topic area) that are agreed with the relevant authorities and key stakeholders (e.g. Environmental Health Officers, Natural England, Environment Agency).

2.10 EIA Process Roadmap and Data Management

An example roadmap of the EIA process is provided in Figure 6. The EIAs for the GDF (addressing borehole drilling and GDF applications) will inevitably lead to the production of substantial data, models, graphics and text, and its effective management will be a major consideration for the EIA team, so that data and deliverables can be readily accessed, used and interrogated in a meaningful and transparent way. The timescales for these different EIA processes may overlap.

A common criticism of major project ESs is that they are challenging tomes to read and to navigate around, and Non-Technical Summaries can often run to tens of pages.

Immersive visualisations, interactive ESs and explanatory videos are becoming more commonplace. Innovative digital methods of illustrating survey results and the outcomes of assessments, particularly for complex and technical topics, can be explored, as technological advances lead to improved modes of data and results presentation.

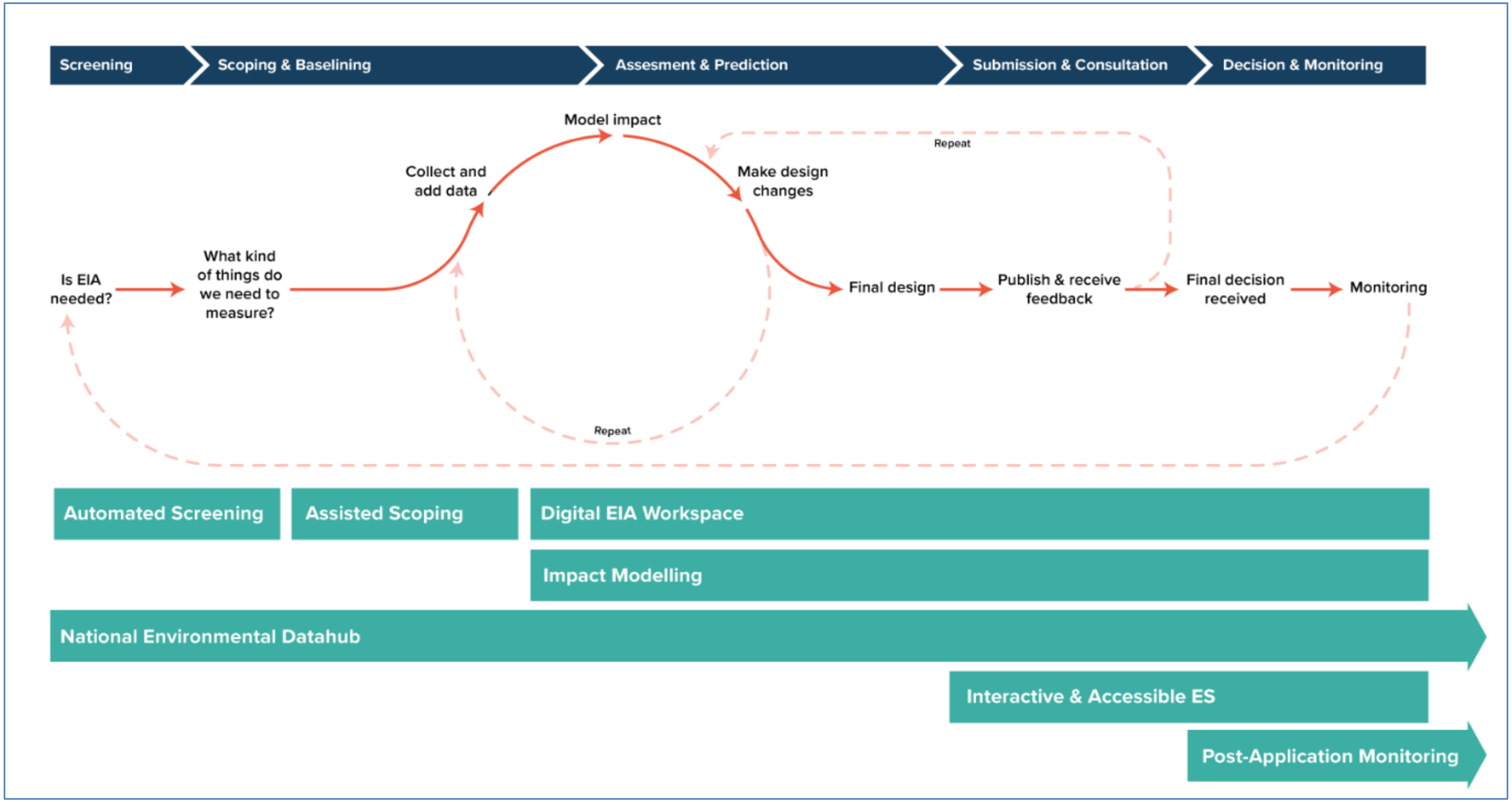

Figure 6: An example roadmap for the EIA process. Source: digitaleia.co.uk

3 Safety Assessment

Safety assessments are required for some aspects of site investigation (e.g. construction of boreholes) and all stages of the construction, operation, closure and post-closure phases of developing a GDF. These safety assessments will require evaluation of the radiological and non-radiological impacts of the development on human health and the environment. Assessments of conventional safety and non-radiological impacts of releases are addressed through the EIA process (see Section 2). Therefore, in this section, the focus is on assessment of radiological impacts. During the operational phase these impacts include those arising from planned releases of radionuclides and from possible accidental releases. If accidental releases could result in significant off-site radiological impacts, this would imply the need for the LA to develop an off-site emergency plan and to specify a Detailed Emergency Planning Zone (DEPZ). The implications of having to define a DEPZ are raised in Section 2.5 and discussed further in Section 4.3. The operational and post-closure safety assessment methodology used by NWS was reviewed in 2019 (Nucleus, 2019a) and are at present (2021) being updated for consistency of approach.

For the post-closure phase, radiological impacts are projected to arise due to the transport of radionuclides in groundwater. Releases in the gas phase or by intrusive actions are also possible. Because radionuclide releases in groundwater and gas are typically of greatest significance and have implications for site characterisation, they are the focus of the following discussion.

3.1 Safety During Operations and for the rest of the Period of Authorisation

Radiological impact assessment calculations will be required for the operational period of a GDF, for the post-closure Period of Authorisation (PoA) (i.e. the period after closure, but during which time the site is still under active control and subject to permitting) and for the subsequent post-closure period when controls on use of the site are taken to have been relaxed. In this subsection, consideration is given to the operational period of a GDF and the post-closure Period of Authorisation (PoA). The subsequent post-closure period after the relaxation of controls is addressed in Section 3.2.

During the operational period, radionuclide releases are likely to be primarily to air, because there seems little reason for the generation of liquid effluents from packaged wastes, although there could be some low activity liquids generated from cleaning of packages upon receipt and in effluents from any contaminated areas within facility buildings or from underground. In the latter context, activity might be leached from packages disposed during the early part of the operational phase that develop leaks prior to closure of the GDF. It is likely that such leakages would be largely captured by the engineered drainage system rather than constituting a source of groundwater contamination. Any such liquid releases should be of little radiological significance. Therefore, they are not discussed further in this report, because they are not considered to impact significantly on requirements for site characterisation. However, it should be noted that they would be subject to permitting and an assessment of their radiological impacts would be required, see e.g. RWM (2016c). This could be implemented through a staged approach. If simplified, stylised calculations were found to be sufficient, there would be little reliance on detailed site data. However, if more detailed calculations were found to be required, then some detailed site data might be needed.

Planned releases to air should be primarily gaseous, as high efficiency particulate air (HEPA) filtration, either at the package or building level, would, if required, be effective in controlling aerosol releases. It is possible that gaseous releases might also be effectively controlled by filtration, e.g. by using activated carbon filters. Consideration needs also to be given to possible accidents, e.g. fires, that could lead to releases of both gases and aerosols. Both routine and accidental releases might be routed via stacks, but they could also comprise vented or fugitive releases from buildings. In accident situations, contamination of the facilities and immediate vicinity could also arise, and radioactive contamination could enter surface waters and groundwaters in consequence. This would be a pathway of secondary importance in the immediate aftermath of an accident and would be addressed through monitoring and control under the specific circumstances of the accident. Because of these considerations, it is not considered to be of significance in defining a programme of site characterisation and is not addressed further in this report.

Following closure of the GDF and during the remainder of the PoA, releases to atmosphere should not arise. Also, at this early stage, releases to the biosphere from the GDF itself, either dissolved in groundwater or as gas, should not occur to any significant degree. Therefore, this phase is of limited relevance in site characterisation. In contrast, in the long-term after the PoA, radionuclide releases in groundwater and in gaseous form may be anticipated (see Section 3.2).

Based on the above considerations, the biosphere aspect of site characterisation relevant to the operational period needs to focus on delivering information relevant to short-term and chronic releases of radionuclides to the atmosphere as both aerosols and radioactive gases.

Because the period of initial site characterisation predates commencement of the operational phase by some years, radiological assessments applicable to the operating phase differ from prospective radiological assessments applicable to operating nuclear licensed sites, which are generally targeted at the next few years of operation. In such assessments, it is reasonable to assume that human habits and land uses are like (but not necessarily identical with) those existing at the time of assessment. On a longer timescale, these similarities may diminish, changing the emphasis on the degree of detail to which these aspects of the environment need to be characterised for assessment purposes.

In order to undertake radiological impact assessments applicable to the operational phase, information is required on meteorological characteristics relevant to the simulation of atmospheric dispersion, occupancy and respiratory parameters relevant to inhalation of gases and aerosols, transfer parameters appropriate to quantitative modelling of food-chain pathways, human habits relevant to radiological impacts, and the characteristics of non-human biota that affect the radiological impacts of short-term and chronic releases of radionuclides during the operational phase on those biota. These various aspects are discussed below.

3.1.1 Atmospheric Dispersion

For both aerosols and gases, the initial consideration is the degree of atmospheric dispersion that occurs between the release location and the locations where a representative person may be present, or from which they may obtain items of their diet. Estimating this degree of dispersion requires data on local meteorological conditions and specifically information on the local wind-rose. This provides the frequency with which the wind blows into each sector, with further partitioning of the data by atmospheric stability category and by wind-speed interval. Once a specific site is identified or a local region that might host a site, the wind-rose can be derived from information obtained from one or more local, pre-existing weather stations with reasonably long records (a thirty-year record is generally regarded as sufficient to characterise present-day climate, and a record of five years or more provides a good indication of inter-annual variability). Data from these weather stations is typically available at hourly intervals and can be processed to give sectorised data, as described above, that can be used as input to a simple Gaussian-plume model of dispersion. Alternatively, the hourly data can be used directly in a more comprehensive dispersion model, such as ADMS[6]. Also, once a site has been selected and non-invasive surface investigations have commenced, a standard local weather station can be installed, and site-specific meteorological data can be obtained. Initially, the short record available can be used to confirm the validity of using data from pre-existing local stations (by

[6] http://www.cerc.co.uk/environmental-software/ADMS-model.html

comparing the data records over the same period) and, in the longer-term, the site-specific record can be used directly.

During the site-investigation phase, the buildings present on site are unlikely to be representative of the building configuration that will be present during the operational phase. Therefore, building-wake effects on dispersion can only be estimated from theoretical models or wind-tunnel simulations, considering potential future locations and sizes of buildings on the site. Site characterisation cannot contribute to the quantification of those effects, though it may influence decisions on the configuration of surface structures at the site.

3.1.2 Human Factors Relating to External Exposure and Inhalation

Irrespective of the calculational method used, atmospheric dispersion modelling will be used in assessments to provide time- and location-dependent potential atmospheric concentrations of radioactive gases and aerosols. These will result in potential human exposures by external exposure, inhalation and ingestion of contaminated food products. Site characterisation has little to contribute to assessments of the external exposure and inhalation pathways. Once atmospheric concentrations are known, radionuclide intake rates are determined primarily by the human occupancy at the location and by the breathing rate during that occupancy. The extent to which site characterisation can provide information on human habits is addressed further in Section 3.1.4.

3.1.3 Characterisation of Food-chain Pathways

The first stage of the food-chain pathway is deposition to plants and soils (inhalation by animals is generally of little significance). For chronic releases, it is radioactive gases that are likely to be of predominant importance. These could include tritium-bearing hydrogen, water vapour and methane, C-14 bearing carbon dioxide and methane, radon and other noble gases, e.g. Kr-85. Because radon and the noble gases are only of potential significance by external exposure and inhalation, they do not need to be addressed further. Hydrogen gas is not readily taken up by plants and the uptake of H-3 in water vapour can be addressed through a specific activity calculation that relates the specific activity in plant water to the specific activity in air. Similarly, the uptake of C-14 from carbon dioxide can be represented using a specific activity approach. For H-3 and C-14 in methane, there is an additional modelling step that addresses the oxidation of methane to water and carbon dioxide in the soil zone. Any H-3 released will be incorporated into water molecules. For C-14, plant uptake will be determined by the transport and mixing of the resultant C-14 bearing carbon dioxide through the plant canopy, and by photosynthetic uptake. In this context, initial assessment studies can be based on literature data on methane oxidation rates in various soil types and at various degrees of soil saturation, but these studies could be refined by site-specific measurements of methane oxidation rates *in situ*. For agricultural crops (including pasture), the degree of mixing in the plant canopy is not strongly affected by the plant type, so site-specific data on agricultural practices are of limited significance.

Aerosols are likely only to be of significance under accident conditions. Therefore, the interest is primarily in short-term releases. Because the facilities will be handling packaged wastes, mainly encapsulated in relatively inert waste matrices, releases under accident conditions are likely to be limited (potentially constraining the extent of any DEPZ, see Section 4.3). Furthermore, in the short-term following such accidents, inhalation exposures would be likely to dominate, with external exposure from ground deposits plus inhalation of resuspended material becoming of greater significance when the initial plume had dispersed. Also, in contrast to reactor accidents, short-lived radionuclides, like I-131, would not be of significance. Therefore, it seems likely that releases would be dominated by volatile Cs-134 and Cs-137, plus smaller contributions from other longer-lived radionuclides such as Sr-90 and various actinides. For food-chain pathways, foliar deposition and translocation to internal plant parts would dominate at early times, with deposition on soil and uptake by roots a much longer-term consideration. Foliar deposition and translocation can be readily assessed using generic data from international compilations. Although these data are rather sparse, the limited significance of accidental releases and of food-chain pathways associated with those releases indicates that site characterisation does not need to focus on this pathway. Indeed, if an accident were to occur, monitoring of the contaminated environment would take precedence over modelling projections of plant uptake and associated radiological impact.

In respect of transfers to domestic animals, the focus can be on uptake of H-3 and C-14 from pasture or fodder crops. Again, specific activity models can be used to relate concentrations in diet to concentrations in animal tissues. This means that site characterisation activities do not have a role in refining radiological impact assessments for this pathway.

3.1.4 Human Habits

The assessment modelling described above provides radionuclide concentrations in various environmental media, including plants and animal products. Therefore, what remains is to use this information to assess annual effective doses to humans. These annual effective doses arise from external exposure, inhalation of resuspended material, ingestion of water, and ingestion of contaminated foods (which may include a small contribution from adventitious ingestion of soil). Dose factors for external and internal exposure are typically taken directly from compilations such as those of the US Environmental Protection Agency (EPA) (external exposure) and International Commission on Radiological Protection (ICRP) (internal exposure). Therefore, the main additional data requirement is occupancy of contaminated areas and intake rates of contaminated water and food products. Inhalation exposures are determined by resuspension factors and breathing rates, for which it is generally appropriate to use generic data because site-specific studies would not provide more definitive parameter values.

Occupancies of different areas and consumption rates for the local population at the present day can be determined from detailed surveys. In the UK, it is the practice to conduct such surveys on a regular basis around all nuclear licensed sites. Thus, such surveys would be required around the site of the GDF. However, rather than waiting for the operational phase, it would be useful to conduct such a survey initially during site characterisation. This would yield more detailed data than would be required for assessment purposes but would provide a database that could be used to justify simplified habits profiles based on a cautious (but not unduly cautious) interpretation of the available data. Alternative simplifications could be used for the operational and post-closure periods, bearing in mind the greater degree of extrapolation required to address the post-closure period and differences in the projected mix and spatial distribution of activity in the two periods.

3.1.5 Non-human Biota

A non-human biota assessment would be required only for planned releases of radioactive gases because radionuclide discharges in liquid effluents should be so low during the operational period and post-closure PoA that a site-specific assessment of the radiological impact of such discharges on the terrestrial and aquatic environments is unlikely to be justified. Therefore, the focus would be on H-3 and C-14 bearing gases. The approach to evaluating concentrations in the tissues and organs of biota would largely be based on specific activity approaches, as discussed in Section 3.1.3 in relation to human food-chain pathways. This would result in relatively uniform distributions of H-3 and C-14 throughout all tissues and organs, with those concentrations determined by the concentrations of hydrogen (as water and organic forms) and carbon present. Because both H-3 and C-14 are pure, low-energy beta emitters, radiation dose rates for a given concentration in tissues are independent of the size of the organism. Thus, once H-3:H-1 and C-14:C-12 ratios in tissues and organs have been determined, dose rates follow directly from the hydrogen and carbon contents of those tissues and organs.

These values are known generically across a wide range of taxa and do not need to be determined in site characterisation.

In the absence of a particular site or region of interest, the ERICA assessment tool[7] provides a useful means of performing a site-generic assessment of potential dose rates for plants and animals using the default reference organisms: a specific activity approach has been used as the basis for evaluating the uptake of both H-3 and C-14 from air to terrestrial reference organisms. However, in the current context, once a specific site is identified or a local region that might host a site, it will be necessary to identify more site-representative species for assessment. These would likely be considered in addition to the default, generic organism types.

Ecological surveys performed for EIA will identify species of specific ecological interest in the environs that may be impacted by activities at the site during construction (including areas affected by any related infrastructure development). A wider focus may, however, be appropriate to identify representative species for assessment to ensure that the types of plant and animal present throughout the area that have the potential to be impacted because of atmospheric discharges are comprehensively identified and characterised (noting that the identification of representative species for the operational phase will also be of interest for the post-closure phase).

In addition to representative species for the region of interest, it will also be necessary to identify any sites falling under ecological protection designations (e.g. Special Protection Areas, Special Areas of Conservation, Ramsar and SSSIs) that could be affected by discharges from the site. An approach to evaluating dose rates to all species of interest within UK Natura 2000 sites (i.e. the UK network of Special Areas of Protection and Special Conservation Areas designated under the European Birds and Habitats Directives) has been developed on behalf of the EA (EA, 2003; Allott et al., 2009). No additional site characterisation activities would therefore be envisaged. However, it should be noted that assessment for conservation sites should take account of all planned discharges with the potential to impact the site of interest.

3.2 Post-closure Safety

In the long-term after the PoA, radionuclide releases in groundwater and in the gaseous phase[8] may be anticipated. These releases are projected to occur on timescales of hundreds of years to many thousands of years after closure of the GDF.

[7] http://www.erica-tool.com/

[8] In principle, pulse releases in the gas phase are possible, but it is here assumed that the GDF would be designed and located to limit the possibility of such pulse releases.

For a GDF located in an onshore location, releases of gases may occur to overlying soils, see e.g. RWM (2016b). These releases to the soil zone are likely to be primarily in the form of C-14 bearing methane, the bulk carrier gas being a mixture of hydrogen and methane. In the soil zone, the methane is likely to be quantitatively oxidised to carbon dioxide, at least in well-aerated agricultural soils. Thereafter, the pathways of interest are as discussed in Section 3.1. Thus, the main additional consideration in the post-closure phase is the pathways by which bulk gases can reach surface soils. To a large degree, this relates to the structure of the geosphere and hence is an issue for the geosphere component of site characterisation. However, if the geosphere is considered to extend only to the upper boundary of intact rock and not to include the overlying unconsolidated sediments, then characterisation of the structure and water-saturation of those sediments is relevant to mapping gas pathways from rockhead to the surface. Because this issue of mapping the structure and water-saturation of these materials is relevant also to groundwater-mediated pathways, it is discussed in that context below. Once C-14 reaches surface soils and/or the atmosphere, the information requirements of associated assessment modelling (see Hoch, 2014) are adequately encompassed by information needs in support of assessment of the groundwater pathway, which is discussed below.

For a GDF located in an offshore location, releases of gasses may occur to the sea-bed. C-14 bearing methane released via this pathway will either dissolve in the sediment pore water or the overlying water column and can be treated like a groundwater discharge[9]. Requirements for assessment of radionuclide releases to estuarine, coastal and marine environments are discussed further in Section 3.2.7.

Radionuclides dissolved in groundwater can be transported to the near-surface environment. They may discharge into a terrestrial environment or into a coastal environment that could include an estuary, beach and foreshore, and nearshore waters. In general, radiological impacts will be larger for discharges to a terrestrial environment than for discharges to estuarine, coastal and near-shore environments, and assessments to-date have focused on such discharges (Walke et al., 2013a,b). Therefore, the focus here is on characterisation of terrestrial environments, but with a supplementary commentary on the characterisation of the other environments. In respect of terrestrial environments, the main considerations relate to the characterisation of surface-water catchments, the uptake of radionuclides by plants from groundwater and well water used for irrigation, uptake of radionuclides by domesticated animals, the characterisation of human habits and the evaluation of potential radiological impacts on non-human biota. These topics are addressed in the following subsections before considering the additional issues that arise in the context of estuarine, coastal, inshore and offshore environments. This highlights the need to adjust a general site

9 This is also pessimistic, because C-14 dissolved in water would be available for uptake by marine biota rather than being lost to the atmosphere.

characterisation programme when site environments are known. After this, some remarks are made on the potential significance of palaeoenvironmental data collected during site characterisation that can be used in developing scenarios for consideration in post-closure safety assessments. Then, in Section 3.3, consideration is given to the degree to which the existing generic operational and post-closure assessment models would be made site specific as site characterisation progresses.

3.2.1 Characterisation of Terrestrial Surface-water Catchments

In the current NWS assessment approach (Walke et al., 2013a), the biosphere model is provided with a flux, Q_i (Bq y^{-1}) of each radionuclide from the geosphere modelling. However, the model assesses radiological impacts for two pathways, the groundwater discharge pathway and the well pathway (where the well draws from shallow groundwater in unconsolidated near-surface sediments). These two pathways require as input the flux per unit area (Bq m^{-2} y^{-1}) and the concentration in well water (Bq m^{-3}), respectively. Thus, the flux supplied from the geosphere must be divided by the area of discharge, A (m^2), for the groundwater-discharge pathway and by the flow rate in the aquifer in which the well is located, F (m^3 y^{-1}), for the well pathway. In recent assessments, emphasis has been given to estimating values of F and A. This has been done through a review of gauged surface-water catchments in lowland Britain, examining their areas and stream discharges in comparison with data on annual precipitation, and focusing on the smaller catchments, because these are associated with smaller areas of discharge and smaller aquifer dilution values.

Although this approach is useful in a generic context, it is likely to be unduly simplistic for application to a specific site (e.g. Towler et al., 2011). Groundwater flow in the near-surface is likely to exhibit a complex 3D pattern that will change with time, due to time-dependent precipitation and wetting and drying of the subsurface, but within constraints determined by the current topography, lithology and stratigraphy of the site, which are likely to change only slowly in the long-term, at least until a future glacial episode occurs resulting in the advance of the margin of the ice-sheet to or beyond the site. Furthermore, radionuclide transport in this changing, 3D flow field will depend on the degree of sorption of each individual radionuclide (or the degree of sorption of several radionuclides when decay chains are considered). To characterise the flow field and the pattern of saturation, it is appropriate to define a model at the spatial-scale of a surface-water catchment or sub-catchment, such that water flows across the boundaries of the model domain are known to be limited and a well-defined water balance exists. This catchment-scale model should be matched to the slowly varying characteristics of the site, i.e. its initial state should be determined through site characterisation and its slowly changing properties projected through geomorphological modelling complemented by observations from appropriate analogue locations.

The above considerations mean that the development of a spatially distributed, surface-water catchment model is an important consideration in biosphere site characterisation, bearing in mind that this will be applicable at the present day and will require adaptation and modification to represent future conditions. Such a model requires the following information:

- climate data, including, but not limited to, time-series of temperature and precipitation, with a sub-daily time-step;
- surface topography of the catchment, expressed as a digital elevation map;
- bedrock topography, expressed as a digital elevation map;
- structural and biogeochemical data on the overburden from the surface down to the bedrock;
- hydrological properties of the various materials comprising the overburden, preferably obtained *in situ*, e.g. in trial pits or boreholes, or from undisturbed samples;
- recharge and discharge across the bedrock-overburden interface;
- stream flow, as time-series, measured at locations within and at the outlet of the catchment (possibly complemented by spot measurements, e.g. using current meters); and
- vegetation characteristics and patterns.

These data can be used in the development and parameterisation of a model, but can also be used in its validation (e.g. by using newly acquired climate data to predict changes in water saturation within the catchment and time-dependent stream flows at gauged locations).

Development of a surface-water catchment model could begin as a desk study as soon as a site had been identified, as much of the information would be available from existing maps (topography, soil types, Quaternary cover, hydrology, biogeochemistry, land use, vegetation). However, there would also be data that could only be acquired after site access was obtained. This would include seismic, electromagnetic and ground-penetrating radar studies of the geometry and characteristics of the overburden, measurements of hydrological properties in the field and on laboratory specimens and gauging and flow monitoring of surface streams. Initial studies might be completed in two or three years, but there would then need to be an on-going programme of collecting time-series data for improved model calibration and validation. It is important that the focus should be on areas where releases from the GDF might reach the near surface under present day and potential future conditions. Such areas may be remote from the location of the surface and underground facilities and may lie outside the area characterised in detail in the EIA.

To make projections of radionuclide transport in such a catchment, the above data need to be complemented by measurements of radionuclide sorption to the various materials comprising the overburden.

If abstraction of the water is from the bedrock rather than the overburden, then it may be appropriate to develop a catchment model that extends from the surface to some depth in the bedrock and includes a representation of changes in groundwater flow due to the effects of abstraction from a deep well or well field located within the model domain. Information relevant to this model would be drawn from both biosphere and geosphere site characterisation, emphasising the importance of integrating both field studies and modelling across the whole programme of site characterisation and assessment modelling. However, the types of data required for catchment modelling are not substantially altered by this extension, though it may be necessary to recognise that explicit account must be taken of lateral inflows and outflows of groundwater into and out of the model domain in the bedrock, because the size of the regional groundwater catchment may be substantially larger than the size of the surface-water catchment.

3.2.2 Uptake of Radionuclides by Plants from Discharging Groundwater

In the current assessment model, radionuclides in discharging groundwater are routed into the subsoil. A 1D, two-layer soil model is adopted with a subsoil compartment, overlain by a topsoil compartment. Water fluxes are specified between the two compartments and lateral flows from upslope as well as drainage downslope are included. These flows include surface runoff, as well as subsurface flows. In general, if a surface-water catchment model were used, flows in the subsoil and topsoil domains, and both vertical and lateral flows would be calculated explicitly. Therefore, use of a soil model of this type does not impose any additional requirements on site characterisation. Rather, as site-specific data are acquired, it is likely that the assessment model would be enhanced, e.g. with more layers or by extension to a 2D, hillslope model. However, it would be appropriate to include soils and subsoils in a programme of sorption measurements because sorption in these media may differ from that in other overburden sediments, and measurements on today's soils may provide a useful indication of the characteristics of future soils derived by aging of current soils or created by pedogenic processes from similar parent materials.

Both sorption and plant uptake depend upon the radionuclide under consideration, the plant type and the soil type. In principle, a wide variety of different plant and soil types could be considered, with many different values of distribution coefficient and plant:soil concentration ratio proposed. However, in practice, even though very extensive databases of values exist, the variability in the observations make it difficult to justify making fine distinctions and distributions of values are typically given for broad categories (e.g. sand, loam, clay and organic soils). In site characterisation, site-specific values of distribution coefficient and plant:soil concentration ratio may be measured, but these also will be subject to substantial variability and care has to be taken not to give undue weight to a few local measurements compared with the overall, generic database. In the context of assessments of currently operating sites, measurements of site-specific distribution coefficients and transfer factors are only exceptionally required, and there is substantial dependence on the use of generic data. Thus, during site characterisation, there is likely to be a slow and incomplete shift from relying on generic data to relying partly, but never wholly, on site-specific data (see Sheppard, 2005, for example).

In this context, site-specific data may arise largely from measurements of stable-element concentrations in various media, partly because simultaneous multi-element analyses can be undertaken (see Sheppard, 2011, for example). Care must be used in interpreting such measurements because the physico-chemical form of the element may differ substantially from that of the same element entering the system in groundwater.

3.2.3 Uptake of Radionuclides by Plants from Well Water

Radionuclides entering topsoil in groundwater will be relatively uniformly distributed vertically and will be available to plants by root uptake (though some activity may also be present bound to external plant surfaces either in soil particles or sorbed from soil solution). In contrast, radionuclides in abstracted well or stream water will enter the soil-plant system in irrigation water (and radionuclides may also be transferred from surface waters and their sediments in flooding events, if a site is selected that would be prone to flooding now or in the future). Thus, some activity will enter the soil directly and be available for root uptake, whereas some will be intercepted by, and retained on, plant surfaces. Some of this activity may subsequently be removed, e.g. by wash-off or leaf fall, and enter the soil, whereas some may be taken up into plant tissues. These processes have been extensively studied in the context of routine atmospheric releases (though some of the data are for dry deposition rather than wet deposition) and a substantial international database of information is available. This database can be used for generic modelling. In contrast to the groundwater pathway, where reliance can be placed, albeit with care, on site-specific stable-element data, gathering additional data for the irrigation pathway would require specific experimental studies. Furthermore, the key parameter governing this pathway (e.g. interception, weathering and translocation) are primarily dependent of the form of radionuclide input and plant-type specific characteristics, rather than site-specific characteristics. Therefore, it seems unlikely that site characterisation activities would substantially enhance radiological impact assessments in this respect.

3.2.4 Uptake in Domesticated Animals

Radionuclides entering the soil zone are assumed to enter surface streams (where they may be accumulated by freshwater plants and animals, as discussed in the context of aquatic systems; see Section 3.2.7). Therefore, domesticated animals may have intakes of radionuclides in both stream water and well water. In addition, they may have intakes in contaminated plants (pasture and forage crops). Radionuclide concentrations in tissues and organs are estimated from daily intake rates using animal transfer factors (units d kg[fresh weight]$^{-1}$). There is an extensive literature estimating such transfer factors, based partly on field measurements but also on laboratory experiments on a wide variety of species, often interpreted by kinetic analyses and allometric scaling rules. Both stable element and radionuclide data are used, and the same cautions apply as with plants concerning the relevance of the physico-chemical form to which the animal is exposed.

In the context of site characterisation, it may be useful to obtain stable element concentrations for animals local to the site to compare with corresponding concentrations in local soils and animal feedstocks (bearing in mind that animals are likely to be fed a mixture of pasture-derived material, fodder crops and imported feed) and that radionuclide uptake and retention in animals will depend mainly on the type of animal rather than site-specific characteristics. Engagement with local food producers may be appropriate in this context and could be useful in confidence building with the local community.

3.2.5 The Characterisation of Human Habits

As discussed in Section 3.1.2, occupancies of different areas and consumption rates for the local population at the present day can be determined from detailed surveys. Such surveys yield more detailed data than would be required for assessment purposes but provide a database that may be used to help justify simplified habits profiles based on a cautious (but not unduly cautious) interpretation of the available data. Alternative simplifications may be used for the operational and post-closure periods, bearing in mind the greater degree of extrapolation required to address the post-closure period and differences in the projected mix and spatial distribution of activity in the two periods.

3.2.6 Evaluation of Impacts on Non-human Biota

For the post-closure period, radionuclide concentrations in non-human biota relative to environmental media (mainly soils and surface waters) would currently be estimated using biota to environmental medium (e.g. soil, sediment, water) concentration ratios. Because of the diversity of species and taxa for which such factors are required, and the range of radionuclides of interest in post-closure assessments, the available database is rather sparse. Furthermore, in a site-specific context, there may be populations or species of interest for which the available data are judged either irrelevant or only marginally relevant. Therefore, it is likely that a programme will need to be put in place to identify key or representative populations and species (expanding beyond that undertaken for the operational phase to encompass a wider geographical area that may be affected by releases from the geosphere) and to derive the necessary parameters to allow their representation in a site-specific context.

The programme is likely to involve the measurement of stable element concentrations in the tissues of representative species and in the environmental media they inhabit to enable site-relevant concentration ratios to be derived. It should be noted that there may be restrictions with respect to the sampling of some representative species of interest (e.g. due to protection status) such that analogue species may be required. The programme should be targeted to address key data gaps and uncertainties and be designed to account for the spatial ranges of populations (to ensure derived parameters are representative of the assessment populations), and for potential seasonal variability in the behaviour of the species, where such behaviour could affect uptake and retention of elements. Key data gaps and uncertainties can be identified from the existing body of safety assessment documentation and the latest international experience and scientific output, as discussed in Section 1.3. Analyses of the mass and dimensions (length, breadth, height corresponding to an ellipsoid proportionate to that of the species of interest) of individuals of representative species may also be warranted (e.g. where sufficiently different to available reference organisms), along with the range of individuals for mobile species to inform the spatial area of interest for protection of populations. This information could then be used to tailor assessment calculations to those types of organisms. It should be noted that the approach needed to assess the potential impact of non-radiological pollutants on non-human biota differs from that for radioactive species. NWS is currently undertaking work to review the assessment of non-radiological (chemical) pollutants as well as review UK and EU legislation surrounding their fate in the environment and their impact on wildlife and fauna.

3.2.7 Estuarine, Coastal, Inshore and Offshore Environments

NWS's approach to assessing radionuclide releases in groundwater to estuarine, coastal and marine environments in the post-closure phase is described in Walke et al. (2013b).

For estuarine, coastal and near-shore environments, the primary consideration is the initial dilution of the groundwater discharge into the biosphere domain. Thus, catchment modelling is replaced by a consideration of estuarine and coastal geometry, tidal and residual current flows, sediment deposition/erosion and transport, variations in redox conditions and sorption to estuarine and coastal sediments. In addition, diurnal and seasonal changes in salinity and stratification of the water column should be considered. In the case of estuaries and coastal landforms, there is a specific issue that, in soft coastlines, they evolve rapidly (on timescales of a few hundred years). Therefore, there are limited benefits in studying current estuarine form and processes in detail, because a robust post-closure safety assessment would need to consider the range of landforms that could develop in the post-closure period considering climate change and, more importantly, a range of sea-levels from up to 20 m above present in greenhouse-warmed conditions to more than 100 m below present in glacial conditions.

Setting aside these broad considerations, measurements of stable element concentrations in organisms and the media to which they are exposed would have similar benefits and be attended with similar caveats to those arising in terrestrial environments. This is particularly the case for estuarine biota dose assessments for which concentration ratios between organisms and environmental media are particularly scarce.

In terms of human habits and behaviour, current habits surveys around nuclear licenced sites address occupancies of estuarine and coastal areas, and consumption of marine foods. This would apply also to surveys conducted in relation to a GDF. The handling of the data from such a survey could be as proposed for the terrestrial environment, e.g. simplification of food categories and use together with complementary generic datasets to define a robust basis for assessments.

In respect of the thicknesses of sediment layers, the continuity of the layers, and the properties of those layers, the coastal regime poses specific difficulties for survey, e.g. whereas seismic surveys are reasonably straightforward to conduct either onshore or in the offshore domain, they are much more difficult to conduct (because of difficulties in transmitting suitable mechanical shocks to the ground and detecting reflections) and interpret (because of discontinuities in structures across the highly dynamic coastal domain, where both erosion and sedimentation can be rapid).

3.2.8 The Role of Palaeoenvironmental Data

The primary aim of site characterisation is to describe the site as it is before and during construction, operation and closure at an adequate level of detail. However, for post-closure safety assessment there is often a demand to make projections of its future characteristics. To do this, knowledge is required concerning processes and rates of environmental change. Therefore, palaeoenvironmental observations are relevant. For example, at sites potentially subject to future permafrost conditions, examination of soil and sediment structures associated with ground freezing may provide useful insights into the depth of past permafrost and whether it substantially altered the deep hydrogeology of the site. Similarly, at sites where glaciation has occurred, patterns of sediment deposition due to the ice sheet and subsequent active hydrological regime may provide useful insights into how superficial sediments may be reworked in similar future episodes. However, the identification of useful palaeoenvironmental studies is highly site-specific and goes beyond the scope of this report in describing studies of direct applicability in assessing radiological impacts in the operational and post-closure phases. Nevertheless, it is relevant to note that palaeoenvironmental data gathered from a site is likely to be fragmentary (e.g. originating from sediment cores spanning a limited time interval) and representative only of some of the types of environment that may arise at the site in the future. Thus, palaeoenvironmental data from the site will need to be interpreted by reference to, and in combination with, data gathered at a larger spatial scale, e.g. long records from sediment cores providing pollen, coleoptera and plant macrofossil data, or evidence of former coastal or lake shorelines. In turn, these regional data will typically need to be interpreted within a global framework of past global change as derived, for example, from the interpretation of data from ice cores and deep-sea sediment cores. In addition, it may be useful to identify and characterise sites considered to be analogues of potential future conditions at the site of interest. Analogue sites may be particularly informative in understanding the implications of interactions between changes in different aspects of the site, including the style and intensity of the various processes governing site evolution.

3.3 Safety Assessment Modelling

The biosphere models currently used by NWS to assess radiological impacts of radionuclide releases from a GDF, both in the operational and post-closure phases, are generic in nature. As site characterisation progresses, it will be appropriate to tailor those models to make them site specific. Also, NWS is currently developing models to assess the impact of the non-radiological pollutants of potential importance for a GDF in the context of the protection of groundwater in the post closure phase, but these models do not include a representation of the biosphere (Nucleus 2019b, 2020).

This requires consideration of appropriate conceptual model structure, in terms of the components of the biosphere that are to be represented, the processes operating within and between those components, and the ways in which the identified biosphere components should be represented (e.g. as one or more well-mixed compartments or as spatially distributed continua). This process of conceptual model development implies a degree of abstraction from the results of detailed process-related studies and modelling because the dose assessment model does not need to represent all aspects of the site in detail but needs to focus on those components and processes that are of prime importance in determining radiological impacts on human health and the environment.

The creation of a site-specific conceptual model of the biosphere provides a basis for developing a corresponding mathematical model or models. In practice, this is likely to mean adapting the current NWS generic model to take account of insights obtained from site characterisation. Such adaptations may involve changes to the structure of the model, but often they may simply require that the information from site characterisation is used to support the choice of input parameter values or distributions of input parameter values. In turn, application of these site-specific models and data sets in assessment studies is likely to yield new insights into those aspects of site characteristics that are of significance in radiological assessment but are either only poorly understood conceptually or have been inadequately quantified. Thus, there will be a continuing interchange with site characterisation informing safety assessment modelling that will, in turn, help to steer and focus subsequent site characterisation activities comprising both field and laboratory studies and process-based modelling.

It is emphasised that site characterisation, although essential to informing assessment modelling, is not the only input. Site characterisation necessarily focuses on the site as it is at the present day, with palaeoenvironmental data providing some insights into the history of its development. However, assessment modelling has an emphasis on the future characteristics of the site, both during the operational phase and, more particularly, in the much longer-term post-closure phase. Thus, the characteristics of the assessment model are determined by site characterisation data plus other sources of information, e.g. long-term modelling of projected changes in climate and sea level plus simulation of geomorphological responses to these changes, including information obtained from analogue sites. Consideration of these other factors may, in turn, influence site characterisation activities, e.g. if coastal erosion is found to be a significant consideration in radiological impact assessment, site characterisation may give an increased emphasis to determining the erosion resistance of the cliff line, to measuring rates of cliff retreat at the present day, and to the identification of palaeo-shorelines associated with past sea-level highstands.

4 Other Considerations

As stated in the introduction, the biosphere site characterisation should be seen as a task strongly integrated with the general site characterisation programme and with a general goal to achieve a common system understanding. Radiological safety and environmental impact assessments described in sections above constitute the main end users. However, to fully optimise a biosphere site characterisation programme, other aspects within a GDF-programme should be part of, and included in, the planning and execution. In the sections below we discuss the importance of the linkage between site investigations and site modelling, monitoring, design and construction. Another consideration discussed is the need for integration between programme parts as well as suggested implementer competence requirements by using insights from other national programmes.

4.1 Site Descriptive Modelling

Site descriptive modelling has proven to be a large and important part of on-going national programmes. As the GDF-programme progresses, more and more site-specific information will become available. This information will provide an input to major decisions relating to disposal concept and design, site investigation impact assessments, site selection, site adaptation, assessment methodology development and handling of EIA-issues (known and not yet known). Therefore, development of a biosphere site characterisation roadmap should consider the site descriptive modelling tasks that are needed for delivering a common SDM. An SDM includes both the biosphere and geosphere; both components will be developed together during the iterative cycles of investigations, modelling and assessment.

4.1.1 From Data to Site Descriptive Models

A GDF programme that considers specific sites by necessity needs to include site-specific assessments of future radiological and non-radiological consequences to humans and non-human biota. This implies that site data and site-specific conditions must be documented, understood, and expressed in terms of models such that they can be used in the assessments to be performed. Thus, site understanding is central to the development of site descriptions, and for the identification of plausible projections concerning long-term conditions at the investigated site. Site understanding builds on four main components: site data, development of site-specific conceptual and numerical models, reporting of site descriptive models, and the increase in general scientific knowledge and personal expertise that each iterative programme cycle provides.

The overall assessment methodology employed by NWS should include this stepwise enhanced site understanding based on information from site investigations. Site data are the basis for building discipline-specific conceptual and numerical models describing present properties and processes of the natural system at the site. The discipline-specific models should be integrated into a common SDM that preferably uses multiple lines of evidence from different scientific disciplines to achieve an overall “site understanding” in both general conceptualisations and for specific properties, features and processes. The SDM should also be the basis for developing descriptions of possible future conditions at the site(s) of interest.

Site understanding requires site data, i.e. data obtained from measurements or other observations at the considered site. With respect to temporal variations, site data can be subdivided into two types, i.e. parameters that are expected to be constant and hence (in principle) can be measured on a single occasion, and parameters or states that vary significantly during the observation period and hence cannot be sufficiently well characterised by a single measurement. In the latter case, time series data are required and obtained from monitoring. Data obtained from monitoring constitute an important basis for site understanding and, therefore, validation in relation to performance criteria. Experience shows the importance to construct and have the ability to adapt the IT infrastructure (e.g. databases) to both biosphere site characterisation and end user needs and to include members of the site investigation and modelling teams in the planning of data management, see Appendix A.2.

In any assessment of consequences where changes are to be related to an “undisturbed” present state, this present state must be established. This reference state is commonly referred to as the “baseline description”. Note that the word “baseline” can be used in two ways: i) as the undisturbed conditions prior to GDF construction (as in Section 2, relating to EIA), and ii) as the initial state of the system after closure (as built). The latter is often used in safety assessments and should not be confused with baseline for the undisturbed state.

The SDM is multi-disciplinary, in that it covers all potential properties of the site that are of importance for its overall understanding, for the design of the GDF, for safety assessment and for the environmental impact programme.

It should be noted that the SDM itself can be seen as a stand-alone supporting document to the safety case, with a best available understanding on site conditions relevant to a radiological waste management programme.

The SDM task should preferably be divided into scientific disciplines or sub-disciplines. In Figure 7, an example is shown from the Swedish programme that illustrates how the SDM (upper section of Figure 7) can be divided into scientific disciplines that together form the overall and integrated site description. The biosphere (in Figure 7 "ecosystems" and lower section of the figure) is shown as part of the site description and is linked to the hydrology/hydrogeology. For each discipline, a method description is produced that describes the data required, modelling steps involved, and resulting products to deliver. These method descriptions are then reviewed internally to make sure that links and integrations between each discipline are taken into account and that the final products deliver end user needs. In Section 4.1.2 below, an illustrative example of a method description for hydrology is summarised. Note that the discipline-specific method descriptions should follow the timeline of a general roadmap as described in Section 5, but also specify tasks and linkages in more detail than is feasible in the common and more generalised version (see Figure 13 in Section 5).

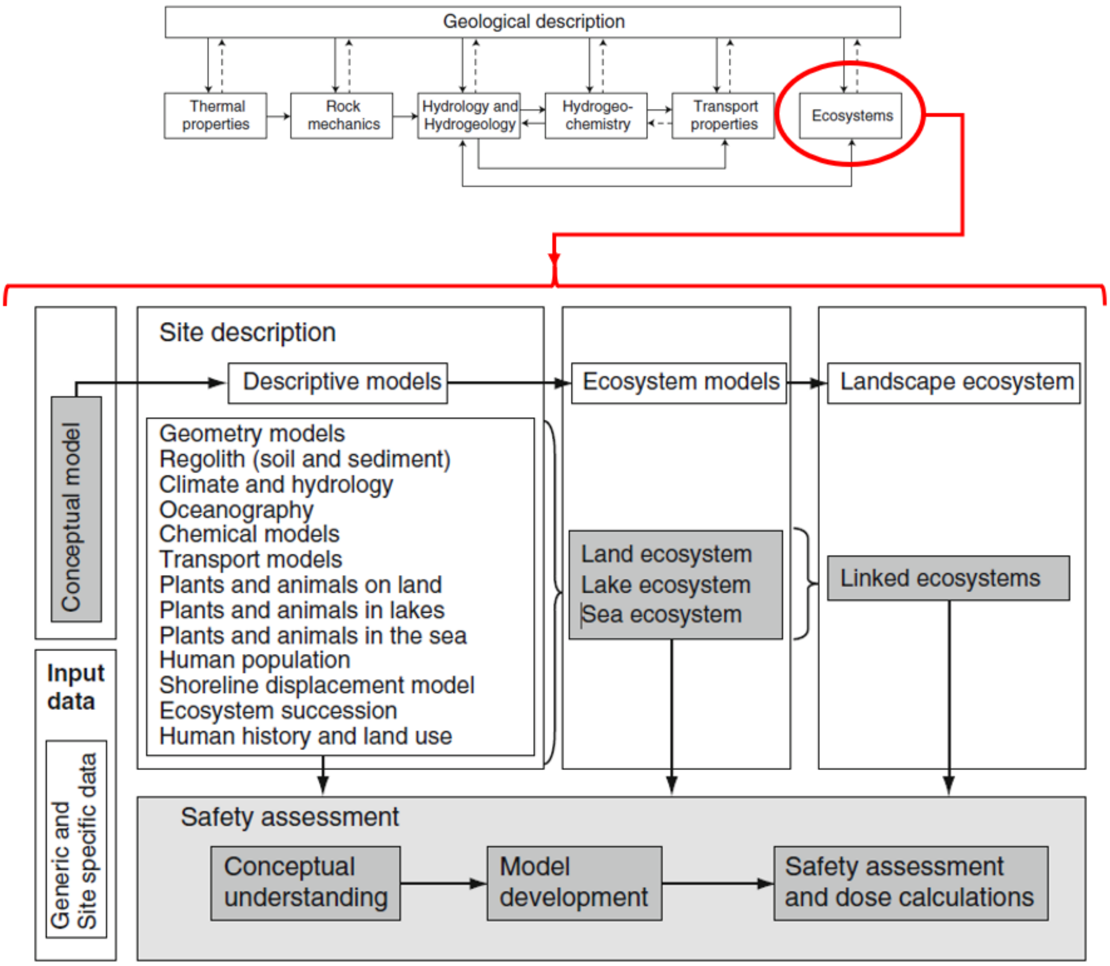

Figure 7: Example from SKB biosphere site descriptive modelling planning. The biosphere roadmap (here for ecosystems) is part of the planning, as well as the natural way to structure an SDM. A stepwise enhancement going from conceptual models to a description of ecosystems with underlying supporting models for relevant scientific disciplines is shown. Modified after Andersson et al. (2013). See also Appendix A.2.1.

4.1.2 Example of Hydrological Site Characterisation

In Figure 8, an illustrative example of how to work with hydrological data evaluation, interpretation and modelling as an iterative process from site generic and regional mapping to site-specific models within the overall site characterisation is given, drawing on experience gained with SKB's programme. The example is focused on the hydrology and the shallow groundwater system and highlights the need for integration with other disciplines and for an iterative approach. The idea is to increase the level of complexity and the amount of site-specific data in each step from initial site investigations to detailed site investigations.

Hydrosphere Task Team

With the aim of identifying critical questions, data needs and requirements and to achieve continuity throughout the site characterisation process, a hydrosphere task team is recommended to be formed in the initial site investigation phase. The early forming of the group and maintenance of its continuity throughout the site characterisation process is illustrated in Figure 8 (part A). The team is a group of hydrological and hydrogeological internal and external experts including representatives from different end users such as safety assessment, environmental assessment and facility design. Forming such a task team increases the likely degree of integration both within the hydrological and hydrogeological disciplines and in relation to other disciplines. A central task for the team is also to support and review the development of the methodology and strategy for hydrological-hydrogeological site descriptive modelling from initial site investigation to detailed site investigation phase.

The aim of the team is to assure a proper integration between the bedrock and surface water systems and that the data and model requirements from each end user are covered. This group should be responsible for the establishment and development of the integrated hydrological and hydrogeological conceptual model. From this conceptual understanding several quantitative models at different temporal and spatial scales are established, each one taking different processes into account that are relevant to the questions at hand.

The hydrosphere task team should, in turn, be integrated with other task teams focusing on other disciplines from where supporting models are used to describe and understand the hydrology and hydrogeology, e.g. the geosphere task team and the biosphere task team.

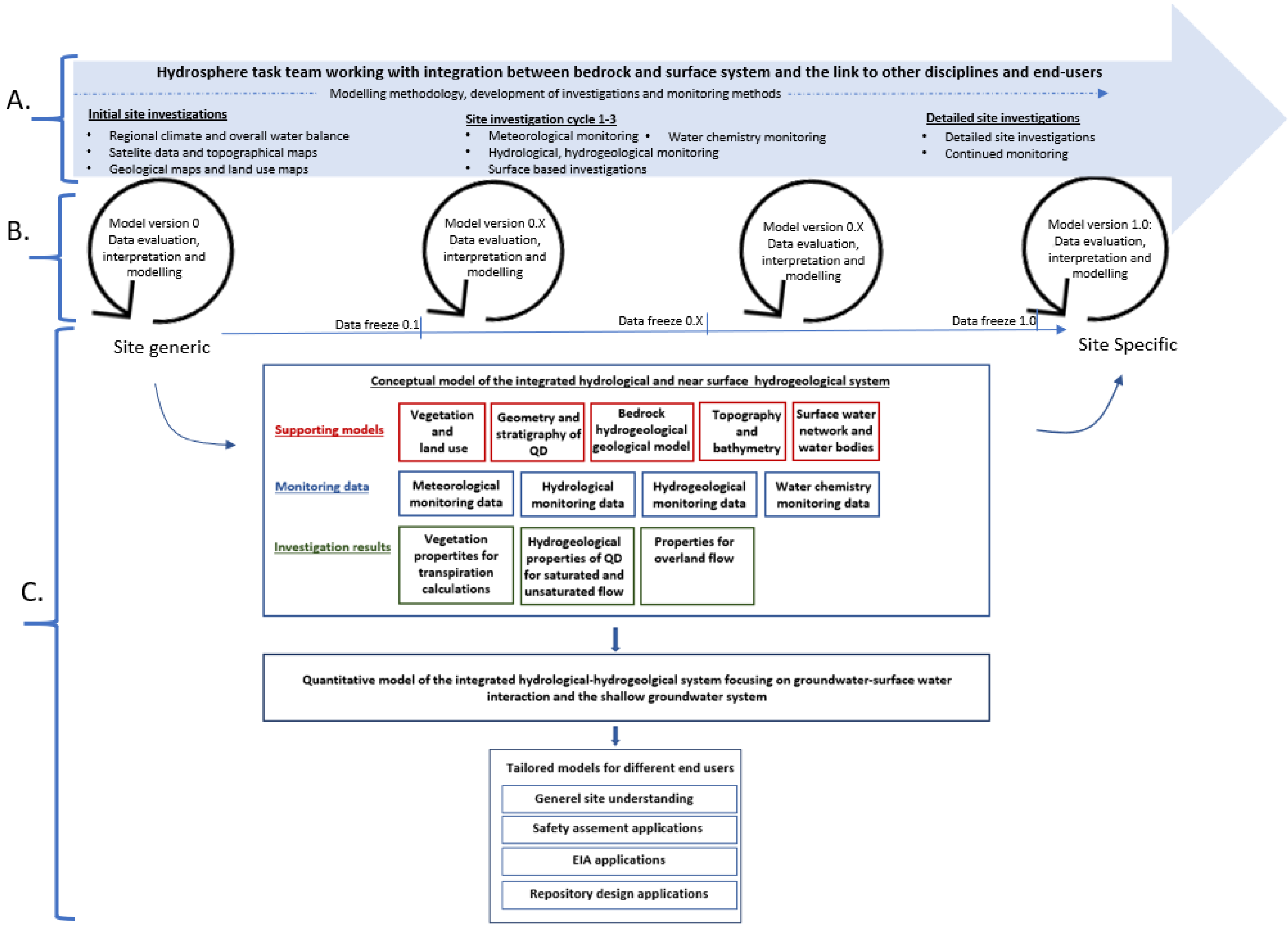

Figure 8: Illustrative example of a timeline for hydrological-hydrogeological site characterisation from initial to detailed site investigations.

Data Evaluation, Interpretation and Modelling: An Iterative Process from Site Generic and Regional Mapping to Site-specific Models

Despite the need for generic data and supporting models during the initial site investigation phase, the same structure (Figure 8 part C) should be used for the conceptual and quantitative hydrological-hydrogeological models throughout the different site investigation cycles (Figure 8 part B), i.e. work through the same steps in each loop. The development of strategies and methodologies for modelling as well as investigation and monitoring methods should be initialised during the initial site investigation phase, and the methods further developed based on findings in each site investigation loop. Knowledge gaps are identified in each modelling cycle and data needs and requirements are updated throughout the process such that uncertainties are reduces in each iterative loop by reliance on increasing amounts of site-specific data. Following this iterative approach, the conceptual and numerical models can be used to identify uncertainties and gaps in the data, and model outputs in each loop can instigate new investigations.

Conceptual Model of the Integrated Hydrological and Near-surface Hydrogeological System

In Figure 8 part C, an example of the different parts of the conceptual model is illustrated. The conceptual model is built on supporting models and data from other disciplines, monitoring data and data from site investigations. Examples of data and information to be used in different stages of the site investigations are given in Figure 9. During the initial phase, the regional hydrological-hydrogeological setting is described. Based on regional mapping, satellite data and data from national and regional monitoring programs, the overall water balance, the regional pattern of recharge and discharge areas, and the main water bodies in the area can all be described. Throughout the investigation phase the amount of site-specific information will increase such that a conceptual model based on local data and a thorough understanding of integrated hydrological-hydrogeological processes can be established.

Examples of supporting models are those for vegetation and land use, geological models of bedrock and overburden and models of the surface-water networks. Figure 10 gives examples of the types of information that can be used in the different phases of the site investigation to establish the different supporting models.

Meteorological, hydrological and hydrogeological monitoring data are central to the conceptual understanding of the integrated hydrological and hydrogeological system. Figure 11 gives examples of the types of data that can be collected, compiled and interpreted in each phase.

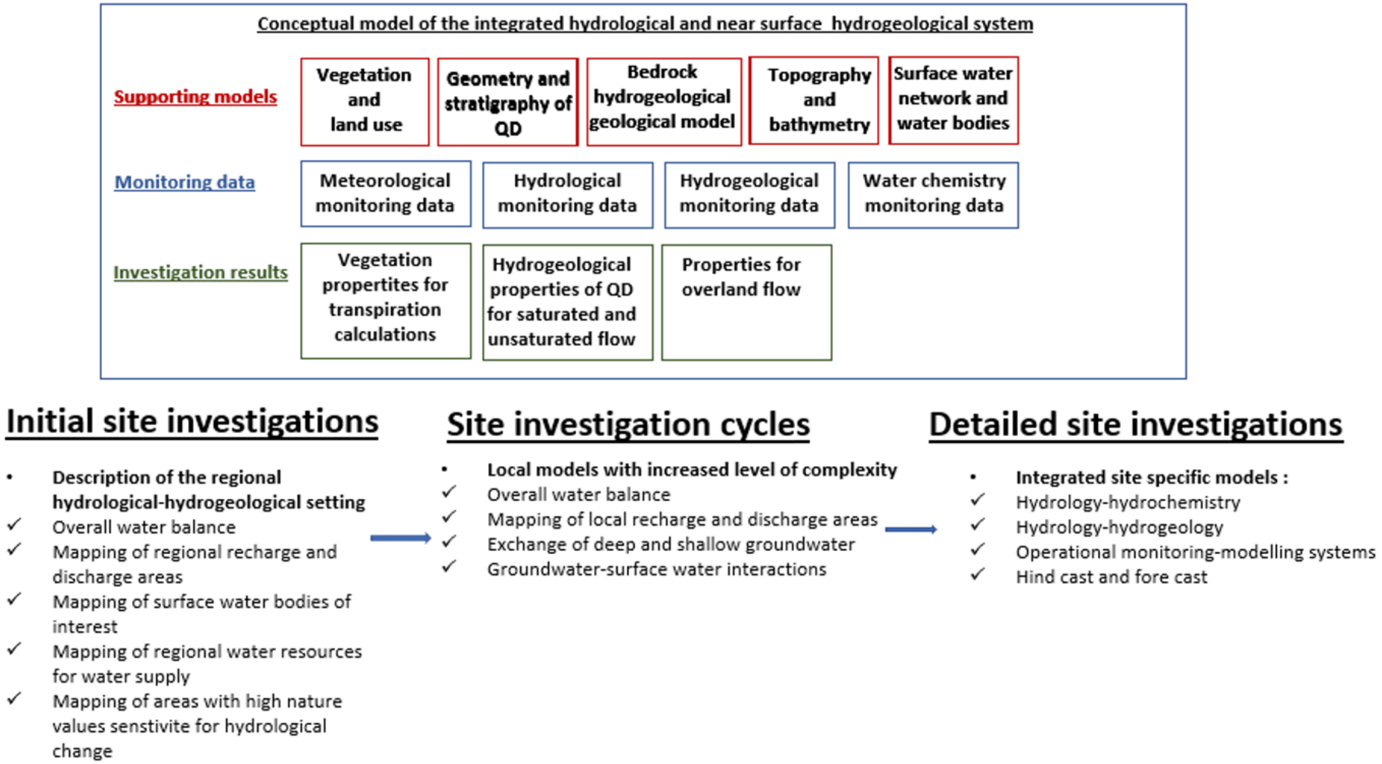

Figure 9: The platform for conceptual modelling and example of how the model is developed throughout the site investigation process.

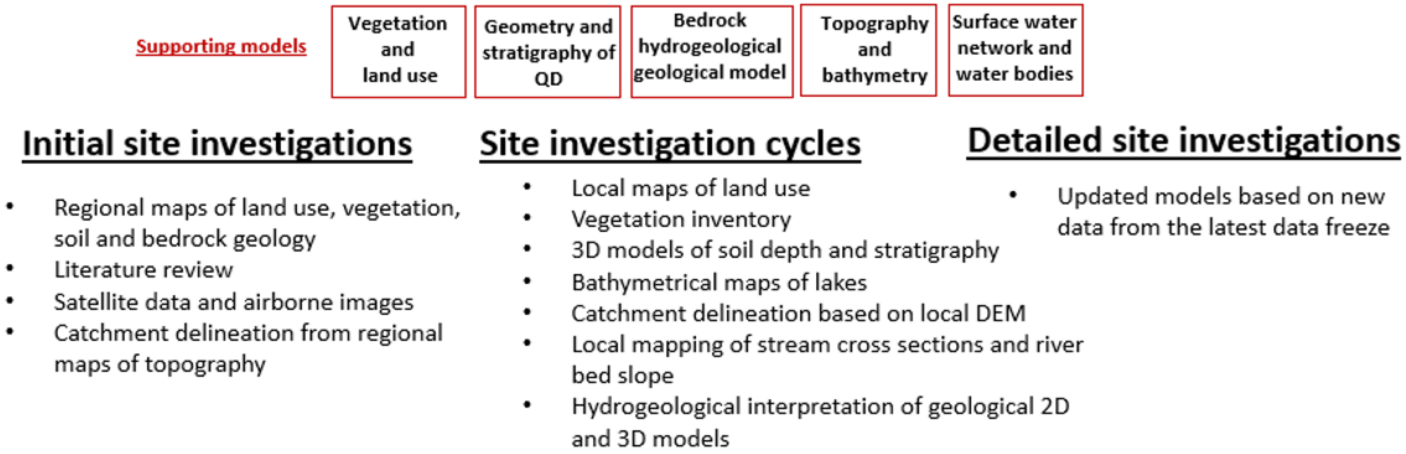

Figure 10: Example of information and data to be used for supportive models.

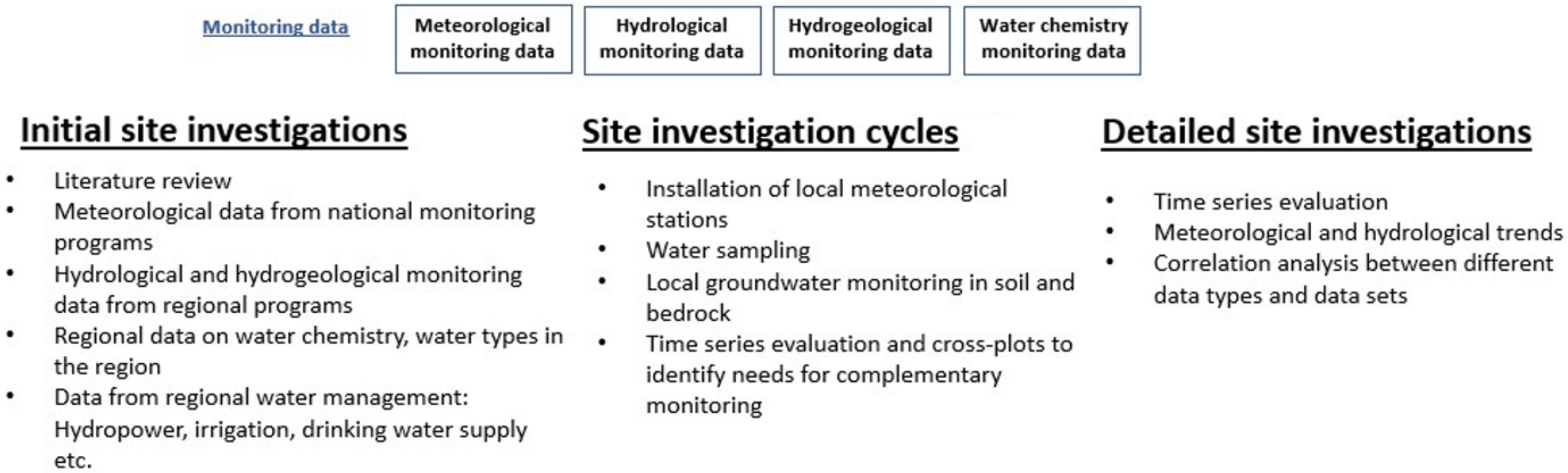

Figure 11: Example of monitoring data to be collected in the different phases of the site investigations.

Important Lessons Learnt from the SKB Site Investigation Programme

Below is a list of lessons learnt from the SKB programme related to hydrology and near-surface hydrology that should be taken into consideration during planning and implementation of the biosphere site characterisation. Lessons learnt with impact on the construction of a roadmap for the biosphere characterisation have been taken into consideration in this report (e.g. hydrology – hydrogeology interactions, monitoring, integration of end user needs and early involvement in planning).

- ▲ If a coastal site is investigated, decide how to describe oceanographic data and models and how to handle the link between groundwater, surface water and seawater including submarine groundwater discharge. It should also be clear which discipline is responsible for the sea-bed mapping (bathymetry and marine sediment).
- ▲ In the overall time planning, make sure there is enough time for iterations between (i) the hydrology and shallow groundwater models, and (ii) the deep groundwater models.
- ▲ In the overall time plan, make sure there is enough time for integration between the hydrogeochemical characterisation and the hydrological-hydrogeological characterisation
- ▲ Involve EIA and GDF design early in the process. Link EIA baseline data to the data needs for hydrological/hydrogeological characterisation and modelling in a cost effective and strategic way.
- ▲ Bedrock characterisation starts at bedrock surface, and not where the borehole casing ends. The upper bedrock and the interface between the bedrock and overlying strata is of importance to be characterised.
- ▲ Local variations in climate motivate the installation of local automatic weather stations. If snow is frequent, a station taking solid precipitation into account is extremely valuable.
- ▲ Monitoring of each component of the hydrological system (surface water, unsaturated zone, groundwater in soil and bedrock, and evapotranspiration) is important to quantify the water balance for the site and to be able to make predictions on how this might change during construction and operation of the GDF.
- ▲ Photo documentation with time-lapse cameras is very cost effective. By linking time series data to photographs the origin of data outliers can often be explained.
- ▲ Groundwater monitoring should be carried out in both recharge and discharge areas.

- Well clusters with wells at different depths should be installed for monitoring of hydraulic gradients.

4.2 Site Monitoring

Time series data have proven to be extremely useful in capturing and enhancing understanding of both natural site-specific properties and processes, and man-made disturbances or releases, see e.g. Berglund and Lindborg (2017) for a thorough description of a monitoring programme for a suggested geological disposal site in Sweden. As part of the system to be assessed, both the biosphere and geosphere need to be monitored during site characterisation, construction and operational phases of a GDF programme. A well-planned monitoring programme should be integrated into the site investigation planning and produces data that, combined with sampling and measurement campaigns, provides necessary information to the site description as well as to day-to-day environmental control. Typically for a biosphere site characterisation programme, characteristics of hydrology and weather, biogeochemistry (including element mass balances), biota and radionuclides (normally occurring and released during operation) merit monitoring. Given the long timeframes involved in geological disposal programmes going from siting to closure, it may be relevant to capture natural succession (vegetation, lake ingrowth, shoreline displacement and soil erosion/denudation) and land use.

An important aspect of monitoring is to help establish baseline conditions. If the site has been used previously, prior disturbances or pollution should be identified and accounted for. Baseline conditions can also take years to establish. A one-year dataset is not enough to capture normal conditions and it often takes several years of data before a “normal year” can be described and justified. In the sub-sections below, an overview of monitoring considerations related to radiological safety is given as a support to the biosphere characterisation roadmap. See Sections 2.5 – 2.6 for topics related to monitoring and timeseries needed in the context of EIA.

4.2.1 Safety During Operation and the Period of Authorisation

As discussed in Section 3.1.1, atmospheric dispersion is a key consideration in performing radiological impact assessments applicable to the operating phase of a GDF. At the initial stages of site selection, when generic assessments are appropriate, it is adequate to rely on regional data on quantities such as atmospheric stability categories, and windspeeds and directions. However, when a site or a limited region encompassing one or more sites has been identified, reliance can be placed on local, existing weather stations with sufficiently long records. Furthermore, when a site has been selected and is the subject of site investigations, these local stations can be supplemented by an on-site weather station. Such a local station should be maintained throughout the period of site investigation, construction, operations and closure. This will provide comprehensive data with high temporal resolution, and over this period there will be increasing reliance on the site-specific data as the duration of the record increases.

Although local and on-site weather stations deliver all the information required for atmospheric dispersion modelling, they also deliver other time series of monitoring data that are relevant in various assessment contexts. Thus, temperature, precipitation and relative humidity data are provided. In turn, these permit quantities such a potential evapotranspiration to be computed. These various measured and computed quantities are directly relevant to estimating the water balance in the surface-water catchment at the site.

Whereas it is appropriate to gather time-series data on meteorological conditions, many of the other characteristics of the site relevant to the operational safety assessment can be determined in snapshot surveys. However, it should be appreciated that the characteristics of the site and its surrounding area will change with time during site investigations, construction, operation and closure, not least because of the process of development of the GDF and its associated surface facilities, including its socio-economic influence on local communities. Therefore, there will most likely, be required to undertake repeated surveys of various aspects of the site, e.g. of land use and of human habits. By comparing the results from sequential surveys, it should be possible to determine the robustness of the various characteristics and to distinguish persistent trends, e.g. in human habits, from variability between surveys. Specifically, from repeated habits surveys it should be possible to develop robust estimates of occupancies and consumption rates that can be carried through into both operational and post-closure radiological impact assessments. Similarly, it should be possible to investigate whether populations of key non-human species are stable, increasing or decreasing.

During the period of operations, there is the potential for routine discharges of radionuclides and non-radioactive pollutants from the GDF. Radionuclides would be likely to be dominated by H-3, C-14, radon and radioactive noble gases, e.g. Kr-85. Routine monitoring of concentrations of all these radionuclides in air, and of H-3 and C-14 in various environmental media, would be directly relevant to the operational radiological assessment and could be relevant in parameterising radiological impact models applicable to the post-closure period. In order that maximum use can be made of these data in modelling, the magnitude and time-dependence of releases from the facilities should also be monitored, e.g. through measurements of concentrations and fluxes in stack discharges, if such discharges are the dominant contributor to releases. Concentrations of naturally occurring radionuclides should be measured before and during the operational phase, to demonstrate that these concentrations are not being altered significantly by the construction and operation of the GDF, bearing in mind that the rock extracted during construction may have naturally occurring radionuclide concentrations that differ from those in the overburden.

4.2.2 Post-closure Safety

For the assessment of the post-closure period, a key consideration within the biosphere site characterisation is the flow regime in the surface-water catchment into which radionuclide discharges are projected to occur in the future (assuming that discharge is to the terrestrial environment). Although that flow regime will differ from that at the present day, due, for example, to changes in climate, present-day time-series data are useful in demonstrating that the model of the surface-water catchment adopted gives hydrological responses consistent with observations. Therefore, time-series of quantities such as stream flow, groundwater level in boreholes, and soil moisture distribution are useful both for model calibration and validation. These data would need to be complemented by snapshot surveys of other relevant quantities, e.g. vegetation cover.

In addition, in the long-term the context in which radionuclides would discharge into the environment would depend on how the landscape evolves. In turn, this depends on the rates and styles of geomorphological processes and current rates of these processes could be investigated by monitoring. Specifically, erosion and sedimentation rates can be estimated by measuring rates of change in landscape topography (e.g. using LIDAR) and sediment loads in stream channels. Such studies require multi-year programmes of measurement, and it should also be recognised that the rates observed may be profoundly affected by the processes of site investigation and GDF development.

Geomorphological process studies may be particularly useful in estuarine and coastal contexts where rates of change could be high. However, in such contexts, they may mainly serve to emphasise that current landforms are not a good guide to future landforms and that safety arguments may need to be based on generic modelling that is robust against the changes in the landscape that are projected to occur over very long timescales.

4.3 Off-site Emergency Planning Zone

An important consideration in evaluating the potential socio-economic impacts of the construction, operation and closure of the GDF is that it will handle and store radioactive and fissile materials and will be classified as a nuclear licensed site prior to the start of construction. Such sites come within the remit of the Radiation (Emergency Preparedness and Public Information) Regulations (REPPIR). From 2001 until 2019, the development and implementation of off-site emergency plans applicable if an incident with significant off-site radiological consequences could be reasonably foreseen was governed by (REPPIR, 2001). However, in 2019, these regulations were replaced by (REPPIR, 2019). These regulations require that, for sites that could give rise to accidents with off-site effective doses of more than a few mSv, an off-site emergency plan needs to be prepared and a DEPZ needs to be defined. The DEPZ has implications for the areal extent relevant to characterisation, especially with regards to socio-economic activities and planning.

Whereas under REPPIR (2001) the extent of the DEPZ was determined by the Office for Nuclear Regulation (ONR), under REPPIR (2019) it is determined by the lead LA, which is the LA with responsibility for the area in which the installation is located. Under REPPIR (2001), the DEPZ could be determined based on a 'reasonably foreseeable accident' and a dose contour of 5 mSv. However, under REPPIR (2019) the concept of a 'reasonably foreseeable accident' is no longer allowed. Instead, there are several different requirements that must be considered when setting the extent of the DEPZ:

- age and other characteristics that would render specific members of the public especially vulnerable (e.g. in respect of requirements for care while sheltering or in respect of sensitivities and special requirements during evacuation or relocation);
- inclusion of all relevant pathways;
- use of a representative range of source terms; and
- address a range of weather conditions to account for situations that are less likely but would have greater consequences.

In addition, the limiting dose contour is now 7.5 mSv rather than 5 mSv.

To define the location of the 7.5 mSv contour, the site licensee must produce a consequences report. This report must provide details of the environmental pathways of exposure that require consideration and the atmospheric stability conditions adopted in calculating the dispersal of radioactive materials beyond the site boundary.

Typically, the consequences report will define the 7.5 mSv contour as a circle centred on the installation. This defines the minimum extent of the DEPZ. However, the lead LA may then define the DEPZ as a larger area to avoid, for example, drawing the boundary through a community, or to use stable and readily identifiable aspects of the landscape. Within the DEPZ, the off-site emergency plan includes detailed provisions for warning and informing residents and visitors, evacuation, relocation, and access of the emergency services to the site of the installation. Outline guidance is also included on how the plan may be extended in the event of an accident with larger radiological impacts than those considered in the consequences report.

In the context of socio-economic impacts of the installation, the main concern is with the impacts of the DEPZ on potential developments within its boundaries. In brief, ONR will not advise against such a proposed development if the lead LA provides assurance that it can be accommodated under the off-site emergency plan. However, in practice, Las may be reluctant to provide such an assurance. This means that development can be substantially constrained within the DEPZ. This can have a substantial local socio-economic impact. For example, for AWE Burghfield the REPPIR (2019) determination places the 7.5 mSv dose contour at 3160 m from the centre of the Burghfield site (AWE, 2019). It is possible that the DEPZ for the GDF facility could be somewhat smaller, but this is yet to be established.

The likely existence of an extensive DEPZ needs to be factored into the extent of the region requiring characterisation, especially in relation to potential socio-economic implications (an explicit component of the EIA, see Section 2.5). It has implications for defining the area over which information needs to be gathered on human communities and their activities, e.g. population density by census area, major retail, commercial and sporting venues, transport routes, and locations of groups of vulnerable persons such as schools and care homes. It also has implications in terms of developing the off-site emergency plan in collaboration with the lead LA and other stakeholders, including the emergency services.

When undertaking the EIA and in planning for development of the GDF, NWS will need to liaise closely with the lead LA and other stakeholders in helping to develop the off-site emergency plan. The need to develop such a plan may impact on siting of the surface parts of the GDF, because this could influence whether existing critical facilities, such as schools, care homes, hospitals and large venues, are located within the likely extent of the DEPZ and, if so, how close they would be to the site boundary (which is a factor in choosing between sheltering and evacuation in the early stages of an accident). Such facilities and others (e.g. commercial premises) would be required to develop their own emergency planning arrangements within the overall framework of the off-site emergency plan. This would have implications for the training of staff to ensure that they remained competent to implement their component of the emergency plan, as required.

4.4 GDF Design and Construction

The GDF design is dependent on data from the surface environment to be able to select locations and design the surface part of the facility. Prior to, and during construction, there is a need to calculate surface and bedrock water drawdown effects during construction (given suggested construction methods) and, in the end, effects on the safety functions of the GDF. Also, soil properties such as type, strata and thickness are used to plan and design surface installations. Hydrology, soil science and biogeochemistry are therefore important disciplines in a biosphere site-characterisation programme to support both design and prognosis modelling prior to and during construction. A typical timeline for above site information and data needs should follow the overall programme of design development and construction and be part of the plans to deliver site descriptive models.

4.5 Programme Integration and Competence

A general issue in many on-going national programmes is the need to make individual disciplines and functions aware of linkages and overlaps to other parts of the programme. This is a general management question but can only be successfully addressed if the different parts of the organisation think, and are allowed to think, outside of their individual responsibilities or typical discipline boundaries. In any case, to fully understand individual responsibilities, each part or unit within the organisation needs to understand its function in how to make the overall programme successful. An optimised biosphere site characterisation programme should, therefore, serve all end users and be developed, together with the geosphere site characterisation, as a general and as a stand-alone plan. If the site characterisation programme development is "owned" by one of the end users, the responsibility to make sure that all information necessary is captured, lays on that task owner. However, this does not mean that the rest of the programme should not interact in the task, or not demand to give input. To facilitate such interaction and integration between parts of the GDF programme, a useful method seen in some national programmes, is to develop the site characterisation plan as a multidisciplinary task force including representatives from all internal stakeholders. This strategy not only enables a planning with all aspects accounted for, but also forces individual organisational parts to think holistically – i.e. considering all aspects together not in isolation, ensure integration where needed, avoiding that solving one problem does not create another, avoiding duplication of effort and foster a common understanding on what is required and why, see e.g. NEA (2019). The end product of such a task force should be an operational site characterisation plan for each GDF programme phase.

One example of the above strategy is that some of the main requirements of safety assessment relate to the acquisition of meteorological, hydrological and hydrogeological survey and time-series data. These types of data are also of relevance in the wider EIA context and a single integrated programme of measurements and interpretation would be appropriate. In addition, both EIA and radiological assessments require information on key populations of non-human biota present within the area potentially impacted by site investigations, and by the construction, operation, closure and potential surface discharge areas. In this context, relevant data might be collected primarily for the EIA and used in the context of radiological safety assessment. Also, habits data would necessarily be collected for radiological assessment purposes. However, the surveys that are undertaken are both extensive and comprehensive, and methodologies for the collection and interpretation of the data are well developed. Therefore, the datasets provided should be appropriate as inputs in other contexts, e.g. for assessing the impacts of chemical discharges as part of the EIA.

4.5.1 Organisation and Staff Competence

Planning, executing, and delivering operational nuclear waste facilities in a national programme is a multidimensional task and often without similar previous national reference. Many questions are related to on-going scientific research, and the programme may find itself as one of few drivers for several scientific and technical questions. Long programme timeframes put another challenge on management, namely the need to make sure that knowledge and insights gained in earlier programme phases are not lost. Knowledge management including tacit knowledge and a high ambition human relations programme to maintain skills/experts and key individuals is, therefore, an important management component. A nuclear waste management programme is, therefore, not to be treated as a typical industrial project. It has been shown in other national programmes that the task should be acknowledged as a confidence builder in both sociological and scientific issues and should expect to encounter demands well above normal standards.

For each stage in the programme, there are several pathways to take, and it is important that all programme functions are aware of them and who is in charge of making the decisions. Furthermore, decisions made in one part of the programme may have consequences for other parts, therefore holistic thinking and an integrated management culture and implementer organisation that ensure that the whole system is accounted for in decision making are crucial, see Lindborg et al. (2021) for further discussion on system understanding and competence needs.

The GDF design function must use expert competence apart from rock engineering, within:

- design of system components and structures;
- rock mechanics;
- buffer systems and designed facility functions; and
- natural system properties and processes (geosphere, hydrosphere, and biosphere) – here you also find the link to biosphere site characterisation planning.

The strategy should be to work in an integrated way to design a GDF system that, during the programme phases, becomes increasingly enhanced and refined as information and feedback from biosphere site characterisation and safety evaluations/assessments becomes available.

Research and safety assessment develop in parallel during the programme stages. As suggested by IAEA, e.g. IAEA (2013) and applied by others (see Appendix A), a stepwise approach with concepts, design, detailed design and later, site adaptation is suggested. This allows for the flexibility that the programme needs to be able to adapt to new information during long-term and complex projects, and arisings of new or unanticipated waste streams from novel uses of radioactive material or as a result of accidents and incidents. From the beginning, during concept evaluation and thereafter at each stage, a review of issues needing further development to address them should be made and a log kept of how they have been addressed. These issues are typically directly related to uncertainties identified in safety assessments, or conservative estimates that lead to difficulty in demonstrating compliance with safety requirements.

High-level competences in the biosphere system, as permanent or long-term contract personnel is needed to make sure that issues can be handled, answered, and used in supporting an evolving safety case. Typically for a biosphere system development and research expert competences comprise:

- general safety assessment and dose modelling experts;
- hydrology and hydrogeology;
- biogeochemistry and hydrogeochemistry;
- elemental behaviour and transport processes (stable and radioactive isotopes);
- ecology/ecosystem properties and processes;
- soil science; and
- climate and long-term site evolution.

The biosphere site characterisation should follow the main programme phases. First, and before site investigations, a review of already available information should be conducted. This feeds into the planning of site investigations. A first generic or semi-generic assessment is needed to be able to evaluate the GDF concept and site conditions.

After selection of sites for site investigations, information is gathered according to a site investigation programme. A site modelling (SDM) programme runs in parallel.

Typical competences to run a biosphere investigation programme and seen in other on-going and advanced programmes are listed below.

- Manager of the site investigations with ability to assess issues on a system scale and with insights into the science of the natural system.
- Hydrological and hydrogeological investigations of surface and groundwater conditions.

- ▲ Chemical sampling and analysis of water, groundwater, bedrock/fractures, soils, and biota.
- ▲ Ecological investigations (ecosystem descriptions) and mapping of topography, bathymetry and physical soil properties.
- ▲ Weather station installations and surface water runoff gauges as part of a monitoring programme. Monitoring of EIA issues as well as repository performance indicators, preferably as one integrated monitoring programme with long-term planning beyond individual programme phases.
- ▲ Site investigation activity leaders for each discipline.
- ▲ Coordinator of investigations and linkage to end users (e.g. operational safety, safety after closure, EIA programme and GDF design).
- ▲ The site investigation organisation should include and allow for a strong interface between the scientific/geological/engineering and communication functions within the overall organisation.

The biosphere component of site descriptive modelling typically needs competence in producing conceptual, distributed, and numerical models on the following scientific disciplines:

- ▲ hydrology and weather data;
- ▲ hydrogeology;
- ▲ biogeochemistry;
- ▲ elemental transport;
- ▲ ecology and dose modelling; and
- ▲ soil science and geometrical models (topography and bathymetry).

The competences needed to perform the biosphere component of site descriptive modelling are similar to the capability needs seen within safety assessment tasks handling the total natural system. Therefore, these groups have a strong relationship and share many integrated tasks. Dose modelling noted in the list above together with ecology is an example of such relationship where an expert in safety assessment should be part of the site modelling to ensure that site specific models can support or reject assumptions and simplifications made in the dose model. Site descriptive modelling, including the biosphere, should preferably be seen as an organisational function that integrates system understanding and ensures a scientific level of ambition that can be used as support in safety case arguments.

The EIAs will include consideration of the disturbances that investigations, construction and operation of a GDF will impose on a site and key receptors. This environmental impact is directly related to the "sensitivity" or magnitude of change on the site/key receptors and therefore, a site selection process should from the beginning make sure that the potential impact is manageable. To be able to deliver supporting information to the EIA, several discipline competences are of use, such as:

- hydrology and hydrogeology;
- geology and soil science;
- ecology and experts in potential endangered species; and
- biogeochemistry.

A lesson learnt from the Swedish programme is that it is very useful to interact and cooperate with local organisations and individuals such as birdwatchers, fishing clubs, forestry companies, hunters etc. This not only informs biosphere understanding, but also builds trust and confidence in the GDF programme among local inhabitants and the community.

The environmental assessment team must be actively involved in planning the overall site characterisation. This will help ensure that site information is sampled, measured or/and modelled according to the needs of the environmental assessment process.

4.5.2 Stakeholder Interactions

During a site selection process including the site characterisation stage, the need for communication between the implementer and the rest of society is very important. From communication with reviewing authorities through to information, listening and discussion with nearby residents at potential locations. The purposes of communication are many and the type of information flow is different depending on stakeholder type and issue. An important prerequisite for being able to site and construct a GDF is that the project receives confidence in its methods and expertise. Another condition is to show that local conditions have been taken into account, that requirements for authorising and permitting development are understood, and that other people's issues are recognised and addressed.

Another important topic for biosphere site characterisation stakeholder interaction is the need to demonstrate both trust and scientific quality. By engaging universities and experts in site characterisation and producing papers on methods and results, recognition and acceptance amongst the scientific community will enhance confidence in the overall programme. If needed, research projects should be initiated on identified topics with less general scientific support, e.g. gaps of knowledge in natural sciences on topics of interest for the GDF programme. This could be on identified sites but could also be conducted on analogue sites or established field stations with on-going research. Lessons learnt from other national programmes show that it is very useful to link the site monitoring to national monitoring programmes. This will give the site monitoring reference data and at the same time increase the credibility of the GDF programme.

Communication on “biosphere topics” has proven to be very useful to gain local trust in other programmes. This is because the biosphere is visual compared with the bedrock system and all local stakeholders interact with and have their own understanding of the present-day biosphere. Investigations and models of the biosphere component of the system have, therefore, also a purpose to enhance confidence in the overall programme. The argument goes: “if you don’t understand what we all can see on the ground surface, how can you then argue for conditions below ground?”. Acknowledging wider stakeholder interests and concerns as one of the important inputs to developing and maintaining a programme for biosphere site characterisation is, therefore, important.

5 Biosphere Site Characterisation Roadmap

Taking into account key considerations from Sections 2-4 above and lessons from international experiences (Appendix A), an illustrative roadmap for biosphere site characterisation has been developed with focus on upcoming site selection phases for the GDF. The roadmap includes general components as tasks, deliveries and links to other programme parts and is to be seen as an overarching structure for further and more detailed planning. The illustrative biosphere site characterisation roadmap is intended as input to NWS planning.

A roadmap for biosphere site characterisation should build on a common GDF programme roadmap, including geosphere characterisation, with associated links to end users and their information needs over time. A relevant example of such input to be used as support when constructing a roadmap can be found in SKB (2011), where an assessment model flowchart displaying a logical structure of the safety assessment task is shown. Typically, a roadmap displays the main activities and the information flow needed to support applications. They can be produced in various ways, but roadmaps often are displayed as Gantt charts or sketches to emphasise the main tasks and the integration needed between programme functions. In Figure 12, an example of an information flow diagram is shown that was used by SKB during the site investigations at Forsmark and Laxemar/Simpevarp during the planning of site descriptive modelling. Note the importance of interactions and feedback between programme functions. These types of information flow diagrams are useful when constructing roadmaps but are to be used together with a knowledge and requirement management system to fully capture demands and dependencies.

In Table 5 and further displayed with programme interactions in Figure 13, an illustrative roadmap (or timeline) for NWS biosphere site characterisation is shown. Names of components/functions in the roadmap are taken from international examples and may not exactly match the NWS organisation today. The roadmap was produced as part of this work and is to be seen as an example and early draft. However, the needs and links are taken from and supported by Sections 2-4 in this report and should describe the main components and tasks identified. To fully include all tasks, products and linkages, the whole GDF programme with individual components must be involved to feed information or respond to suggestions. By that, also key milestones can be recognised and added. Lessons learnt from the SKB programme show that it is useful to produce this type of roadmap as part of a programme component/function integration. Given that roadmaps and timelines are used for strategic planning and should contain all of the main activities, products, and linkages/deliveries to other parts of the GDF programme, internal programme stakeholders must be involved. Also, a series of internal workshops where plans are presented, discussed, and developed have proven very useful in other national programmes (see Appendix A).

The overall aim with a final roadmap is to show how all necessary supporting documents are prepared to readily move forward through the programme phases. Therefore, roadmap construction should also be reviewed by all GDF programme related groups or functions displayed on the timeline. It should be noted that this type of high-level roadmap needs to be supported by more detailed plans for each individual site characterisation discipline (see example in Section 4.1.2, hydrology/hydrogeology). By developing discipline-based documents (e.g. for hydrology, biogeochemistry, ecology, soil science) describing the site characterisation task (for each discipline), information needs, and products of delivery, detailed roadmaps for each site characterisation discipline can be linked to the overall and more general biosphere roadmap showed in Figure 13 and 14.

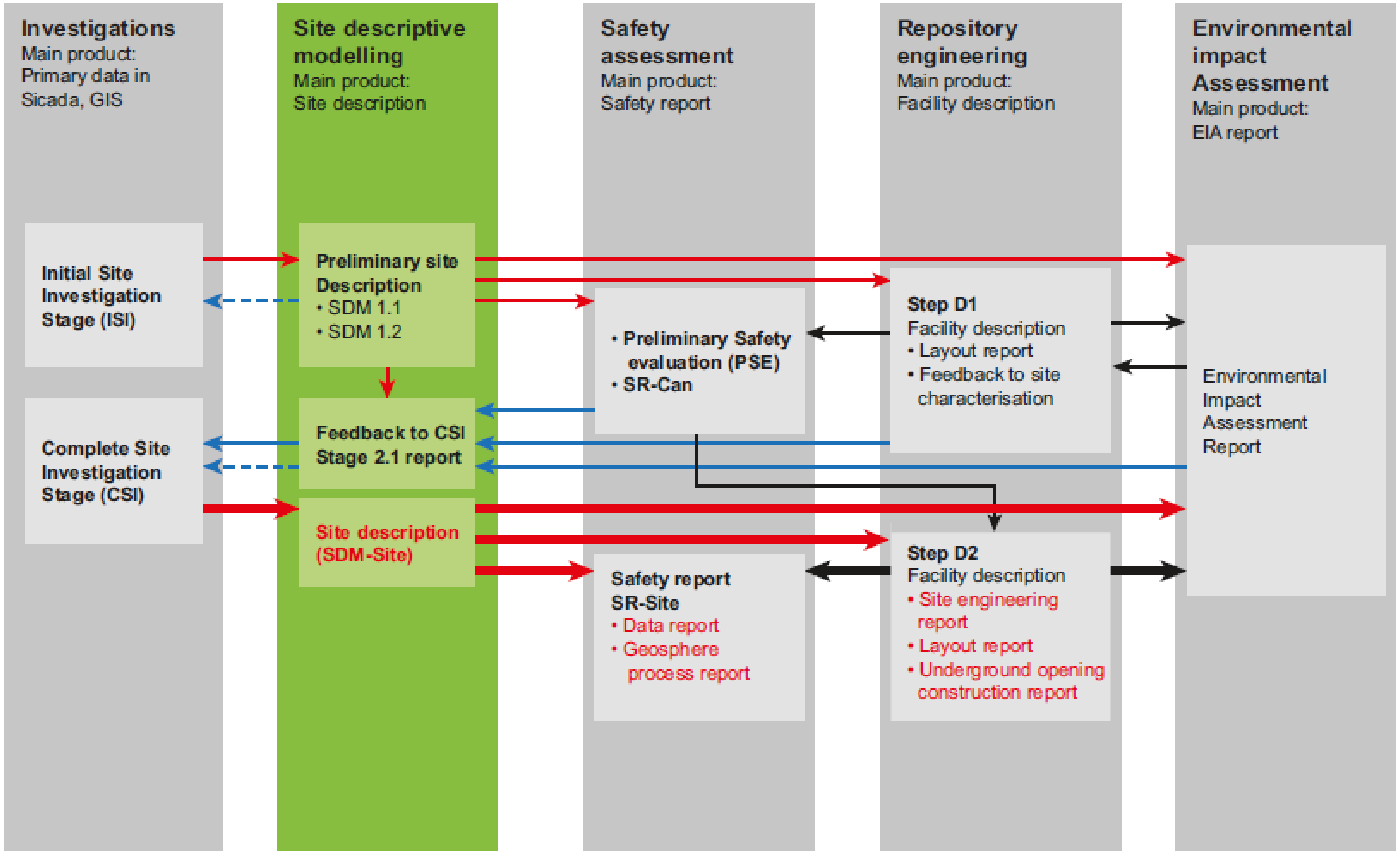

Figure 12: Information flow diagram showing site characterisation in green with a timeline going from top to bottom and relations to other programme parts as arrows. From SKB (2008).

Table 5: Indicative draft roadmap structure for biosphere site characterisation with main activities for programme components.

Programme Component	Activity	Site evaluation and selection	Initial site investigations	Detailed site investigations
Knowledge acquisition and synthesis	Baseline surveys (site investigations)	Literature and map based	Walkover, ground-penetrating radar, electromagnetic	Boreholes, seismic surveys, water, soil, sediment, plant and animal sampling and analysis, gamma spectral surveys
	Monitoring	Records from existing weather stations and local logged catchments	Automatic weather station installation	Installation of stream gauging, current monitoring, accumulation of local weather station data, time-lapse photography
Site modelling and synthesis	SDM development	Conceptual model, identification of skills requirements, formation of task teams	Development of discipline-specific models, synthesis in overall model, identification of requirements from detailed site investigations	Further development of discipline-specific and overall models
Safety assessment	Operational assessments	Generic, but conditioned with local windrose data	Generic, but conditioned with local windrose data	Complementary data
	Operational accidents	Generic, based on preliminary accident source terms, but conditioned with local windrose data	Generic, based on preliminary accident source terms, but conditioned with local windrose data	
	Post-closure	Generic, but with models conditioned with information from desk-based studies	Model structure and data modified to conform to desk-based information confirmed and enhanced by on-site observations	Model structure and data further modified as site-specific information increases in extent and detail
Environmental impact assessment	All aspects	Literature and map based	Supplemented with local observations at the site and in the local area to give a baseline survey	Augmented survey and evaluation of key trends with time

Programme Component	Activity	Site evaluation and selection	Initial site investigations	Detailed site investigations
GDF selection and optimisation	Siting	Based on literature and map-based information - focus on selecting a site	Based on desk studies plus local non-invasive studies - focus on confirming site selection	Borehole data used to confirm appropriateness of site selection
	Depth and overall layout	Initial suggestions on depth and overall layout, but with no, or limited, subsurface data acquired from third parties	Initial suggestions on depth and overall layout, but with no, or limited, subsurface data acquired from third parties	Confirmation of views on depth and layout - on-going process of developing a detailed design, giving consideration to interactions with biosphere, e.g. water-table drawdown
	Design	Conceptual generic design	Generic design adapted to perceived site conditions	Iterations of detailed design to conform to site and limit adverse impacts on the surface environment
Engagement and communications	Regulators	Pre-application discussions	Pre-application discussions and application for borehole construction	Regulatory supervision of borehole programme and application to construct
	Local communities	Initial discussions with volunteer communities; further discussions during site selection	Detailed discussions of the site investigation programme and local interests for the selected site - emphasis on impacts of the borehole investigations	Detailed discussions, involvement with the site-investigation team, specific studies to address local concerns - emphasis on GDF construction and operations
	Other stakeholders	Briefing on programme developments	Consultation on relevant concerns	Consultation on relevant concerns
Knowledge management	All aspects	Development of a QA and QC regime for knowledge management, including set-up, testing and implementation based on information from desk studies	Testing and enhancement with the inclusion of non-invasive site-specific information	Testing and enhancement with the inclusion of invasive site-specific information

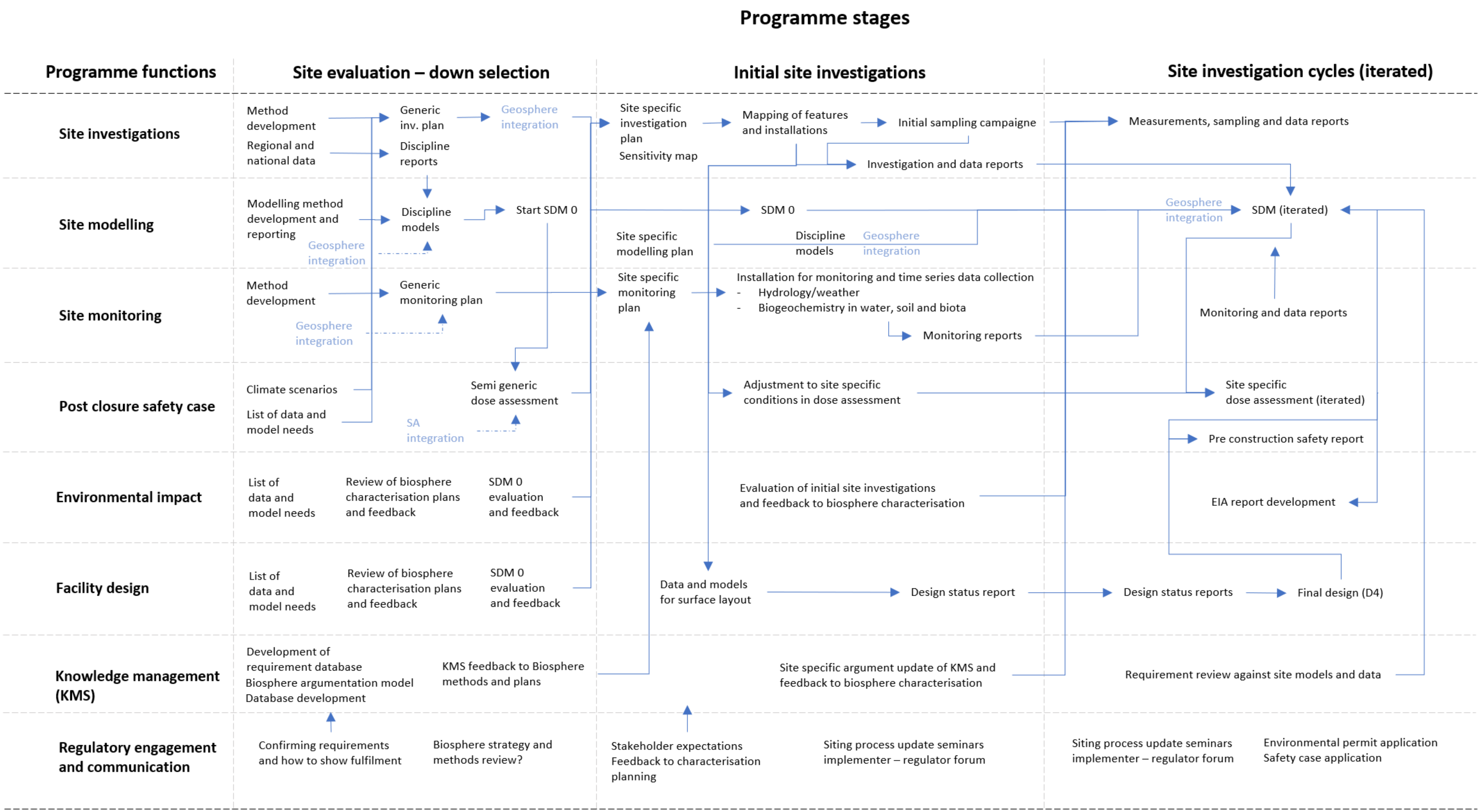

Figure 13: An indicative draft biosphere site characterisation roadmap for initial programme phases and with linkages to the geosphere site characterisation and end-users.

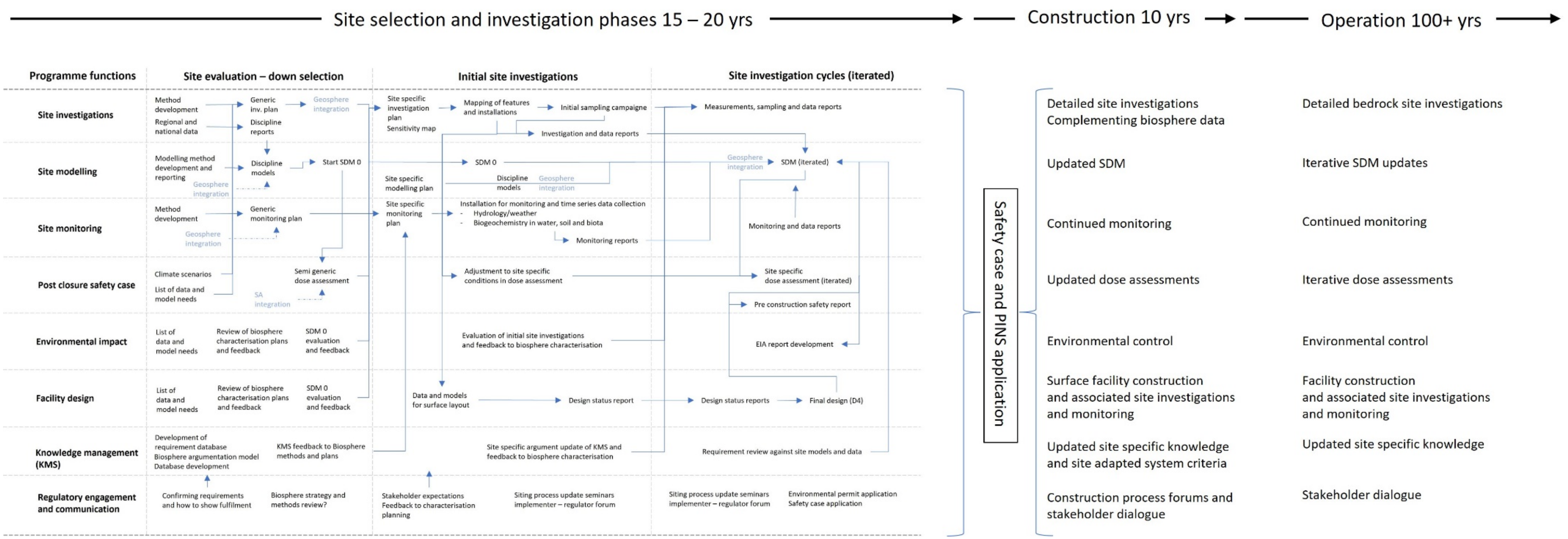

Figure 14: Illustration showing the biosphere roadmap in Figure 12 extended to the operational phase, with indicative time frames taken from RWM (2020a).

The biosphere site characterisation roadmap in Figure 13 starts from the left where identified programme functions of interest are placed in "swim-lanes". During the initial phase of site evaluation and down selection, method development and planning of the biosphere site characterisation uses input from post-closure safety, environmental impact and facility design to detail requirements into tasks and characterisation programmes (investigation and modelling). This is generic at first, and is then more site-specific once the initial site investigation phase starts at selected sites (equivalent to the borehole investigation phase). During all phases, integration with the geosphere programme is needed as well as deliveries of inputs to a general SDM that synthesise the natural system for end users and in support of an application to start construction/operation (Figure 14). During construction and operation, the biosphere site characterisation will continue and provide a basis for updated SDMs, safety assessments and applications but with more focus on synthesis of monitoring data and gaps of knowledge. As stated earlier, the roadmap displayed here should be seen as a first step towards integrated planning of all necessary site characterisation tasks within NWS.

6 Conclusions and Key Recommendations

This report draws on international experience to emphasise the need to have an overall strategy for site characterisation that recognises the role of system understanding as a core function in the GDF programme to guide planning, execution and decision making. System understanding needs to draw on knowledge of the natural system (biosphere and geosphere) and of the GDF design, such that biosphere site characterisation is one part of an integrated approach. The natural system (areas or volumes) of interest to site investigation and modelling may differ depending on end user needs and changes in emphasis during the programme timeframe. The biosphere characterisation strategy presented in this report draws on experience from other programmes and projects (see Appendix A) and would help optimise both site characterisation as well as the overall GDF programme.

The importance of integration between operational functions in a GDF programme is highlighted and examples are given in the text, hence biosphere characterisation should not be considered in isolation. To facilitate a well-integrated biosphere site characterisation programme, a key task is to involve multidisciplinary teams drawn from across GDF programme function borders. These teams should, in an iterative way, coordinate, produce plans, methods and review results as the GDF programme progresses. For biosphere site characterisation, this could be manifested in (i) a team that integrates all site characterisation disciplines with end users, as well as (ii) teams for each biosphere discipline with suggested links to geosphere disciplines (e.g. hydrology/hydrogeology, biogeochemistry/hydrogeochemistry, soil/sediment geology). It is suggested that NWS organise both the biosphere site characterisation as well as the overall site characterisation in a way that facilitate the development of these teams, including end users such as safety assessment, EIA and facility design.

The biosphere site characterisation consists of site investigations, monitoring and modelling activities (see Section 4). The results from these tasks should be interpreted via a SDM that synthesises and integrates all biosphere and geosphere disciplines together. The SDM is developed in an iterative way following the overall GDF programme stages and key milestones. Examples of key milestones include EIA for borehole drilling/investigations, and EIA and safety assessments for the construction application. This iteration allows for important feedbacks from end users that will enable site characterisation to be refined, optimised and focused on key areas.

Issues management and a well-established knowledge management system (KMS) are needed to handle and keep track of both the feedback from users and the site information gained. A requirement database should be linked to this KMS. It is recommended, and experience shows, that NWS develop a KMS that is (i) designed for end user needs, and (ii) keeps track of requirements linked to the disposal system (biosphere, geosphere and designed parts). These requirements should be drawn from international guidance and national regulations, disposal system criteria (method and site specific), and keep track of societal expectations. The importance of handling tacit knowledge and maintaining in-house research is also emphasised. Experienced experts have been shown to provide an important input to programme development in other national programmes, whereas organisational changes and staff turnover can be a hinderance, see e.g. Andersson (2020) and Ewing (2020).

Planning for biosphere site characterisation should take all end users into account and deliver a SDM useful for safety assessment, environmental assessment, GDF design/construction and stakeholder communication. This helps optimise the programme and ensure that a single, integrated version of site understanding (interpretation of data and models of the natural system) is developed and maintained as a foundation for assessment studies. When applicable, it is recommended that NWS fully integrate biosphere characterisation with geosphere characterisation and encourages a culture of holistic thinking among discipline specific employees and contractors (see earlier discussion on interdisciplinary teams). The conceptual understanding of the total system should always go in parallel with discipline specific processes or features.

The biosphere site characterisation programme represents a good platform for communicating with local stakeholders. A good understanding of site conditions, or showing willingness to achieve knowledge, is crucial to gain trust from local inhabitants and stakeholder groups. This purpose of the biosphere site characterisation can be as important as any other and is recommended to be part of early planning. The planned 'Working in Partnership' approach should help facilitate this and ensure that relevant stakeholders with local connection are included in communication forums with constant dialogue on biosphere characterisation plans, its execution and findings.

Important lessons learnt from other national programmes have been used when producing this report. A list of key issues that have emerged during the work is provided below for consideration when further developing the biosphere site characterisation planning as illustrated in the roadmap shown herein. Note that not all of these topics have been discussed in the main body of the report and that some issues are relevant to site characterisation as a whole (and not just to the biosphere part).

- ▲ An accessibility map is very useful to help site investigations to avoid disturbance of sensitive areas and/or protect valuable species. This map should be produced in a geographic information system (GIS) and be constantly updated (see Appendix A).
- ▲ Recognise that biosphere areas requiring investigation and characterisation may differ between the different end-users within the GDF programme.

- ▲ When conducting extensive site investigations, protected species will likely be found. The programme should be prepared for this and be ready to prepare management plans and mitigating actions in response. Indeed, the protection that can be afforded for habitat areas in relation to GDF siting can be a positive aspect.
- ▲ The value in characterising the top of the bedrock and overburden should be recognised when sinking deep boreholes. This relates to development and fostering of a holistic culture, whereby each part of the programme recognises interdependencies across technical domains.
- ▲ Capture hydrological data early and continue monitoring to allow for numerical distributed modelling at catchment level (weather, water flow, soil water levels, water in unsaturated soil, soil/sediment properties).
- ▲ Establish links with universities for research support to site characterisation. If possible, link national monitoring programmes to the site.
- ▲ Ensure clear links between research-level studies/modelling and associated drivers in support of interpretation/site descriptive modelling/EIA and assessment modelling. This can be managed through issues management and tracking.
- ▲ Consider multi-element sampling and analysis at the detailed site characterisation stage and establishment of ecosystem-level element balances for key elements.
- ▲ Plan for sample preservation and storage, allowing for potential reanalysis in future as techniques advance, and establishing an environmental specimen 'bank'.
- ▲ Produce reports and supporting papers. Not only internal documents. A reporting plan is a good tool for general and long-term site characterisation planning and publications help share knowledge/understanding gained and helps build confidence in the degree of scientific rigour.
- ▲ Generic FEP-lists can be used as checklists in terms of system understanding and assessments. A good, integrated understanding of the system needs to be established to support site-specific process descriptions/reports.

In summary, the suggested way forward would be to use the compiled information and illustrative roadmap to define priorities in biosphere characterisation. This is based on lessons learned from international and national experience in biosphere site characterisation and application to EIA and safety assessment. The roadmap includes general tasks, deliveries and links to other programme parts and provides an overarching structure for further and more detailed planning. Specification of the level of precision needed in site characterisation is challenging but is aided by iteration, whereby important factors can be recognised and associated understanding refined, consistent with an overall strategy for managing uncertainty.

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Glossary of Key Acronyms

A glossary of key acronyms is provided below, along with associated description/context.

DCO	Development Consent Order	Consenting regime for NSIPs in England and Wales under the Planning Act 2008. Projects are granted a DCO if approved by the Secretary of State (SoS); as opposed to receiving planning permission from a Local Authority (LA) under the Town and Country Planning Act 1990. The DCO Examination process only starts when an application is formally submitted and accepted by the Examining Authority (PINS) and can last c. 12-15 months. The process is front-loaded with pre-application assessments (e.g. EIA) and consultation requirements, which, depending on the complexity of the project, can take several years to complete. The final decision on granting a DCO rests with the relevant SoS and development can only commence after a DCO is granted, including compulsory acquisition powers.
DEPZ	Detailed Emergency Planning Zone	The Radiation (Emergency Preparedness and Public Information) Regulations (REPPIR) 2019 require that, for sites that could give rise to accidents, an off-site emergency plan is prepared, and a Detailed Emergency Planning Zone (DEPZ) is defined. Once defined, future development of land within, or in proximity to, the DEPZ, could potentially be restricted or constrained.
EIA	Environmental Impact Assessment	The structured process for assessing the potential environmental effects of a project, undertaken by technical specialists following published guidance and/or using accepted methods. Typical process: screening/scoping, establish baseline conditions, determining and assessing potentially significant effects of the proposals, and agreeing appropriate mitigation/management plans. Consultation with key regulators/stakeholders undertaken throughout.
ES	Environmental Statement	The main and final deliverable of the EIA process following consultation on the PEIR, submitted with other supporting documents with the DCO submission to PINS. Brings together the EIA technical contributions, including plans, drawings, tables and modelling outputs. The audience of the ES is typically at the technical level and is primarily focussed on analysing the potential significant effects. A non-technical summary of the ES is provided for easier digestion of the EIA process/outcomes.
GDF	Geological Disposal Facility	Geological disposal facility for the UK's higher-active radioactive waste.

LA	Local Authority	The district or borough council/unitary authority with responsibility for the area within which the GDF may be developed.
NSIP	Nationally Significant Infrastructure Project	A large-scale, national project (often in the infrastructure sector, such as energy, transport, water, waste) that has been designated by PINS to be relevant under the Planning Act 2008. The majority of NSIPs are transport related. Current NSIPs include: A303 Stonehenge, Sizewell C, East Anglia One & Two Offshore Windfarms.
PEIR	Preliminary Environmental Information Report	A sufficiently detailed description of the project and the outcomes from baseline studies and impact assessments for each topic/sub-topic. Used to inform key stakeholders, PINS, and the local community at the consultation stage (pre-application) of the potential significant effects and proposed mitigation and management measures; to allow consultees to comment and to raise issues, which are then considered and addressed by the proponent's team, with any agreed amendments/changes reflected in the finalised ES.
PINS	The Planning Inspectorate	The Planning Inspectorate's role is to examine and provide recommendations and advice on a range of planning-related issues. PINS is the Examining Authority for NSIPs and each project they examine is led by one or two appointed Inspectors and their team who report back to the relevant SoS with their recommendation once the Examination process is complete.
PoA	Period of Authorisation	Period during which the GDF is still under active control and subject to permitting.
SDM	Site Descriptive Model	The product of site characterisation and associated interpretation, including modelling, sufficient to support end users including EIA, facility design, operational and post-closure safety assessment/safety case.
SoS	Secretary of State	Secretary of State with responsibility for particular decisions.

Appendix A: Review of Other Projects

Biosphere characterisation for a geological disposal programme is not a new discipline and substantial amounts of work have already been undertaken in several other national programmes (Thorne et al., 2011). Therefore, NWS has contracted a review of lessons learnt from biosphere characterisation in other national programmes and contexts, as input to planning for the GDF programme.

This appendix summarises the main strategies and lessons learnt from several national programmes and other projects with relevance to the UK GDF biosphere programme. It does not provide a detailed review, rather it aims to capture lessons that can be learnt as input to planning for the UK programme.

Geological disposal programmes and other projects encompassed in the review are introduced in Section A.1. Observations relevant to planning for biosphere characterisation are then drawn together under the following topical themes:

- biosphere data and site investigation are covered in Section A.2;
- phasing through initial characterisation to site monitoring is discussed in Section A.3;
- modelling in support of biosphere characterisation and interpretation is covered in Section A.4;
- programme interactions and integration are considered in Section A.5;
- organisation and staff competence are discussed in Section A.6;
- stakeholder interactions are considered in Section A.7; and
- examples of roadmaps for biosphere characterisation are covered in Section A.8.

References are provided at the end of the Appendix.

A.1 Identified National Programmes or Projects of Relevance

In this section, a list of national radioactive waste management programmes and other projects of relevance for a biosphere site characterisation programme are summarised. The text aims to give an overall description and does not necessary discuss specific topics. In later sections (Sections A.2 to A.8), topics of interest identified as specific strategies or lessons learnt are discussed with reference to relevant programmes described below.

SKB (Sweden)

The biosphere site characterisation programme in Sweden was developed during the late 1990's and over a few years subsequently. Its main purpose was to be able to feed information to the spent fuel disposal programme, but other repository waste programmes conducted by SKB have adapted the strategy and used its results (i.e. the programmes related to the SFR repository and SFL repository concept). Site investigations were performed at two sites (Laxemar/Simpevarp and Forsmark) and were conducted from 2002 to 2008. Even though the formal site investigation phase has ended, monitoring and several complementary field activities have been performed through to today (2021), with a focus on the Forsmark site which, in 2011, was selected as the site for a deep geological repository (DGR) for spent nuclear fuel. Even though the basic strategy was developed 20 years ago, on-going updates, developments and adaptation to the programme phases have been, and are still being, performed in preparation for the upcoming detailed site investigation phase during construction of the repository accesses (planned to start in 2023).

The overall strategy can be summarised as follows: the biosphere is handled as a part of the overall repository system and is included in the general site characterisation programme, see SKB (2001). The biosphere site characterisation planning and execution has been ambitious, aiming at conceptual and system understanding, ecosystem modelling and having a process focus with strong linkages to on-going relevant research at universities, internal research at SKB, and safety assessment dose modelling development. In many cases, the biosphere safety assessment team, environmental assessment team and invited people from academia were instrumental in initiating and/or planning site characterisation tasks. Constant iterations and feedback from site characterisation to end-users were built-in to the site characterisation strategy. A rough estimate is that the biosphere site characterisation had a budget of 2 million euro/year for investigations, modelling and reporting during the peak years around 2002-2008 and used c. 20 full-time workers.

Posiva (Finland)

The Posiva programme can be described as a twin programme to SKB, with similar site characteristics and repository methods. A big difference, and this due to the legal framework, was that the Finnish programme performed site selection as part of an environmental assessment before site investigations. Therefore, the Posiva site characterisation programme could focus on just one site, Olkiluoto. The programmes were run in parallel up until start of construction of the ONKALO underground research facility that has since been further extended into the disposal facility for spent nuclear fuel. Due to similarities in the projects and general focus areas, the Finnish biosphere programme used a strong relationship with research and development at SKB. This cooperation led to successful methods development, planning and well-conducted site characterisations that both parties gained from.

Posiva's environmental monitoring programme began in 2004. Key objectives of the programme were: to monitor environmental impacts to fulfil requirements of environmental licensing and other regulatory criteria, including establishment of a radioactivity baseline that will inform the operational monitoring programme; to map land use changes in the area that could affect the results of other monitoring and research activities (e.g. construction impacts on the site); and, to produce input data for radionuclide transport modelling in the surface environment, in line with regulatory requirements for assessments to be underpinned with site-specific data (T. Sojakka in BIOPROTA, 2018).

The Posiva ecosystem characterisation strategy can be summarised as follows: it is an iterative process aiming at achieving an adequate site understanding in order to evaluate the appropriateness of different models and of the literature data to the site, and to provide data of sufficient scope and quality to underpin the safety case development. The iterative nature also implies that there are already well-established models in use by the later programme phases. However, the existing models need to be audited and evaluated for comprehensiveness, fitness for purpose, and updated according to the latest site knowledge and data. The developments in modelling, on the other hand, raise needs for new data and process understanding. Iteration arises also from the stages of the repository programme, with increasing demands on the quality of the safety case and the need to produce updated versions of assessments.

Furthermore, the extent of ecosystem characterisation needs to be reasonable in relation to the overall repository programme development, the significance to the safety of the spent fuel disposal and the regulatory requirements. This graded approach means providing continuous improvement at a level that is reasonable in the overall context.

Therefore, the characterisation and assessment work needs to be kept focussed on systematically identified key issues of relevance. This identification process involves feedback from the regulator and from other stakeholders as well. See site characterisation and assessment reports Posiva (2012a, 2012b, 2012c, 2013a, 2013b, 2013c, 2013d, 2014). These reports can be regarded as the core publications related to biosphere site characterisation and strategies at Posiva.

The monitoring programme had an annual operating budget of around 1 billion euros, reducing to around a third of this annual budget from 2016 (T. Sojakka in BIOPROTA, 2018).

NWMO (Canada)

In 2002, the NWMO was created by Canada's nuclear energy generators (Ontario Power Generation, New Brunswick Power and Hydro-Québec) and NMWO started its work to develop a long-term management approach for Canada's used nuclear fuel. A three-year study was conducted in which thousands of citizens with different backgrounds, expertise and geographical location were involved with the aim to develop a management approach that was socially acceptable, technically sound, environmentally responsible, and economically feasible (NWMO, 2010). In 2007, the so-called Adaptive Phased Management (APM) was selected by the government as the best plan for Canada. A fundamental tenet of Canada's plan is the incorporation of learning and knowledge at each step, to guide a process of phased decision-making. The APM approach includes a site selection process to identify an informed and willing host for a deep geological repository. The APM project will be implemented in phases and will operate for many decades. It has an estimated cost (Canadian dollars, $) of $16 billion to $24 billion (NWMO, 2010).

The site selection process is itself based on a multi-phase approach, in which the level of detail in the evaluations is increased stepwise[10]. 22 municipalities and indigenous communities expressed interest. NWMO followed a phased approach to screening those regions through technical site evaluations and social engagement. This included initial screening, followed by 'Phase 1' desktop studies. Examples include the Township of Manitouwadge, located in north-central Ontario, who expressed interest in participating in the site-selection process. The Phase 1 preliminary assessment for Manitouwadge (Golder, 2014) provided high-level descriptions of the biological and physical environment within the community and surrounding area which, along with geoscientific information, was used to evaluate the potential for a facility to be safely constructed and operated in the vicinity.

Those sites that continue to warrant further study proceeded into 'Phase 2' assessments, which focus on fieldwork. Geophysical surveys, environmental surveys, and geological mapping are undertaken to further assess potential suitability and identify smaller areas that have the potential to meet the technical site evaluation factors. These are then followed by more detailed studies that focus on potential repository sites within an area.

In the context of the Township of Manitouwadge, for example, Phase 2 studies have been conducted in the area and the findings are described in NWMO (2019). The information and data from the environmental monitoring which include surface water, terrestrial soil and aquatic sediment quality sampling, terrestrial plant and wildlife surveys, and aquatic habitat surveys facilitate the identification and assessment of any potential environmental effects resulting from siting activities, but the information would also

[10] https://www.nwmo.ca/en/Site-selection/About-the-Process

support the biosphere assessment of the site. Data required for biosphere characterisation is incorporated in the environmental monitoring programme. A programme for environmental base line studies is presented in NWMO (2016).

At present, the NWMO have narrowed down the site selection and is engaging with two remaining potential siting areas, the Township of Ignace in north-western Ontario, and the Municipality of South Bruce in southern Ontario.

OPG (Canada)

In parallel to the used nuclear fuel programme in Canada, in 2011 OPG applied for a site preparation and construction licence for a deep geologic repository (DGR) for low and intermediate level operational reactor and refurbishment wastes. This facility was proposed to be constructed at 680 m depth in the Cobourg limestone formation at the existing Bruce nuclear site. The existence of the Bruce nuclear power plants and Western Waste Management Facility (WWMF) at the Bruce site meant that biosphere characterisation and safety assessment approaches were already established. The 2011 Environmental Impact Statement (EIS) (Golder, 2011) in support of a licence application encompassed both EIA and safety assessment. Biosphere characterisation in support of the EIS drew extensively on the existing understanding based on EIA for the Bruce site and WWMF.

Andra (France)

In 1999, the French Government authorised Andra to build a research laboratory with a view to disposing of high-level and intermediate-level, long-lived radioactive waste in a deep repository within a consolidated clay/mudrock stratum. The proposal is that such a repository would be located geographically close to the location of the underground research laboratory, which has been constructed at Bure in the southern part of the Meuse district. It is in the eastern part of the Paris Basin within a zone of limestone plateaux. Before developing the underground laboratory, Andra undertook a comprehensive assessment of the characteristics of the site (Andra, 2009) and this has subsequently provided the basis on which to develop an on-going monitoring programme (BIOPROTA, 2018). The monitoring programme is integrated within various international and national networks, to involve organisations with diverse expertise ranging from environmental banking and databases to ecosystem monitoring at a territory scale. Topics covered in the initial site characterisation and subsequent monitoring include climate evolution (through the use of palaeoclimatic reconstructions), geomorphology (with an emphasis on incision over the Quaternary and covering spatial scales up to the whole of the Paris Basin and its context), hydrogeology (including 3D modelling and consideration of potential effects of permafrost), and ecosystems (with an emphasis on soils from sites considered analogous of potential future conditions). An important current emphasis in the programme is the development of an environmental specimen bank, in which it is intended that samples will be stored for at least 100 years. Andra is part of an international group on environmental specimen banks that has been useful in informing optimised strategies for sampling and the preservation of samples. The on-going monitoring programme aims to integrate observations of changes in the characteristics of the site within a scientific approach that will also address perceptions and expectations about the environment from local stakeholders.

LLWR (UK)

The Low Level Waste Repository (LLWR) in west Cumbria is a surface disposal facility for UK low-level radioactive waste that has been in use since 1959. Disposals were originally by loose tipping into minimally engineered trenches, but, since the 1980s, disposals have been in ISO-containers emplaced in highly engineered, concrete vaults. Environmental Safety Cases (ESCs) for both the trenches and vaults are produced at intervals (most recently in 2002 and 2011, with the 2011 ESC subject to subsequent updates). These are used to support applications for permits for the continued operation of the facility, including extensions such as the development of additional vaults. The 2011 ESC (LLWR, 2011a) is supported by a detailed site-characterisation report (LLWR, 2011b). This report provides a description of the history of site use and development, summary details of the engineered features of the site and an overview of the waste inventory. Of more relevance here, other sections of the report provide a description of the geographical and environmental setting. The description covers climate, topography, soils and sediments, geology and hydrogeology, surface waters, coastal processes, flora and fauna, and information on human settlement patterns and land use. Because of the near-coastal location of the site, a particular focus is on estuarine and coastal landforms (e.g. dune formations) and processes, with some attention also given to the characteristics of offshore sediments. In terms of terrestrial systems, the emphasis is on agricultural ecosystems and, specifically, on pasture systems. However, other ecologically rich systems are also addressed with a focus on three local SSSIs. Specifically, the Drigg Dunes are a habitat of Europe-wide significance. The hydrogeological characteristics of the site are of specific importance in radiological impact assessments and calibrated, site-scale, groundwater-flow models have been developed using various software packages. The most recent model uses a 3D lithofacies approach as a framework and extends over a wider region demarcated by topographic catchment boundaries (interfluves).

Dounreay (UK)

As part of the Nuclear Decommissioning Authority's (NDA) decommissioning of the Dounreay site, a planning application was made by the UK's Atomic Energy Authority (UKAEA) to the Highland Council in 2006 to manage solid low level radioactive waste (LLW) through the construction of shallow sub-surface concrete vaults. Up to six engineered vaults, plus a grouting plant and administrative facilities, subsequently received planning permission and the first two LLW disposal vaults became operational in 2014. The total volume of solid LLW in the vaults adjacent to the Dounreay site will be up to 175,000 m^3 derived from the clean-out and dismantling of Dounreay's nuclear reactors, reprocessing plant and other radioactive facilities.

The first two vaults required groundwork excavations up to 11 m below the surface into bedrock and the removal of c. 300,000 m^3 of rock from the site. The concrete walls, floor slab and roof of the vaults is at least 0.5 m thick, and the backfilling and concrete structure of the LLW facility restricts groundwater flow, minimising radionuclide movement.

Pre-planning stakeholder engagement with local residents highlighted their displeasure with the visibility of the LLW facility from their properties in its original proposed position (on the highest point within the site to mitigate for future sea level and climatic changes). A lower alternative siting of the facility was then redesigned but this was on softer, boggier ground, and resulted in extra mitigation measures following additional and/or revised environmental modelling, characterisation, and assessments.

Yucca Mountain (US)

In 1982, the US Nuclear Waste Policy Act (NWPA) mandated investigation of several sites as potential locations for developing a geological facility for the disposal of high-level radioactive waste and spent nuclear fuel. However, in 1987, the Act was amended to focus attention on Yucca Mountain, Nevada as the only potential site for such disposal. From 1987 until 2002, an extensive programme of site characterisation was undertaken to underpin various performance assessments (Rechard et al., 2014). This resulted in the site being recommended to the President by the Secretary of State for Energy in 2002. This recommendation was adopted and led to the submission of a License Application for the proposed facility by the US Department of Energy (DOE) in 2008. However, the adequacy of this License Application was strongly challenged by the State of Nevada and various other parties, who submitted over three hundred technical contentions, almost all of which were accepted as requiring oral hearings for their determination. Subsequently, the DOE attempted to withdraw its License Application, but legal considerations made this impossible, so the possibility remains that hearings on this application could be initiated in the future.

Biosphere characterisation at Yucca Mountain focused on Amargosa Valley. This semi-arid environment is about 20 km downgradient of the proposed repository location and is specified in the Code of Federal Regulations as the location where contaminated groundwater could be abstracted from a deep well and used for various purposes, including irrigation, which is extensively employed in the region, e.g. in the cultivation of alfalfa that is used for cattle feed. The rate of groundwater abstraction is specified in the regulations, as is the Reasonably Maximally Exposed Individual (RMEI) who has habits typical of those of a resident of the Amargosa Township. Thus, biosphere characterisation focused on defining land and water use in Amargosa Township and the food consumption and other characteristics of the local population as they are today and without consideration of how the site might change in future so as to modify habits, in line with the relevant regulatory requirements. A dietary questionnaire was used to determine food consumption rates. This work contributed to defining the structure and parameterisation of the biosphere assessment model adopted, which was used to compute equilibrium biosphere dose conversion factors for use in the overall, probabilistic Total System Performance Assessment (TSPA) model.

WIPP (US)

The US DOE administers the Waste Isolation Pilot Plant (WIPP) deep geological repository for the disposal of US defence-related transuranic waste (intermediate-level waste). Disposal is in a rock-salt formation in a semi-arid region of New Mexico. The repository began receiving waste in 1999 and is regulated by the US Environmental Protection Agency (EPA). The stipulated post-closure assessment period is 10,000 years. A period of 10,000 years was also originally specified for Yucca Mountain, but this was subject to a legal challenge from the State of Nevada and was increased to one million years. Site characterisation studies and performance assessments for WIPP are undertaken by DOE. Because the area is semi-arid in nature, with limited surface-water transport pathways, there appears to have been little significant quantitative evaluation/modelling of the evolution of the site, area or region. Furthermore, the limited projected release of radionuclides from the host rock means that there are no radiological impacts from assessed natural evolution scenarios. Instead, the presence of potentially economically exploitable reserves at the site has led to a focus on human intrusion scenarios (Coffey, 2012).

Site characterisation undertaken prior to construction of the repository addressed the geology, hydrology, climate, air quality, ecology, and cultural and natural resources. FEP identification and screening was used in the identification and specification of scenarios for consequence analysis. Conceptual models were developed to simulate interactions between the natural environment, the engineered structures and the wastes. Partly to meet regulatory requirements, a system was developed to maintain detailed descriptions and histories of data collection, reduction and analysis, including details of modelling code input parameters (Coffey, 2012).

The site characterisation reports that were produced for WIPP rarely distinguish between the biosphere and geosphere. The early site characterisation work dates to the 1970s and then spans the following decades, and the regulatory regime changed in the intervening period. Background data with respect to the characterisation of the biosphere are included in the final Environmental Impact Statement (EIS), and a follow-up supplemental EISs.

Hinkley Point C (UK)

The Hinkley Point C (HPC) new nuclear power station is currently under construction in southwest England. The build consists of a nuclear power station with two European Pressurised Water Reactors (EPRs).

The characterisation programme for HPC began in the 1980s and has supported various phases of the programme, including early due diligence, feasibility and design purposes. A safety assessment was also undertaken as part of pre-application engagement with the Environment Agency. Subsequent characterisation activities then supported the Development Consent Order (DCO) and Environmental Statement (ES) that reports the findings of the EIA. The EIA process is iterative, evolving and building as new data comes available.

Site characterisation in support of the EIA and ES has addressed geology, soils and land use and land contamination, hydrogeology, surface hydrology (including drainage and flood risk), air, water and sediment quality, ecology, and cultural and natural resources. Investigations will have also been undertaken for geotechnical needs. A risk-based approach was used, covering both radioactive and non-radioactive parameters for soils and groundwater etc., to inform and prioritise characterisation needs. Assessment studies were also undertaken with regard to construction impacts (e.g. noise and vibration) and transportation. Furthermore, several sites of nature conservation interest are present in the environs around the HPC site, which required Habitats Regulations assessments to be undertaken.

Nuclear Licenced Site Habits Surveys (UK)

Site-characterisation includes studies of the habits and behaviour of people living or working in the immediate vicinity of the site. In the UK, detailed studies of habits are undertaken around all nuclear licensed sites, as well as in other areas, and any geological disposal facility for radioactive waste would be such a site. These habits surveys provide details of individual habits for hundreds of persons of all ages around the site. In addition, guidance is available as to how these data should be interpreted to derive habits representative of the more highly exposed individuals in the population. For an example of the use that is made of these habits data, see RIFE (2020) and for details of the approach to be used in interpreting the habits data in prospective assessments, see NDAWG Guidance Note 7 (2013).

Graphite Pathfinder (UK)

The Graphite Pathfinder project was established in 2010 to consider the feasibility of near-surface, near-site, disposal of the wastes contained within the Hunterston A Solid Active Waste Building (SAWB) Bunkers 2-5, as a basis for determining the longer term feasibility of the near-surface disposal of core graphite waste at Hunterston A and, potentially, at other sites within NDA's ownership. The wastes considered included broken graphite sleeves (~90% of the waste by volume), metallic fuel channel components, and miscellaneous activated/contaminated items.

The primary objective of the Graphite Pathfinder project was to dispose of wastes from the SAWB Bunkers 2-5 in such a way that impacts to people and to the environment were assessed to be maintained at levels, both in the short and long-term, providing a high level of protection, based on current limits, targets and guidance, without the requirement for retrieval or other intervention measures. The ability to retrieve the waste in the future was designed into the project through the use of metallic storage containers, the NDA Radioactive Waste Management Directorate (RWMD) (now NWS) reference backfill, and the near-surface setting of the facility.

However, due to significant public reaction against the project, the NDA dropped the proposals in 2011.

Prior to the project being suspended, several scenarios were defined, assessed and reported in the preliminary Environmental Safety Case (ESC) report, which extended >100,000 years in the future. The safety arguments were advanced and substantiated using an initial set of calculations to demonstrate a post-closure safety case for near-surface disposal at Hunterston A. Additionally, waste characterisation, ground investigation, an updated groundwater flow model, engineering optimisation, and sensitivity studies were progressed to the point where a full ESC could be advanced if the project was to be reinstated.

A.2 Biosphere Data and Site Investigations

The broad approaches to biosphere investigations and data collection for the programmes that have been reviewed are summarised below, with subsequent subsections concerning site mapping and surveys (Section A.2.1) and sampling (Section A.2.2).

The need for biosphere data from a site-characterisation programme can be described in different ways depending on the overall strategy, level of ambition and stage in the repository programme. If the biosphere characterisation is to cover all aspects within a repository programme, the need will reflect defined end-users going from screening and proof of concept stage to closure. As an example, the SKB programme right from the beginning decided that all parties that had an interest in the biosphere or the "surface system" were potential end-users of data or models. This meant that safety assessment, environmental assessment, geosphere characterisation, repository design and construction, stakeholder communications and the production of a site-descriptive model were all identified as in need of data and/or understanding of biosphere characteristics. In the Swedish programme, a detailed listing was made (Lindborg and Kautsky, 2000) of the properties and processes of interest. This listing was developed through expert judgement and interviews with the above-listed end-users, together with reference to general site knowledge gained during generic safety assessments and the feasibility phase literature survey that preceded the site investigations. The list of needs was then compiled into a site-investigation programme (SKB, 2001). The programme was divided into biosphere entities and scientific disciplines by constructing a conceptual model of the sites of interest. To handle biosphere data, an existing geosphere drill-hole database was adjusted to accommodate the biosphere data. This was not optimal and a lesson from this programme is to make sure that the IT-infrastructure is in place to support biosphere data entry from the outset. A site office was established with a biosphere "activity leader" managing all biosphere investigations and field activities as part of a team of other activity leaders from disciplines relating to the geosphere.

For NWMO, the pre-closure period includes site preparation, construction, operation, decommissioning, monitoring and closure. Much of the pre-closure biosphere characterisation, modelling, assessments and data will be detailed in the environmental assessment and are not discussed in relationship to the site characterisation programme. This organisational division between EIA and site characterisation on biosphere issues is an example of a strategy that excludes the biosphere as part of the site characterisation programme and instead uses the EIA-programme for providing characterisation of the biosphere for safety assessment needs.

As with SKB, Andra committed itself to implementing a specific environmental monitoring plan on its site at Bure for every project phase during the construction and operation of the underground research laboratory. The proposed plan for the construction phase complies with the regulatory requirements but goes further by including additional investigations deemed useful by Andra. The plan was defined considering the potential impacts of the project on the physical environment (climate, air, soil and subsoil, water); the biological environment (fauna and flora); and the human environment (architecture and landscape, sound and vibration levels).

The purpose of the plan has been to detect all abnormal situations, locate them, identify their causes and implement corrective measures accordingly. The frequency of the measurement campaigns depends on the environment to be monitored. For instance, the chemical and biological composition of groundwaters and surface waters is recorded on a quarterly basis, whereas the hydrobiological quality of the Orge River is measured every six months. Radioecological monitoring is carried out once a year and the fauna (birds and mammals) are studied every two years.

During the operational phase of the underground laboratory, Andra continues to review its environmental monitoring activities on a regular basis in consultation with relevant administrations and partners (Andra, 2009). These characterisation and monitoring activities now relate to an area of around 900 km^2, centred around the location that will be used for the repository. Observation points are systematically distributed throughout this area and include continuous water quality monitoring stations, a flux tower, three biogeochemical forest stations, one atmospheric station and two agricultural stations. Satellite and aerial observations are also made across the site with data from the site being coupled to GIS data. The monitoring programme is not conducted in isolation, it is integrated with international and national networks. A memory of the programme is being established by maintaining good records and databases. The monitoring programme has been developed in relation to the landscape and so includes forests, atmosphere, soils, the hydrosphere, land use and biodiversity. Socio-economic data are also gathered (BIOPROTA, 2018).

Because the UK LLWR has been operating for many years, site characterisation is well developed and is associated with the production of environmental safety cases, of which the most recent is the 2011 ESC (LLWR, 2011a). 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.

Yucca Mountain, Nevada was identified as a potential site for disposal of US commercial and military spent fuel and high-level radioactive waste under the Nuclear Waste Policy Act in 1982. However, it was only when that Act was amended in 1987 that the main site-characterisation programme was initiated. That programme was conducted by US DOE and USGS between 1988 and 2001. This work, together with pre-existing information, led to the Yucca Mountain Site Description. There have been some subsequent further site characterisation activities but of limited extent. Although, in principle, a continuing performance confirmation programme should have been undertaken, because of the current hiatus in licensing activities and the desire of the US DOE to withdraw its License Application, this performance confirmation has not been pursued. In any event, because of the highly prescribed regulatory position relating to the biosphere, it would have mainly focused on the near-field and geosphere.

A four-step strategy, called “strategy for issue resolution” was used to define the information needed to address the principal regulatory requirements for Yucca Mountain and develop (and document) the site-characterisation process: (i) develop a preliminary licensing strategy; (ii) identify performance measures; (iii) identify information needs; and (iv) develop testing strategies to produce the needed information. This was aimed at both determining the suitability of the site for development of the planned repository and subsequently obtaining licensing.

Similarly at the operating WIPP, site characterisation and performance assessments are undertaken by the US DOE, with the site being regulated by the US EPA and requiring recertification every five years. Because only very limited releases of radionuclides to groundwater are anticipated for a repository located in a rock salt deposit, the focus has been on potential human intrusion with little significant quantitative evaluation/ modelling of the evolution of the site, area or region. The site characterisation programme at WIPP was carried out prior to constructing the repository and described the 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.

For site characterisation as part of determining a location for waste disposal at the Dounreay site, UKAEA followed a BPEO (Best Practicable Environment Option) study which was introduced by the Royal Commission on Environmental Pollution. LLW facilities are located at the northeast perimeter of the Dounreay licenced site; a location selected with a view to long-term safety considerations and the desire to minimise impacts on nearby residents from the construction and operation of the facilities. The site is sufficiently distant from the sea to ensure no significant risk from coastal erosion or marine inundation, the layout is designed to avoid major geological faults in the area, and the facilities have been located to minimise noise and visual intrusion for local residents. Further factors considered included the occurrence of protected species, archaeological sites, and the need to minimise the overall footprint of Dounreay. Moreover, siting the facilities on the land at Dounreay avoids the need to transport LLW on public roads, and is consistent with the 2010 NDA strategy on management of LLW from the UK nuclear industry to protect the public and environment.

A.2.1 Site Mapping and Surveys

One of the first tasks to be undertaken with a view to being able to plan site sampling is to produce maps and spatially distributed models showing biosphere characteristics. In the SKB biosphere characterisation programme, this was partly done during the feasibility studies that preceded site investigations. Maps describing vegetation, land and ecosystem types, topography and bathymetry, soils and Quaternary deposits, surface-water bodies and running water and giving a wetness index were produced. Aerial photographs were taken to capture the site characteristics before any activity had started and as a baseline for long-term site evolution monitoring. These first models and photographs, together with field visits were the basis for further detailed planning on sampling, surveys and equipment installation.

Another important mapping activity undertaken by the biosphere team was the compilation of a digital accessibility map in GIS, which was used (and is still used at Forsmark) to make sure that the site investigations did not disturb nature values, existing species of flora and fauna (in both time and space), wells, historical artefacts etc. This accessibility map was (and still is) also used as a planning tool to make sure that different investigations did not and do not interfere with each other.

To further strengthen the basis for site characterisation planning, discipline-specific reporting on national, regional and local biosphere characteristics was performed prior to and during the initial site characterisation phase. This included synthesis of available information on hydrology/meteorology, land use, human behaviour (present and historically), description on ecosystem types, topography/bathymetry, soils, and site history. These reports describing available information prior to site investigations were then further synthesised into a first site descriptive model together with disciplines describing the geosphere. Lessons learnt from the SKB programme show that early data compilations/synthesis (with reporting) were very useful to motivate and kick-start both the planning of site investigations as well as the site modelling, see e.g. Brydsten (1999), Larsson-McCann et al. (2002), Boresjö Bronge and Wester (2002) for examples of discipline specific reporting prior to site investigation.

An important consideration in mapping and survey studies, which may include both walk-over and aerial surveys, as well as the evaluation of satellite images, is the spatial scale over which mapping is required. Indeed, mapping and other survey activities may be required over different spatial scales. For example, the Andra programme, centred on Bure, had an emphasis on the geomorphological evolution of the environment. This resulted in a need to characterise the landscape at various scales, with the largest scale encompassing the whole of the Paris Basin and surrounding context. These geomorphological studies related to quantification of past evolution of the area, e.g. through geomorphological mapping. The geomorphological studies of the site were complemented by studies of analogue regions, numerical modelling of the physical processes involved and simulation of the evolution of the landscape under the combined influence of climatic and neotectonic processes, and conceptual syntheses of the observational data and modelling results to provide scenarios for future landscape evolution. Mapping studies were directed to interpretation of slope processes in the valleys, examining river-capture processes by consideration of palaeo-valleys, and examination of the special features of evolution of karst landscapes. Field studies included characterisation of stages of valley erosion through the examination of river terraces. Correlations of terraces between different palaeo-valleys were based, in part, on the use of electron spin resonance dating of quartz. Dating of the degree of incision of valleys used uranium-thorium dating of speleothems.

Because disposals at the UK LLWR have been on-going since 1959, there has not been a pre-site-selection mapping and survey phase. Rather, the site characterisation programme has developed continually and in response to changing needs. However, in recent years the recognition of the vulnerability of the site to coastal erosion, notably under conditions of rising sea level, has led to a focus on mapping and survey activities directed to establishing rates and styles of coastal erosion and sediment transport along the coastal frontage of the site (Fish et al., 2010).

In the case of Yucca Mountain, the detailed topographic and geological mapping that was undertaken related to the disposal site (see Stuckless and Levich, 2007; Stuckless, 2012). However, only limited characterisation was required for the biosphere because this was closely constrained by regulation. The focus was rather on a detailed survey of human dietary habits, as was required to determine the characteristics of the Reasonably Maximally Exposed Individual (RMEI) (US DOE, 2005). In the UK, detailed dietary surveys are similarly required around nuclear licensed sites. Specifically, the RIFE programme monitors the environment and the diet of people who live or work near nuclear sites throughout the UK. Each report brings together all the results of monitoring of radioactivity in food and the environment by the RIFE partners. The most recent report in the series is RIFE-25 (RIFE, 2020) and this should be consulted for details of the monitoring undertaken.

The surveys that underpin the RIFE reports provide details of individual habits for hundreds of persons around each installation, and include data for adults, children and infants. In addition, surveys are conducted of other areas of specific interest remote from licensed nuclear installations.

The main aim of the RIFE programme is to monitor the environment and the diet of people who live or work near nuclear and other sites. From this monitoring, estimates can be made of the amount of radioactivity to which the public is exposed, and specifically the amounts associated with those small groups of people who are most exposed because of their age, diet, location or way of life.

In the UK, recommendations for preferred approaches to the use of habits data in both retrospective and prospective assessments have been documented by the National Dose Assessment Working Group (NDAWG). The NDAWG specifically excluded issues relating to the disposal of solid radioactive wastes from its remit. Nevertheless, several of its guidance notes and reports contain relevant information (NDAWG, 2004; 2005; 2009a; 2009b; 2013).

The HPC programme made use of available surveys and mapping in the early stages of site characterisation, including soil surveys, historical maps, agricultural land quality and surface water quality and location and designation of conservation interest sites, including presence of protected species (EDF Energy, 2010). These desk-based studies were then used as the basis for identifying data gaps for assessment studies and informing the forward plan for surveys and characterisation activities.

A.2.2 Site Sampling

In Sweden, the SKB biosphere site sampling programme for the investigation phase was described in the general site investigation report (SKB, 2001). Furthermore, a biosphere site-modelling report was later produced that specified sampling needs and the data usage in parallelly conducted modelling tasks (Löfgren and Lindborg, 2003). Detailed planning and execution of sampling was only reported for internal purposes in task descriptions. However, the resulting wealth of information on methods and data for individual sampling activities are available as SKB P-reports, which are downloadable from www.skb.se. In brief, sampling was undertaken for water, soils/sediment and biota to cover all different types of components identified in the conceptual site model and their biological, chemical and physical properties. This was to capture site conditions of relevance to all interested parties.

The SKB programme shows that for hydrological purposes, the chemical sampling of soils and water is of high relevance. Especially, chemical characterisation (cation concentrations and oxygen isotope ratios) of different water types can be used both for the conceptual understanding of water flow paths and origins, but also may be used as proxy data for calibration of hydrological/hydrogeological numerical models. Also, sampling with the aim of analysing the physical properties of soils is needed. Soil samples for determination of stratigraphy, grain-size distribution and total porosity were required, but also undisturbed samples were needed to determine properties relevant to unsaturated zone flow (e.g pF-curves).

Posiva's biosphere sampling and characterisation programme applied a hierarchy to the spatial and temporal intensity of studies with basic data and understanding being initially collected using inexpensive survey methods over extensive areas, which then provided a foundation for targeting more detailed studies on smaller scales (Posiva, 2013a). In the biosphere characterisation and monitoring programme since the construction license submission in 2012, a key focus has been the sampling of representative fauna and flora species to derive necessary assessment data for the biota dose assessment in support of the operational safety assessment license application, in order to address the regulatory requirement for the assessment to be underpinned by site-specific data. The dimensions and mass of each sampled species were recorded and element analysis performed. Environmental media were also sampled from the ecosystems relevant to each species for element analysis to allow concentration ratios to be derived.

The NWMO biosphere programme will supplement existing biosphere data by site specific data collected in the site characterisation activities. It is unclear whether these investigations are to be part of the site characterisation plan (geological site characterisation) or, as earlier stated, part of the environmental team planning. Site characterisation will also provide additional information on local interest and habits that will contribute to the range of potential exposure groups in future site-specific assessments.

Extensive sampling is a characteristic of the Andra programme. Most recently, a key focus has been the development of an environmental specimen bank (ESB) for the Bure site. This has the objective of keeping a memory of the environment that will allow for retrospective analyses of the local food chain and bioindicator samples, as well as being used for project-specific interests. The storage of samples will also allow analyses to be made using new techniques as they develop into the future. A further aim of the ESB is to involve and inform local stakeholders through a dedicated open access visitor centre. The ESB may also support future specific programmes requiring environmental samples and could be used for the storage of samples from other programmes.

Between 2007 and 2012, the project to develop the ESB was focussed on the gathering and development of expertise, on the design and construction of the building and on the design of the sampling strategy. The facility was completed in 2013 with the first sampling campaign being undertaken in 2014 with the objective being to test the infrastructure. The first reference state monitoring programme took place in 2015.

The sampling strategy was used to inform the facility dimensions. It is intended that samples will be stored for at least 100 years. Based on the current sampling plan, the building is designed to accommodate at least 20 years' worth of samples. However, it may be necessary in the future to reduce the sampling intensity to comply with the amount of storage available.

Prioritisation of environmental samples has been based around a step-by-step process. Priority has been given to a selection of raw and processed samples representative of local production or bioindicators of the chemical quality of the environment. Costs influence the frequency of sampling and overall intensity and the sampling plan has been developed in the light of the envisaged costs. The programme will be kept under review and revised as required.

The proposed repository location is within an area of Protected Designation of Origin for the cheese Brie de Meaux and a cheese dairy is located within the reference area. This has been addressed in the sampling plan with locally produced milk being sampled. Four dairy farms have been selected along with one cheese dairy. A control dairy farm has also been selected. The current sampling frequency is four times per year with a composite annual sample for each dairy farm being created.

Andra is part of an international group on environmental specimen banks, which has been useful in informing on optimised strategies for sampling and the preservation of samples. This has helped optimise the sampling programme and informed on quality assurance of sample processing.

A.3 Site Monitoring

Site monitoring has multiple purposes and examples from around the world show a variety of strategies. However, an important goal, which is to monitor a site for increased knowledge on properties or process changes, remains the same. In the SKB programme, the monitoring started immediately when access to the site was granted, with surface-based installations measuring hydrological and meteorological parameters, chemical data on water bodies and soil as well as aerial photographs for site evolution and baseline information at a landscape level. The biosphere monitoring was planned and executed as part of a general site monitoring programme that evolved over the site characterisation period. As for site investigations, the monitoring focus and level of ambition changes when moving between programme phases. A comprehensive description of the SKB monitoring programme, strategies and suggested adjustments when entering detailed investigations and when going underground during construction can be found in Berglund and Lindborg (2017), see Figure A1.

Lessons learnt from SKB related to hydrology include the need to monitor all components of the water balance and also the storage changes. Surface and groundwater levels are often monitored as well as surface-water fluxes in streams and rivers. However, the unsaturated zone and the different components of the total evapotranspiration are traditionally not monitored. To have a base line of the unsaturated zone water content is important if a hydrological impact occurs due to construction at the site. Plants extract water from the unsaturated zone and a lowering of the water table does not automatically imply a decreased amount of plant-available water. However, monitoring the water content is a relatively cheap, but effective method to monitor changes in the water balance that might be an issue for the EIA assessment. Additionally, a local meteorological station is useful when calculating the water balance for a site. Local differences in precipitation have a large influence on the water balance which in turn is central for dose calculations and modelling of elemental transport within and between different ecosystems. See Bosson et al. (2008), Johansson (2008), Johansson and Öhman (2008) for a comprehensive description of data evaluation, quantitative modelling and interactions with chemistry to construct a hydrological conceptual site understanding.

Activity	Target species/ functional group	Start	Number of monitored objects	Number of monitored years (through 2015)	Frequency	Recent references
Wildlife monitoring	Large mammals	2002	na	4	Every 5th year	P-12-20 (Truvé 2012)
Hunting statistics	Moose	2002	na	14	Annually	P-12-16, P-12-17 (Cederlund et al. 2012a, b)
General bird monitoring	Breeding birds	2002	na	5	Every 3rd year	R-14-16 (Green 2014)
Threatened bird species	11 species	2002	na	12–14	Annually	R-14-16, P-16-04 (Green 2014, 2016)
Aquatic birds*	7 species	2002	7	14	Every second month	Adill et al. 2014, 2016, Adill and Heimbrand 2015
Threatened plant species	Fen orchid	2012		4	Annually	P-14-02, P-15-02, P-16-01 (Collinder 2014, 2015, Collinder and Zachariassen 2016)
Reptiles and amphibians	Pool frog, great crested newt and common newt	2011–13	15	3–5	Annually	P-14-02, P-15-02, P-16-01 (Collinder 2014, 2015, Collinder and Zachariassen 2016)
Artificial ponds	Chlorophyll, turbidity	2012	4	4	Monthly	P-14-01, SKBdoc 1422519 (Qvarfordt et al. 2014a, Wallin et al. 2017)
	Vegetation and invertebrate fauna	2012	2	4	Annually	P-14-03, R-15-07, R-16-03 (Qvarfordt et al. 2014b, 2015, Wallin et al. 2016b)
Ponds	Chlorophyll, turbidity	2010	4	4	Annually	P-14-01, SKBdoc 1422519 (Qvarfordt et al. 2014a, Wallin et al. 2017)
	Vegetation and invertebrate fauna	2012	2	4	Annually	P-14-03, R-15-07, R-16-03 (Qvarfordt et al. 2014b, 2015, Wallin et al. 2016b)
Lake	Chlorophyll, turbidity	2002	4	14	Monthly – 4/year	P-10-40, SKBdoc 1459924 (Nilsson et al. 2010a, Wallin et al. 2016a)
	Fish	1991, 2001, 2004	2	3	na	P-04-06 (Borgiel 2004a)
Sea	Chlorophyll, turbidity	2002	3	14	Monthly – 4/year	P-10-40, SKBdoc 1459924 (Nilsson et al. 2010a, Wallin et al. 2016a)
	Macrofauna*	1985	2 + 4 (ref. area)	31	Annually	Adill et al. 2014, 2016, Adill and Heimbrand 2015
	Fish*	2003	1 + 1 (ref. area)	13	Annually	Adill et al. 2014, 2016, Adill and Heimbrand 2015
Stream	Chlorophyll	2005	4	11	Monthly – 4/year	P-10-40, SKBdoc 1459924 (Nilsson et al. 2010a, Wallin et al. 2016a)

Figure A1: Part of biosphere monitoring (ecology and nature values) in the SKB monitoring programme. Illustration from Berglund and Lindborg (2017). References listed are downloadable from www.skb.se.

Posiva's surface environment monitoring programme has similarly progressed over several decades with regular surveys and monitoring activities undertaken across different terrestrial and aquatic biotopes in and around Olkiluoto Island. A reference area was also established for the study of biotopes that do not currently exist on the island, but are expected to evolve in the future with continued post-glacial land uplift (e.g. mires, rivers and lakes). Surveys of animal species present in different biotopes have been performed (e.g. birds, small mammals, fish and invertebrates) along with annual surveys of game statistics through dialogue with local hunting groups. In addition, intensive monitoring plots were established to further understanding of specific biotopes. For example, forest monitoring plots were established in 2005 that have been subject to both continuous and periodic monitoring to develop understanding and derive data on biomass, productivity, hydrological and element cycling in forest biotopes and how variations in climate influence forest systems (Aro et al., 2018a). Mire plots have also been studied to similarly develop understanding and provide data on biomass, geochemical and physical properties and element concentration ratios and distribution coefficients (Aro et al., 2018b).

In the NWMO programme, environmental monitoring of the near-surface physical and biological characteristics of a candidate site is initiated with field work, for example as part of permissions for borehole drilling. It will expand with the site characterisation activities at the preferred site to support the initial approval of the project. It will then develop into a mature programme that supports the operation of the facility (i.e. confirms that it meets the design and licensing basis), and eventually its closure. During the site selection and characterisation phase, monitoring would be in the context of developing baseline information on the site, from geological conditions to surface conditions.

Site monitoring is a process that continues after initial site characterisation activities and informs an understanding of how the site varies and changes with time, either because of natural processes or due to human activities that may, or may not, be associated with development of waste disposal facilities on the site. Changes occurring at the site or in its vicinity may be of specific interest to the local population and it is notable that when Andra initiated their programme to develop an underground laboratory at Bure, an early action was to set in place a radio-ecological monitoring programme around the site at the request of the CLIS (Commission locale d'information et de suivi), the local information and oversight committee for the Laboratory. At the present day, monitoring at the site is on-going and a collaborative network has been set up involving numerous organisations, both within France and internationally, that have expertise in different aspects of environmental survey programmes, from environmental banking and databases through to ecosystem monitoring at a territory scale. This is important for understanding different scales (local, regional and global) and for inter-comparisons. For example, soils from the study area have been compared with soils across France to gauge soil quality in the area. Earthworm biodiversity has also been compared against national data, showing that the diversity is within the national range for the number of species. Atmospheric C-14 surveys have also been integrated, with comparisons made against reference data from Switzerland and the Netherlands.

In the case of Yucca Mountain, monitoring would have focused primarily on issues such as infiltration into the mountain, as determined by a set of rain gauges, and downward percolation, as determined by seepage into the exploratory drifts and associated experimental niches. However, because of the suspension of the license application procedure, US DOE ceased all activities at Yucca Mountain, including the monitoring activities that would have been undertaken as part of the performance confirmation programme.

At the LLWR, sampling of local environmental media for radionuclides and non-radioactive pollutants is on-going as a requirement of the classification of the facility as a licensed nuclear site. Similarly, habits surveys are conducted at regular intervals. However, an important focus of the programme is the monitoring of coastal processes relevant to the potential long-term erosion or inundation of the site.

Baseline surveys of the nearby coastline were carried out in 2002 and 2009. Survey data were used to generate an understanding of the recent evolution of the coastline and as input to the development of a conceptual understanding of coastline evolution. Current sediment transport processes on the nearby beaches are mainly due to wave action, and sand has been shown to be mobile under wave action in the vicinity of the LLWR. However, the coastal system at Drigg is described as 'inherently robust' thanks to its local sediment source and the coarse grade of sediment on the shore which acts to dissipate waves and is not very mobile. The dune spit is subject to accretion and erosion in places. The sand dune complex in the area forms an important unit. As the dunes are formed of non-cohesive material, they adapt to changing hydrodynamic conditions over short timescales.

A.4 Site Modelling

Site modelling is the synthesis of available site information and is a backbone in a repository programme upon which all other tasks depend. Depending on the national programme context and overall strategy, different methods can be distinguished. However, a common task for the site modelling is to describe the natural system upon which the safety assessment calculations and the safety case arguments rely.

Site modelling is below divided into two different topics that are strongly related, but their differences and dependencies needs to be recognised, site-descriptive modelling and research models.

A.4.1 Site-Descriptive Modelling

In the Swedish programme, the site-descriptive modelling strategy (the acronym SDM was introduced by SKB) was developed in the early years of the millennium (Löfgren and Lindborg, 2003) and the first versions were generic descriptions of the Forsmark and Laxemar/Simpevarp sites prior to the site-characterisation phase (SKB, 2002). As the Swedish programme moved forward, new model versions were reported, and the methodology improved together with the quality of data up until the end of the site-investigation phase (see SKB, 2008; 2010; and Lindborg, 2010). Iterations of investigations, data freezes, safety assessments and reporting fostered a whole generation at SKB on what to achieve and how to do it. See Andersson (2003) and Andersson et al. (2013) for a summarised description of the SKB SDM-methodology, illustrated in Figure A2 and Figure A3 where scientific disciplines are integrated into a common conceptual and distributed numerical site understanding with hydrology as main link between the geosphere and the biosphere.

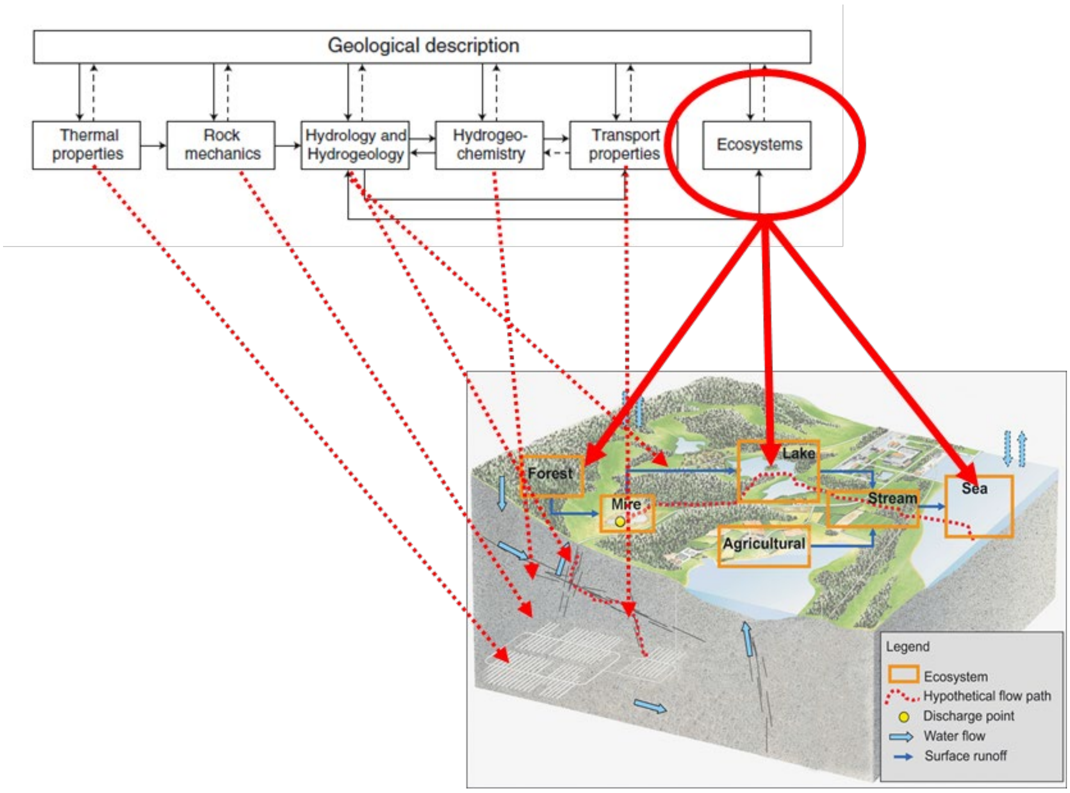

Figure A2: Overall site modelling strategy at SKB displayed on a generic conceptual site model. Original illustrations from Lindborg (2010) and Andersson et al. (2013).

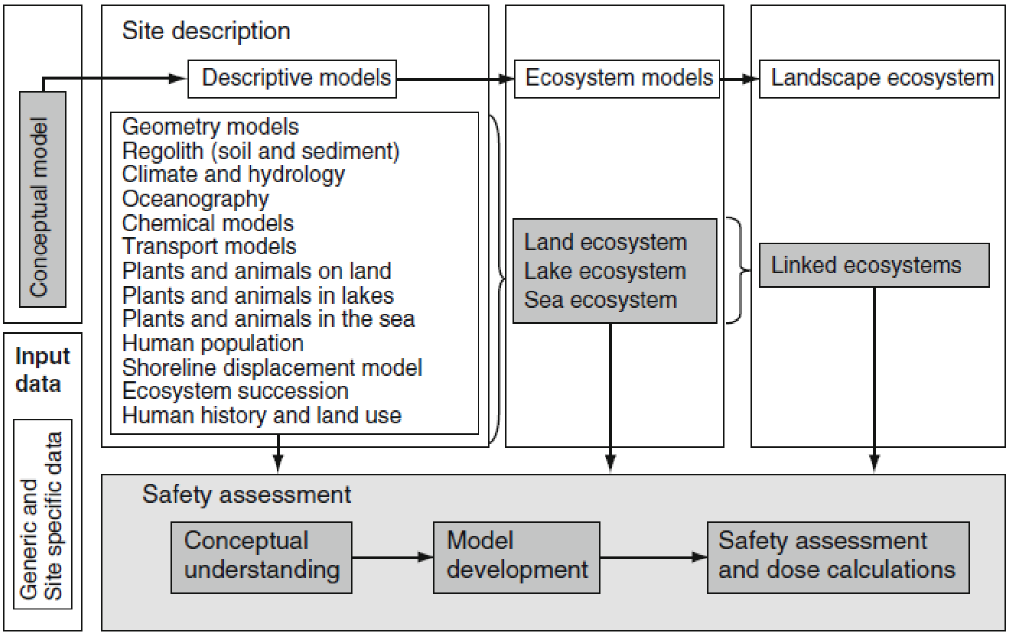

Figure A3: Biosphere or "surface system" site characterisation strategy at SKB as described in Fig. 9 in Andersson et al. (2013).

Andra employ a diversity of climate, geomorphological, hydrological and hydrogeological, and ecosystem models in developing their understanding of the Bure site and its wider environmental context.

In respect of climatology, the approach to climate is to use palaeoclimatic reconstructions based on palaeoenvironmental datasets as a basis for demonstrating that mathematical models of climate evolution can be used to establish patterns of climate change both at the global and local level. In order that they can be used for this purpose, the palaeoenvironmental datasets should be sufficient to understand fluctuations in climate on different timescales and at different spatial scales. Once validated against past climate data, the models can be used to project variations in future climate considering changes in insolation and major multi-millennial forcings such as those due to emissions of carbon dioxide due to human activities.

Palaeoclimatic evolution is addressed on timescales covering the last 50 million years, the last 5 million years and the Quaternary. A long Quaternary timescale is adopted, so the beginning of the Quaternary is set at 2.6 million years (Ma) before present (BP). For the Quaternary, emphasis is placed on the palaeoenvironmental synthesis reported in BIOCLIM (2004). However, more recent work relating to the sediment sequences at La Grande Pile and Les Echets is considered. Various more local studies, such as sedimentary sequences in Lorraine covering the last 16,000 years, loess in Alsace and the Ardennes, multi-proxy studies in the St Omer Basin emphasising fluctuations of climate during the Holocene, and studies on karst landforms of the Meuse/Haute-Marne region dated using speleothems have also been used.

In respect of geomorphology, Andra has emphasised the construction of numerical 3D models to support hydrogeological modelling of the evolving environment; and the physical characterisation of surface environments associated with different types of biosphere corresponding to various sets of climatic conditions.

Work on periglacial environments includes studies of analogue regions and modelling of the processes involved, e.g. permafrost development. Spatially distributed modelling of both past and future permafrost development in the Paris Basin was undertaken. Detailed consideration was given to the effects of permafrost at depth, e.g. hydraulic fracturing, and on surface systems.

For karst landscapes, specific consideration must be given to erosion by sub-surface dissolution. This is dealt with at length in the Andra report, but mainly in the context of the formation of subsurface cavities rather than evolution of the biosphere.

In respect of hydrological and hydrogeological modelling, initial modelling studies by Andra were undertaken in 2D to investigate the effect of blockage of the infiltration of meteoric waters by frozen ground effects and thermohydraulic modelling of the formation and retreat of permafrost was also undertaken. A discussion of qualitative changes in surface-water availability was included.

Modelling of the future evolution of the hydrogeological system under the influence of climatic and geomorphological change was also undertaken. A significant conclusion from these various studies is that neither the geomorphological evolution nor permafrost penetration has significant effect on hydrogeological conditions in the Callovo-Oxfordian host rock.

In respect of ecosystems, the approach adopted by Andra to characterising their future evolution is described as a combination of the use of information on natural analogues together with numerical modelling to simulate ecosystem evolution at large temporal and spatial scales. Natural analogues include some existing at the present day, e.g. in Scandinavia and Canada for boreal conditions, but also those defined by palaeoenvironmental reconstruction. The important roles of archaeological material and lacustrine sediments in palaeoenvironmental reconstructions are highlighted, but the spatially and temporally discontinuous nature of such records is identified as a problem. Distortions in the record are also identified, e.g. the spectrum of faunal remains found at archaeological sites is influenced by human hunting capabilities and dietary preferences.

A detailed discussion is provided of analogue soils in warmer conditions, and this takes account of the characteristics of the underlying karst parent material, e.g. by referring to the Terra Rossa soils from Cuba. For boreal conditions, emphasis is placed on podzolisation and, for frozen steppe conditions, on the possible presence of chernozems.

For the reconstruction of vegetation characteristics, emphasis is placed on pollen records, e.g. from La Grande Pile and Les Echets. It should be noted that the long pollen records from La Grande Pile and Les Echets are relevant at a regional scale and do not apply directly to conditions local to the site.

For the characteristics of Late Glacial and Holocene fauna, the rapid changes in faunal composition in the Late Glacial (16 to 13 ka BP) are emphasised and a brief discussion is provided of archaeological evidence from the Late Palaeolithic (Magdalenian) and Neolithic periods.

In the context of modelling, several complementary approaches are identified. These comprise: detailed mechanistic models that explicitly represent processes such as predation and competition; overall models of communities taking into account positive interactions (facilitation, cooperation), negative interactions (competition), neutral interactions (commensalism) and available resources; large-scale models of food chains based on consideration of functional groups and not on individual species; representations of the movement of populations under changing climate conditions; and representations of chronic human impacts.

For modelling changes in large-scale patterns of vegetation, reliance was placed on coupled climate-vegetation modelling, such as that adopted in BIOCLIM (2004). Local changes in soils and vegetation appear to be addressed only descriptively.

A.4.2 Research Models

This is about the modelling and usage of site data related to specific research questions or scientific collaborations with universities not direct related to the site description. This type of site modelling is common at SKB and is a good example of how to use site understanding to target specific issues. The understanding of these issues can strengthen the overall site understanding and can be incorporated into the site-descriptive model (SDM). One example is denudation and the question as to how much of and how rapidly the surface is eroding over time at Forsmark. This topic was not part of the site characterisation but was performed within the research department to strengthen a poorly supported assumption in the safety assessment. These types of research tasks are also a good way to integrate programme parts and increase the insights on site characteristics in safety assessment and research teams.

In the case of the LLWR, calibrated site-scale groundwater models have been developed using ModFlow, FeFlow and, for the 2011 ESC, ConnectFlow (Hartley et al., 2011). The ConnectFlow model uses a 3-D geological lithofacies model of the site 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.

At Yucca Mountain, 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.

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 characterise geological and hydrological features and properties. Geochemical and isotopic studies were conducted to characterise 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 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.

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) system. Studies included field and laboratory tests. Infiltration studies collected information to characterise 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. In parallel, the State of Nevada sponsored the development of a quantitative geomorphological model of the erosion of the uplifted, tilted block that comprises Yucca Mountain (Stüwe et al., 2009).

A.5 Programme Interaction and Integration

This topic is probably the most problematic area within current national programmes and a lot of lessons can be learnt. A typical on-going radiological waste management programme within an implementing organisation is divided into: design/construction, communication, human resources, economy and management, environmental assessment and applications, research/development and safety assessment, site characterisation/field office. The task of characterising a site or, for that matter, the biosphere component of that site, may easily get lost within the bigger picture. It is therefore of great importance that the biosphere site-characterisation task has a high profile within an overall programme plan. At SKB, a two-year project was undertaken prior to the site investigations to produce a site investigation plan (SKB, 2001) that covered all aspects and possible interactions in the form of internal needs and deliveries. It was also recognised that individual scientific disciplines should form information and discussion groups with representatives from different functions within the repository programme. The existence of so called "Net-groups" (GeoNet, SurfaceNet, ChemNet and HydroNet) guaranteed an informal but nevertheless effective tool for integration and information flow. Amongst people earlier involved in the SKB site characterisation programme, the Net-groups are always mentioned as one of the more successful forms of communication.

Posiva have fostered strong interactions between the biosphere assessment team and, for example, local ecology experts involved in the biosphere characterisation programme. Regular meetings have been held at which ecology experts were briefed on assessment approaches and data needs and members of the assessment team participated in field characterisation and sampling campaigns.

In the NWMO programme, no formal planning is in evidence in published material that facilitates interaction or integration between the biosphere site characterisation and other parts of the programme. A straight link between the environmental assessment and the need for biosphere data can be recognised, but no overall planning on site characterisation with biosphere aspects can be found. Given that the programme is in development, this may be a misleading conclusion and a more integrated characterisation scheme may have to be planned and implemented.

Integration of studies across disciplines is an important consideration in the development of site-descriptive models, but there is also a need for integration with the overall repository development programme. As emphasised in previous sections, in the Andra programme, monitoring is not conducted in isolation, but it is integrated with international and national networks. A memory of the programme is being established by maintaining good records and databases. The monitoring programme has been developed in relation to the landscape and so includes forests, atmosphere, soils, the hydrosphere, land use and biodiversity. Socio-economic data are also collected.

A collaborative network has been set up involving numerous organisations both within France and internationally that have expertise in different aspects of environmental survey programmes, from environmental banking and databases through to ecosystem monitoring at a territory scale. This is important for understanding different scales (local, regional and global) and for inter-comparisons.

At the LLWR, the long period of operation of the site has resulted in a developing understanding of the various aspects of the system, with the existing ESC providing a context into which new findings can be integrated as they arise.

A.5.1 Geosphere Site Characterisation

The flow paths from a deep geological repository to the ground surface are governed by the regional and local topography and the hydraulic connectivity in the bedrock and overburden. The properties and distribution of groundwater recharge and discharge areas in the soil-bedrock interface influence the location of the exit points. The groundwater recharge and discharge are in turn linked to the groundwater-surface water interaction and atmospheric processes including precipitation and evapotranspiration. Therefore, an integrated approach must be applied in the hydrological-hydrogeological site modelling. The shallow groundwater system and the surface water must be linked to the deeper groundwater system in the bedrock. Due to different processes and timescales several models might have to be established for the purpose and question at hand. However, the water flows from ground surface to repository level should be seen as one integrated system, which also highlights the need for an integrated approach to the background media in which the water is moving. The bedrock models and the regolith (overburden) model must be linked and a detailed description of the upper bedrock is of high importance. Due to casing of boreholes, the upper part of the bedrock is typically not characterised. It is of high importance to include upper bedrock characterisation in the investigation programme. A recently published article by Åberg et al. (2021) highlights the need for a detailed description of the upper boundaries when modelling the groundwater recharge and discharge patterns.

A.5.2 Safety Assessment

In the SKB example, the safety assessment team was heavily involved in the site characterisation planning as well as its execution and synthesis. A modelling team was assigned as the interface between field activities and end-users such as safety assessment. In fact, most members of the site modelling team were also responsible for parts of the safety assessment and could therefore ensure that needs associated to safety after closure were handled correctly. One important lesson learnt from the SKB programme is the need for integration between programme parts related to system understanding and a management culture that promote engagement in the overall programme.

One good example of the above is the consideration in the dose modelling for Forsmark of the relatively rapid site evolution in the surface system. This led to a dose model development that was able to handle natural landscape succession. See e.g. Lindborg et al. (2013) and Avila et al. (2013). The argument here is that you must understand the site you model, and the interaction and, if possible, integration between programme parts undertaken during the site investigation.

In the case of NWMO, the post closure safety assessment model (NWMO, 2012) includes representations of forest, wetland, aquatic and agricultural features. Contaminants may migrate through these systems (e.g., via root uptake into vegetation) and subsequently be available in the food chain. The reference model ecosystem represents a constant temperate climate with conservative assumptions applied to assess the potential dose consequences to a small self-sufficient farming family. In the NWMO programme, on-going literature review and participation in international programmes (such as BIOPROTA[11]) will continue, with the objective of ensuring the existing biosphere modelling approach remains appropriate and conservative. Improvements and adaptions will be implemented if warranted.

At Yucca Mountain, the Total System Performance Assessment (TSPA) that is adopted for radiological assessment studies makes use of the detailed process models that have been developed for research and site characterisation purposes. These detailed models can be incorporated directly within the TSPA using 'DLLs' (Dynamic Link Library) or simplified abstractions of these models can be incorporated. Alternatively, the detailed process models can be used to generate look-up tables that can be included within the TSPA, e.g. as Microsoft Excel® workbooks.

Specifically, in relation to the biosphere, a primary output of the site characterisation programme was the biosphere component of the TSPA, implemented in the 'ERMYN' biosphere model (Bechtel SAIC, 2004). Performance (safety) assessment performed in support of site licensing was based on the application of biosphere dose conversion factors. These describe the annual dose from all potential exposure pathways that the Reasonably Maximally Exposed Individual (RMEI) would experience and were used to calculate predicted annual total doses for comparison with the regulatory compliance targets.

[11] www.bioprota.org

A.5.3 EIA and Control Programme

Lessons learnt from SKB related to the consideration that the EIA-related modelling started relatively late, with a major emphasis on the EIA process and not site understanding, and it did not really interact with the site-modelling team at SKB. This turned out to be problematic, since a lot of models developed for safety assessment purposes were used in the EIA assessment. With the site-descriptive model as a platform, other models need to be developed for the issue at hand. The models developed for analysis of groundwater drawdown of a repository were also used in EIA applications. This led to a very conservative case, with a fully open repository, being the case discussed and used in the EIA assessment. A more realistic case with a stepwise construction of the repository would have been preferable. The consequences of hydrological drawdown were highly overestimated in the SKB EIA assessment. Having stated the above, one should realise that the Swedish KBS-3 hearings in the environmental court relied heavily on the planning undertaken with safety assessment goals, and that a well-established biosphere characterisation can serve several purposes.

In addition to the radiological impact assessment reported in the License Application for Yucca Mountain, an Environmental Impact Assessment was undertaken by the US DOE. This was determined to be incomplete in some respects and was complemented by the US Nuclear Regulatory Commission (NRC) in a Supplemental Environmental Impact Assessment that made use of some of the models and data used in the TSPA.

A.6 Organisation and Staff Competence

In the Swedish programme conducted by SKB, a biosphere group was formed with four-to-six SKB employees with a surrounding external base of 20-50 consultants and individuals from academia (the size of group increased over time). This group consisted of highly skilled consultants or scientific researchers with competences in ecology/limnology, soil sciences, hydrology, biogeochemistry, and landscape process modelling and worked with site characterisation, safety assessment and environmental monitoring and EIA-issues in parallel. Organisationally, the biosphere group was divided between different units at SKB, such as safety assessment, site investigations and site modelling units. For historical reasons, the safety assessment unit was initially, during the planning stage, in charge of all biosphere issues. As the programme moved into the site characterisation phase, a new site modelling unit took over the task to produce site models and SDM-reports and a site/field office was established to produce operational investigation programmes and to execute the site investigations. Typical staff competence subject areas relevant to gaining and maintaining site understanding are shown in Figure A4.

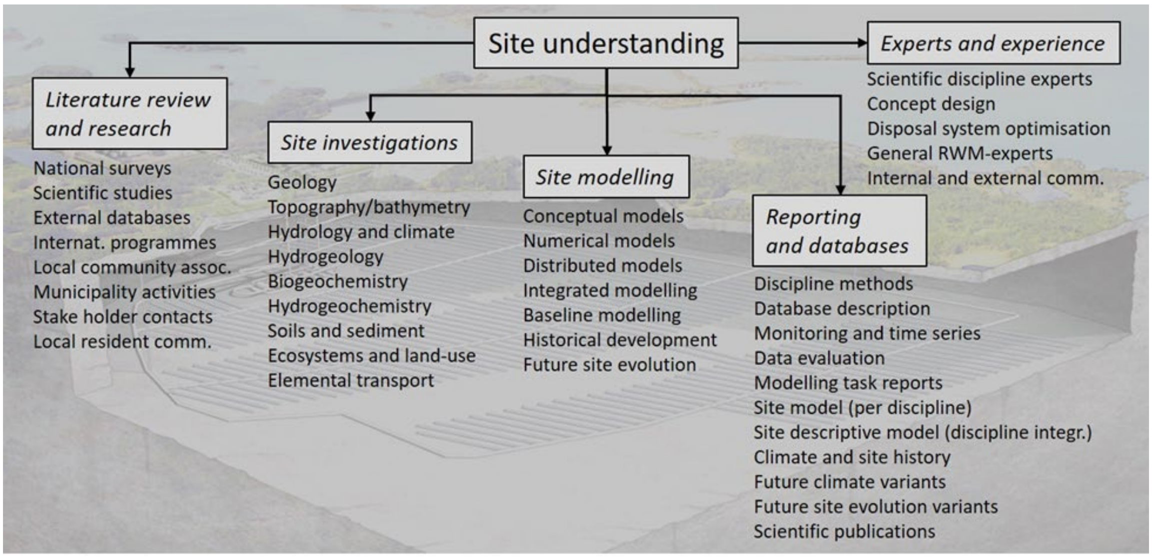

Figure A4: Illustration showing parts and associated tasks/competences involved in the SKB site characterisation programme. Illustration taken from Lindborg et al. (2021).

A.7 Stakeholder Interactions

Stakeholder interactions is a broad subject that for communication-type purposes should be divided into groups. These groups could be: International arena, Regulatory bodies, Municipalities and regional authorities, Local inhabitants and associations, Universities and Antagonists (to learn about their issues and better support the case). Depending on the stakeholder involved, the communication requirements and methods needs to be adjusted accordingly.

The topic has proven to be of great importance and the biosphere site characterisation work can be extremely useful when communicating with stakeholders. In some examples, tasks were undertaken with the primary aim of demonstrating to stakeholders that the programme knows about and understands site conditions. Therefore, this is a high-profile subject when arguing for overall confidence in the repository programme and its results.

For example, the biosphere site characterisation at SKB initiated from the outset cooperation with local associations with interest in the site (bird watchers, fishing clubs, hunters, etc.). This cooperation led to data gathering useful for both parties and an understanding of each other’s questions and needs. During the site characterisation, many seminars with question-and-answer sessions were performed. These seminars typically described results gained from the investigations and modelling. Seminar topics like animal population surveys/monitoring, Forsmark landscape development and climate modelling were covered and generated a lot of interest. A lesson learnt from these seminars was that it is equally as important to listen to the "stakeholder" as it is to present the programme case. This to ensure that people are made aware that their ideas and thinking are appreciated and make a real difference in the programme. Another lesson learnt is that there are a lot of skilled people living at the site who are interested in the programme. The strong message from these interactions was never underestimate the public knowledge and stay humble. This soft topic has, therefore, potential to contribute to a successful programme (or halt it) as much as a well (or poorly) performed safety assessment.

During the environmental court hearings in Sweden, the scientific platform and the wealth of peer reviewed papers available from the biosphere programme was a huge advantage. In many discussions it was an advantage to be able to refer to peer-reviewed material and not only SKB-internal reports. This strategy by SKB, to publish methods and results from the site characterisation in scientific journals, should be seen as a good example for other national programmes to follow, see e.g. AMBIO (2006) and Kautsky et al. (2013).

In terms of stakeholder interactions, Andra has stated that, during the operational phase of the underground laboratory, it will review its environmental monitoring activities on a regular basis in consultation with relevant administrations and partners (Andra, 2009). Also, in the context of on-going monitoring, Andra has noted that changes in the environment are expected to occur over time. For example, construction of the long-term observatory at the site has resulted in changes to the surface environment, and further impacts will result from construction of the repository and associated infrastructure. There will also be changes not related to the repository programme, such as those associated with climate change, social change and changes in agricultural practices. The monitoring programme aims to integrate these different aspects within a scientific approach that will also address local perceptions and expectations about the environment from local stakeholders. In this context, the CLIS (Commission locale d'information et de suivi), the local information and oversight committee for the laboratory, is expected to play an active role. A similar role is played by the West Cumbria Sites Stakeholder Group (WCSSG). The WCSSG was originally formed to replace the Sellafield Local Liaison Committee (SLLC). The change reflected the fact that there were several nuclear licensed sites in the area and was intended to emphasise the importance of engagement with the community, encouraging input in discussions and consultations from all stakeholders. The organisation and ownership of sites has since changed and the WCSSG has changed to correspond, with re-organisation of its sub-committees, but the aim remains the same.

The WCSSG is an independent body whose role is to provide public scrutiny of the nuclear industry in West Cumbria. The group, which includes representatives from local government, regulators, unions and community groups, meets quarterly. Its six working groups scrutinise detailed aspects of the Sellafield and LLWR sites as identified in the site performance plans, including operational issues, environment health, emergency planning and socio-economic impacts. The public is invited to attend all meetings, which are held in locations that are freely accessible to members of the public and press (https://wcssg.co.uk/).

For the Dounreay project, dialogue with stakeholders has been a significant input to decisions on the overall LLW management strategy at Dounreay. One of the Planning Conditions concerns implementation of a package of community support measures, aimed at socio-economic development of the area around the Dounreay site and NDA has committed to pay £4 million to the fund.

A.8 Programme Roadmaps

A programme road map can be found for many national programmes and is often constructed in different levels of detail. A high-level roadmap is often used to show the programme milestones or major phases. For site characterisation, and especially the biosphere component of that characterisation, less available information is available. The SKB spent fuel programme has produced planning documents that can be of use to understand how the work was performed and major deliveries needed. See e.g. SKB (2008) and Figure A5 that show a flow diagram with information exchange and the main technical activities. The site-descriptive modelling shown in the figure incorporates the biosphere characterisation. In Figure A5, note that programme components in need of site characterisation output are used to show the information flow and that the main products to end users are shown for each iterative cycle.

Another timeline produced by SKB during the planning of detailed site investigations is seen in Figure A6. This timeline shows the programme phases, applications and associated tasks for programme parts. It shows a similar approach to mapping the development of the site descriptive model (SDM) as illustrated in Figure A5 but without showing explicit deliverables. The focus in Figure A6 is instead on the development of site understanding in relation to programme phases and overall programme milestones.

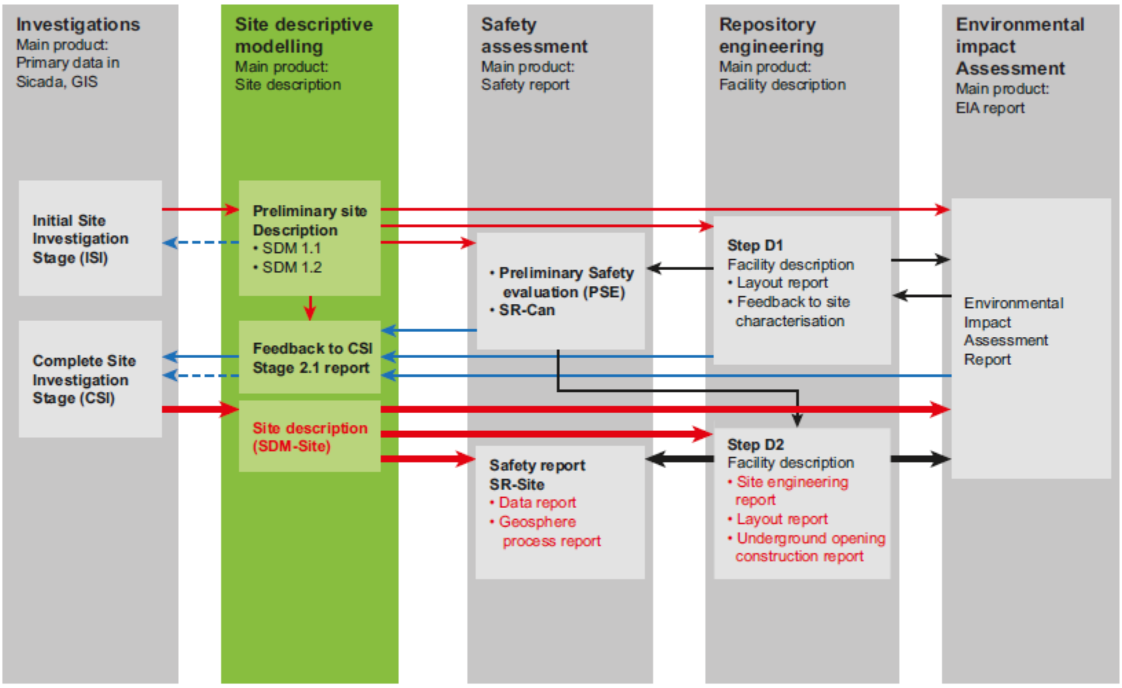

Figure A5: Information flow diagram showing site characterisation in green with a timeline going from top to bottom and relations to other programme parts as arrows. From SKB (2008) (SDM-Site Forsmark)

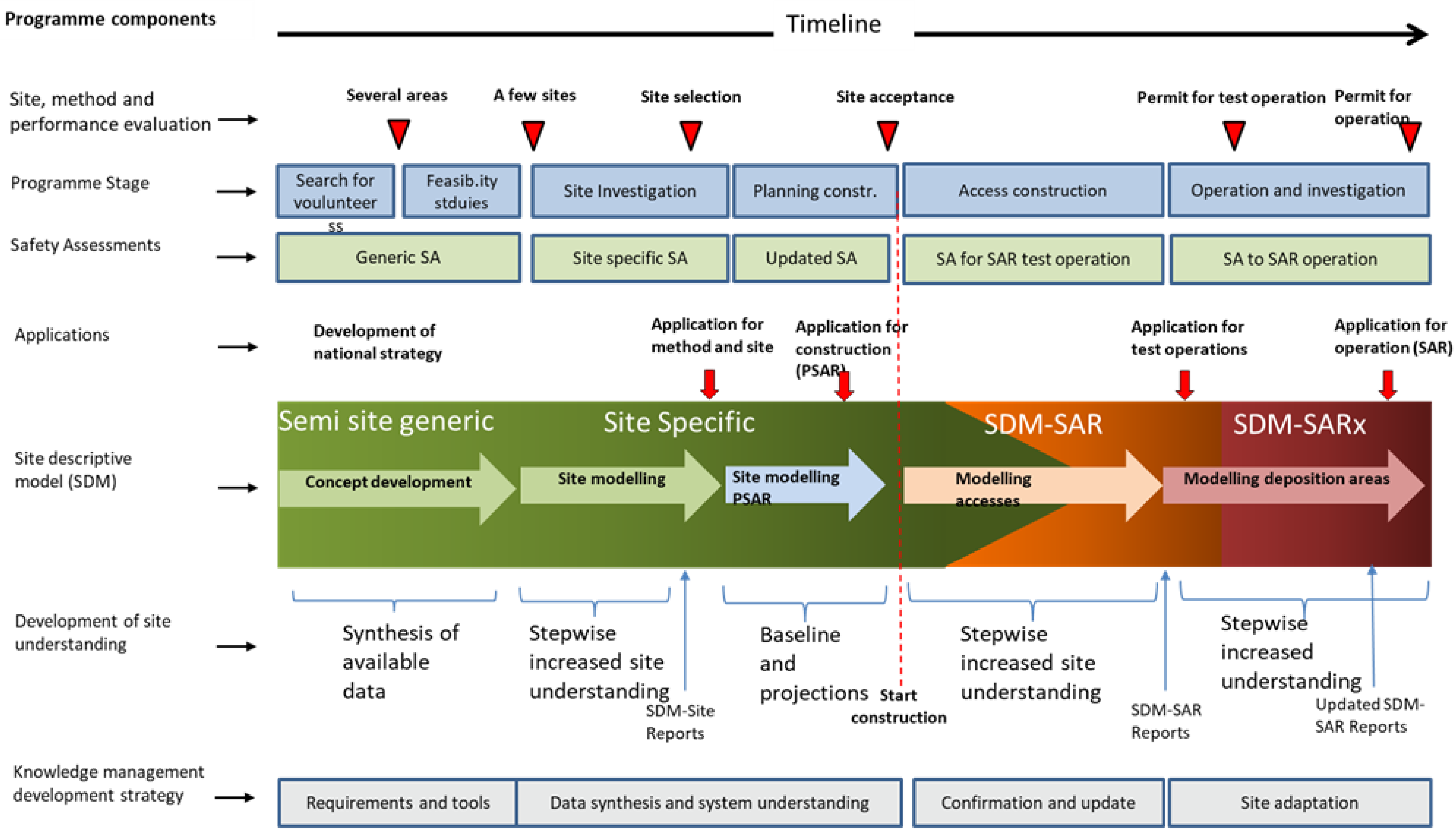

Figure A6: Timeline for site descriptive modelling and site characterisation reporting (SDM) with associated programme parts during construction of KBS-3 accesses at Forsmark. Original figure taken from SKB planning document (unpublished).

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