4.1.3 Biosphere model, Domain Insight

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Overview

This domain is an integral part of the wider sub-theme directed to site description. It relates to the characterization or confirmation of surface ecosystem properties at the present day, but also to the obtaining and applying of data relevant to making projections of the potential evolution of surface ecosystem properties in the future. Thus, although the focus is on characterization, the information and approaches adopted are closely related to assessing how future climate change and landscape development would affect surface ecosystem properties.

Keywords

Ecosystem, community, population, landform, catchment, hydrology, hydrogeology, hydrochemistry

1. Typical overall goals and activities in the domain of Biosphere models

This domain addresses the characterization or confirmation of surface ecosystem properties and their potential evolution in the future. Such characterisation will be ongoing throughout the whole repository development programme from site investigation through to closure and to any post-closure monitoring or performance confirmation programme that is implemented. Site characterisation is required for various purposes. It informs the development of an environmental impact assessment and hence the production of an environmental impact statement, as is required for a wide range of types of development. However, it also informs the approach adopted to assessing the radiological and other impacts of operation of the facility, and the post-closure impacts that are projected to arise. In general, surface ecosystems are not regarded as a barrier to the transport of radionuclides from the disposal system, but they are considered as the domain in which radionuclide fluxes from the geosphere are interpreted in terms of annual effective doses to humans and dose rates to non-human biota. This requires consideration of both the transport and accumulation of radionuclides in environmental media and the resultant exposures of organisms both from external irradiation and incorporation of radionuclides in their tissues and organs.

The overall aim in this domain is to produce a multi-disciplinary conceptual model of the surface environment at the site supported by quantitative data that is suitable for informing an environmental impact assessment and that provides an adequate basis for developing or adapting a mathematical model to represent the transport and impact of radionuclides and other contaminants in the environment. This aim is achieved by various domain-specific studies (e.g. in geomorphology, hydrology, hydrogeology, hydrogeochemistry and ecology) integrated within a programme structure that ensures effective communication between specialists working in each of the domains. Furthermore, because mathematical modelling is integral to interpreting the data and applying them to make projections of future conditions, there is a requirement to ensure effective communications between modellers, experimental researchers, and field staff.

At the site-selection stage, the conceptual model of the site is likely to be developed mainly based on desk-based studies. Thus, existing map information will be fundamental and will include topographic and bathymetric data, surface drainage information, depth and characteristics of unconsolidated deposits (soils and sediments), land use and demographic information, and information on ecologically sensitive or protected areas (e.g. Natura 2000 sites). Time-series data may also be acquired, e.g. meteorological records from local weather stations, groundwater levels in boreholes and stream-gauge records. These data will provide a foundation upon which subsequent site-specific field and laboratory investigations can be based. A particular focus is likely to be on characterising interactions between surface waters and groundwaters, including the definition of recharge and discharge areas within a catchment. At a later stage, these data could inform the development of a 3D hydrogeological model of local surface-water catchments.

Because assessment modelling in the surface environment is typically focused on the transport, accumulation and dilution of contaminants, the natural spatial scale for characterisation is the local surface-water catchment. However, because there is an interest not only in the surface ecosystems currently present, but also those that may exist in the future, it may be appropriate to characterise a larger area, because there may be features in that larger area that are suitable analogues for features that may develop at the site in the future. For example, at Forsmark on the Baltic Coast of Sweden, land uplift is causing the area to emerge from the sea on a timescale of thousands of years. Therefore, studies of the development of lakes between the current coastline and the location of the coastline some thousands of years ago provides insights into how lakes at the site are likely to develop in the future. Such analyses, substituting variations in space for variations in time are common in geomorphological analyses.

It should also be recognised that future discharges of contaminants from a repository may occur at locations a substantial distance from the repository footprint and that it is important to ensure that both the site itself and potential areas of discharge are suitably characterised. The discharge areas should be characterized through the analysis of the interactions between groundwater and surface water. Measurements of groundwater and surface water elevations will allow estimates to be made of fluxes of water that can be complemented with measurements of those fluxes across the groundwater/surface water interface using seepage meters. Also, electromagnetic surveys and tensiometers may be used to evaluate seasonal changes in water saturation in the vadose zone. The information can be integrated into coupled surface water/subsurface water models to reproduce the evolution of the systems and to perform projections into the future.

When site investigation commences, field studies of surface ecosystems can be undertaken. These field studies should be undertaken without delay because the acquisition of long time series may be an important consideration. This is clearly the case for meteorological and hydrological records, but it may also apply in less obvious contexts. For example, at a coastal site, repeated Lidar scanning of the cliff-line may be useful in providing estimates of erosion rates. Likely activities include:

- Installation of a local weather station to complement data from the wider national network
- Measurements of elevation and offshore water depths to inform development of a Digital Elevation Model (DEM)
- Soil and sediment mapping from trial pits and boreholes to inform development of a 3D map of the superficial deposits
- Measurements of the hydrological properties of soils and sediments, including measurements on intact soil cores and in situ
- Installation (as required) of boreholes to measure water-table elevation and tensiometers to determine soil moisture content
- Installation (as required) of gauging stations to measure stream flows
- Development of a spatially distributed model of the hydrology and near-surface hydrogeology of the site
- Ecological mapping of the site, including mapping of rare or endangered species
- Geochemical characterisation of soils and sediments, and hydrogeochemical characterisation of surface waters and near-surface groundwaters

In addition, at some sites, it may be possible to obtain palaeoenvironmental data to characterise the history of the site and throw light on potential future changes in its characteristics. For example, pollen data from sediment cores may be used to characterise changes in local vegetation and, indirectly, may be used to infer how the climate at the site has changed since the Last Glacial Maximum (at about 18 ka Before Present).

At well-defined times during the site investigation, it may be appropriate to declare a data freeze. This does not mean that data acquisition ceases at that time. However, it defines a dataset to be used to inform mathematical modelling and other assessment activities. Activities such as environmental impact assessment and post-closure radiological impact assessment can be undertaken using that dataset. In turn, the results from these assessments can refine or redirect site investigations, by defining deficiencies in the availability of key data or, equally importantly, by identifying where sufficient information is already available, allowing resources to be redirected to other areas of investigation.

When site construction begins, the characterisation of surface ecosystems should continue. However, it may be appropriate to give specific emphasis to aspects of the surface ecosystems likely to be impacted by construction activities, e.g. parts of the site may be disrupted by the construction of new transport routes or by the dumping of waste rock. A less obvious effect is that construction and pumping of underground space can lead to dewatering of the surrounding rock and drawdown of the water table with consequent effects on surface ecosystems. Similarly, characterisation of surface ecosystems should continue during the operational, closure and post-closure monitoring periods. However, characterisation activity in these periods should be less intensive than in earlier periods and may be best characterised as monitoring. In this monitoring programme the emphasis should be on identifying key indicator variables and undertaking time-series monitoring of those variables. Unexpected changes in one or more of these variables would then signal the need to investigate their cause and determine whether this implied a degradation in performance of the disposal system. Conversely, if all variables remained within their anticipated ranges, this would constitute a performance confirmation measure for the disposal system. During the construction phase, numerical models developed and calibrated before and during that phase may be particularly useful in quantifying the projected short-term and long-term impacts of construction using rapid feedback of data from observations.

Domain Goal	
4.1.3 Characterize or confirm surface ecosystem properties and their potential evolution in the future (Biosphere model)	
Domain Activities	
Phase 1: Programme Initiation	Generic studies to identify the categories of information required to characterise the biosphere for the type of waste disposal system under consideration and, if possible, provide broad descriptions of preferred biosphere characteristics to be used in site identification.
Phase 2: DGR Site Identification	Evaluation of geographical regions or candidate sites to identify those that are potentially suitable from a biosphere perspective. This would include collection of pre-existing information in desk-based studies and would provide part of the basis for selecting one or a few sites for detailed characterisation.
Phase 3: DGR Site Characterisation	Expanding upon pre-existing information through field studies to provide a multi-disciplinary, conceptual model of the biosphere and associated mathematical models suitable for application in various contexts, e.g. environmental impact assessment and post-closure safety assessment.
Phase 4: DGR Construction	Continued site characterisation and monitoring, with mathematical models used to provide rapid interpretation of data arising during construction and make projections of short- and long-term implications of those data.
Phase 5: DGR Operation and Closure	Continued monitoring of selected key measures of performance to confirm that the system is performing as expected and to help identify the significance of any observed deviations.

2. Contribution to generic safety functions and implementation goals

Surface ecosystems are not usually considered to be one of the barriers to release of radionuclides or other substances from a repository. However, these ecosystems are relevant to safety because they are modelled to convert radionuclide releases from the geosphere into annual effective doses to humans or absorbed dose rates to non-human biota. In turn, these annual effective doses and dose rates are compared with appropriate criteria to determine whether the disposal system is compliant with overall safety requirements. In some contexts, multiple scenarios for the future development of the disposal system and surface ecosystems are addressed and compliance then needs to be demonstrated, either for each scenario separately or for a weighted combination of scenarios.

Releases from the repository during the operational phase might occur to the atmosphere or to surface waters. However, because wastes are typically packaged for disposal, such releases are likely to be of limited radiological significance. Nevertheless, they need to be assessed and this can generally be done using standard models for routine releases that are also applied in other contexts. Specific attention may need to be given to releases of radioactive gases, e.g. Rn-222 from vented waste packages.

Overall, the features, characteristics and properties of surface ecosystems are most relevant to safety in the post-closure phase of a repository. In that context, releases from the geosphere are mainly expected to occur in groundwater, though releases in the gas phase due to bulk transport of gases (e.g. hydrogen) carrying radioactive contaminants (e.g. methane incorporating C-14) may also occur. Also, human intrusion into the repository or its environs may bring radionuclides to the surface, and, in some contexts, erosive effects may exhume a disposal facility (e.g. due to cap degradation for a near-surface facility, coastal erosion, or fluvial or glacial incision of valleys).

For releases in groundwater, a key characteristic of the surface ecosystem is its hydrology and hydrogeology. The radionuclide flux from the geosphere is typically diluted in the near-surface hydrogeological system that may include a near-surface, often unconfined aquifer. Further dilution and dispersion may then occur in the surface drainage network. However, in other contexts, radionuclides may be accumulated in specific components of the surface ecosystem. For example, a radionuclide may be only retarded to a limited degree in the underlying geosphere but may be highly retarded in the overlying regolith. This could arise because of differences in material composition, but also because of a transition from a reducing domain at depth to an oxidising regime in the near surface. Thus, modelling the hydrogeology, hydrology and hydrogeochemistry of surface ecosystems is important in safety assessment. It is this modelling that defines the pattern of radionuclide distribution in the environment and how it is projected to evolve in time and space.

Once the environmental distribution of radionuclides has been defined, it is necessary to evaluate potential exposures of humans and non-human biota. As a first step this requires that radionuclide concentrations in human foods and in biota are estimated. Standard biosphere models and datasets are available for this purpose, but site characterisation may be used to refine or replace generic data. For example, multi-element analyses of soils and associated plants may be used to derive site-specific plant:soil concentration ratios to replace literature values that may not be specific to the plant and soil types of interest.

Having derived radionuclide concentrations in all the relevant environmental media, dose calculations can be made. For non-human biota, two contributions are typically summed. These are the external dose rate from the contaminated soil, sediment or water body that comprises their habitat and the internal dose rate arising from the concentrations of radionuclides in their tissues and organs. For humans, external dose rates are estimated in the same way as for non-human biota. However, internal doses are generally estimated by computing intakes of radionuclides by ingestion and inhalation and then using generically estimated intake-to-dose conversion factors. For non-human biota, information on the surface ecosystem can be used to assess the spatial extent over which radionuclide concentrations should be averaged for assessment purposes (e.g. based on individual range for animals, or spatial extent of a community). For humans, the equivalent considerations are the area occupied by the most exposed group and the various areas from which the group acquires its foods.

For releases in bulk gas, various studies have shown that the important radionuclide is usually C-14, either as methane or carbon dioxide. However, methane is efficiently oxidised in agricultural soils and the resulting carbon dioxide is rapidly exchanged between the soil atmosphere and soil solution. Thus, modelling of gaseous releases is handled similarly to modelling of groundwater releases. In this case, a radionuclide-specific model is usually adopted because of the fundamental role of carbon dioxide in photosynthesis, which determines the uptake of C-14 by plants.

For releases by intrusion or exhumation, key issues are the spatial distribution of radionuclides in the environment. Characterisation of surface ecosystems would generally have a limited input to modelling this pathway. However, geomorphological aspects of site characterisation could help to define potential patterns of landform develop that could result in exhumation.

3. International examples of Biosphere models

The characterization of surface ecosystems has been most extensively documented in those programmes that have progressed to the site investigation phase or to repository construction and operation. For deep geological disposal of spent nuclear fuel, the sites at Forsmark (Sweden) and Olkiluoto (Finland) have been most extensively studied. These sites are very similar to each other and are located on opposite coasts of the Baltic Sea.

With respect to collecting and managing information on ecosystem properties, SKB in Sweden and Posiva in Finland have used somewhat different approaches, partially due to the site characteristics and in part due to the pacing of the overall programmes. In Sweden, SKB's sample collection has been conducted in parallel with conceptual model development and classification of the landscape. In Finland, the site is an island on a water divide, hosting only two main catchment areas that are reasonably homogeneous in their ecosystem properties. Given this and the need to monitor the impact of the rather heavy land-use pressures at the site and in its vicinity, Posiva has developed a hierarchical network for managing information. This network includes information from surveys (e.g. general descriptions of land use and vegetation patterns), from a number of measurement plots, and from a few 'intensive-level measurement plots' that are instrumented for more or less continuous monitoring activities. In the Finnish case, there has also been a greater need for present-day analogue studies farther away from the site to satisfy the information needs of safety assessments, where similar measurement and sampling plot designs originally oriented to terrestrial systems have been applied and further adapted also to aquatic environments.

Another strategic aspect of striving for integrated and coherent quantification of the ecosystem fluxes and storages employed by both SKB and Posiva is the use of stable-element information as proxies for the behaviour of long-lived radionuclides relevant to the safety assessments. Their experience is that the stable-element analogues allow for considerable expansion of the data basis on the behaviour of the assessment-relevant elements, as well as for many others.

In the SKB programme, the inputs from various scientific disciplines were used to describe the data and analyses needed as identified from the generic conceptual understanding given from the preparatory work on the site. The strategy used by SKB to have the same group of people planning and reporting the site characterization as was involved in the safety assessment was a key decision and is a useful example of how to organize experts in a programme to successfully use the understanding gained from site characterization in the safety assessment.

For the Olkiluoto site in Finland, an iterative succession of such summaries has been presented in a 'biosphere description' series of reports.

In these programmes, the survey and sampling methods regarding the surface environment are like those applied to the field research in the respective scientific disciplines. However, there is much higher demand for the coherence of the methods and for the integration of the results, and thus the methods need to be carefully selected and often somewhat adapted for the site characterization. Also, such a wide and focused combination of individual methods as implemented in these programmes is almost unique and has given rise to interest from universities on conducting research within the site investigation areas.

For near-surface disposal, the Low-Level Waste Repository (LLWR) near Drigg in West Cumbria, UK has been in operation since the 1950s. Site characterization there has been much more incremental than at the Swedish and Finnish sites discussed above and there has been a substantial focus on coastal processes, because sea-level rise and coastal erosion have the potential to degrade and/or inundate the repository. In other contexts, site characterization of near-surface facilities has sometimes been rather limited.

Various site characterization programmes are described in the reports and papers listed in the key references at the end of this section.

4. Critical background information

As noted above, the distribution in time and space of releases of radionuclides and other substances from the geosphere is critical to defining the surface ecosystems that require characterisation. With increasing knowledge of the site and as the design of the disposal system is refined, the areas of interest at the surface will be modified. Therefore, there needs to be a close link between safety assessment and site characterisation, so that attention is focused on the key ecosystems. Also, the physico-chemical form of the releases will affect the relative emphasis placed on different components of surface ecosystems and on the processes of greatest relevance in transporting, diluting or accumulating radionuclides and other substances.

In the early stages of characterisation, considerable reliance can and should be placed on published information. For most sites of interest, map-based information will be available on a range of topics, e.g. topography, near-surface geology, hydrology, land use and ecology. In addition, there are likely to be time-series data relating to meteorological characteristics. These data may be station records from local weather stations, but it may often be more useful to refer to a gridded climatology based on the station data. In this context, it is noted that projections of climate change are typically made on a gridded basis and that projections of future climate can be made by combining a present-day gridded climatology with model-based projections of future changes to that climatology. Less frequently, there will be time series of stream flows from gauged catchments in the area and hydrogeological data such as groundwater elevation records, piezometric maps and numerical models of patterns of water flow in the surface and subsurface. In combination with climate data and site-specific information, such data can be used to parameterise and validate models of the hydrology and hydrogeology of surface-water catchments at the present day.

At all stages of site characterisation and safety assessment, there will be reliance on generic data. Such data include environmental transfer factors for terrestrial and aquatic environments and dose per unit intake data. This reliance will be greatest at the early stages of the assessment process, but at later stages, there will be greater reliance on site-specific data. Throughout, an important consideration will be the relative weight to be given to carefully scrutinised broadly based generic data compared with site-specific data that may be sparse and not fully representative of the site as it is today and may evolve in the future.

4.1 Integrated information, data or knowledge (from other domains) that impacts understanding of the Biosphere Model Domain

The development of a model of the biosphere is an intrinsic part of the development of a description of the natural system (Sub-theme 4.1). Indeed, there is not a well-defined interface between the biosphere and the deeper parts of that natural system, and a distinction is often made for convenience of description or modelling. Therefore, knowledge of the geology, hydrogeology and hydrogeochemistry of the disposal system can be of great significance in developing a biosphere model. Similar remarks can apply to the engineered barrier system (Theme 3), which can have a substantial impact on the biosphere. This is obvious for near-surface facilities that have a direct interface with the biosphere, but applies also to deeper facilities, which can perturb the biosphere, e.g. drainage of a deep engineered facility can result in drawdown of the water table above it. Finally, the development of a safety-assessment methodology and its application (Theme 7) will feed back by setting priorities for biosphere-specific information that needs to be provided from the biosphere model domain. This applies particularly in relation to Sub-Theme 7.2 which addresses the need to combine experimental and field data with scientific understanding and qualitative observations to construct models of the possible future behaviour of the disposal system.

5. Maturity of knowledge and technology

Post-closure safety assessments of various types of repositories have been undertaken since the 1970s. However, modern approaches to the characterisation of surface ecosystems date from the late 1980s onwards. Thus, for example, in 1987 in the UK, Nirex initiated a biosphere research programme covering climatology, geomorphology, hydrology and near-surface hydrogeology, and radionuclide transport in soil-plant systems. This provided a basis for detailed site characterisation activities relating to Quaternary deposits in West Cumbria in the 1990s. However, modern integrated approaches to the characterisation of surface ecosystems have been largely developed by SKB and Posiva since 2000. These studies continued throughout the period 2000 to 2010 and led to reports providing comprehensive site-descriptive models. By 2010, a mature approach to this area had been developed. Since that time the approach has been elaborated and refined but remains substantially unchanged. Therefore, it can be concluded that the characterisation of surface ecosystems is now a mature discipline.

6. Uncertainties

The characterisation of surface ecosystems relies on well-established field and laboratory methods in the various disciplines identified in this section. The main challenge is in integrating the discipline-specific information into an overall conceptual model and in translating that model into a mathematical model that can be used for assessment purposes and to further inform site characterisation.

Nevertheless, uncertainties remain at various levels. First there are uncertainties as to what surface ecosystems will be present at various times in the future. These uncertainties can be addressed by defining alternative scenarios for climate and landscape change, and for alternative land uses, and propagating these through the assessment process. Similarly, where there are alternative conceptualisations of the relevant surface ecosystems, e.g. in terms of the key features, events and processes, these can be explored by developing alternative conceptual models and mathematical interpretations of those models and propagating those through the assessment process. Finally, the significance of uncertainties in parameter values can be explored in sensitivity and uncertainty analyses, using both deterministic and probabilistic approaches.

In applying site-specific information, an important consideration is the relative weight that should be given to generic and site-specific data. Both types have advantages and disadvantages, and work remains to be done to establishing an optimal approach to combining these two sources of information. Bayesian techniques may be helpful, with the generic data establishing prior distributions to be updated with site-specific data.

7. Guidance, Training, Communities of Practice and Capabilities

The key international community in which issues relating to site characterisation and biosphere assessment are explored is the BIOPROTA organisation (www.bioprota.org).

BIOPROTA is an international collaborative forum designed to support resolution of key issues in biosphere aspects of assessments of the long-term impact of contaminant releases associated with radioactive waste management.

Participation is aimed at national authorities and agencies with responsibility for achieving safe and acceptable radioactive waste management, both regulators and operators.

The project focuses on key radionuclides and the key biosphere migration and accumulation mechanisms relevant to those radionuclides. Collaboration through projects focused on mutual research needs is intended to make efficient use of skills and resources, and provide a common, transparent and traceable basis for the choices of modelling approaches and parameter values, as well as for the wider interpretation of information used in assessments.

Apart from a specific report on issues in site characterisation, BIOPROTA has produced reports on methodological considerations, model intercomparisons, the behaviour of specific radionuclides, process modelling, representation of the interface between the geosphere and the biosphere, the inclusion of non-human biota in assessments, and combining assessments for radioactive and chemically hazardous wastes.

More recently, the IAEA has established the MEREIA programme. This programme is intended to help countries further build their capacities for carrying out radiological environmental impact assessments. The programme was launched in October 2021 and will run through to 2025. It aims to help countries apply assessment approaches, conceptual models, mathematical models and data within the broader context of environmental impact assessment. Site characterisation and its relationship to assessment studies is integral to this programme and structured mentoring activities for less experienced professional are included within it.

Guidance
- www.bioprota.org
Training
- Training offered in EURAD - ENEN2plus project, the largest and most integrative nuclear Education and Training (E&T) effort
Active communities of practice and networks
- Bioprota organisation - MEREIA programme

8. Further reading

8.1 Further Reading

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