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Biosphere analyses for the safety assessment SR-Site – synthesis and summary of results

Svensk Kärnbränslehantering AB

December 2010

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Preface

This report presents a synthesis of a number of biosphere analyses undertaken in an assessment of long-term safety of a KBS-3 repository for spent nuclear fuel. The report forms part of the safety assessment SR-Site, which will support the licence application for a final repository in Sweden.

The report was compiled by Peter Saetre, SKB. A number of additional authors have contributed to various sections of the report as listed at the end of Chapter 1.

Stockholm, February 2011

Allan Hedin

Project leader SR-Site

Summary

The Swedish Nuclear Fuel and Waste Management Co, SKB, launched the project SR-Site to conduct a safety assessment of the planned repository for spent nuclear fuel in Forsmark after closure. The assessment focuses on the performance of the repository, the transport of potentially released radionuclides from the repository, through the geosphere, up to and within the biosphere, and the consequences for humans and the environment in the biosphere. The purpose is to show whether humans and the environment are sufficiently protected from harmful effects of ionising radiation.

This report summarises nearly 20 biosphere reports and gives a synthesis of the work performed within the SR-Site Biosphere project, i.e. the biosphere part of SR-Site. SR-Site Biosphere provides the main project with dose conversion factors (LDFs), given a unit release rate, for calculation of human doses under different release scenarios, and assesses if a potential release from the repository would have detrimental effects on the environment. The intention of this report is to give sufficient details for an overview of methods, results and major conclusions, with references to the biosphere reports where methods, data and results are presented and discussed in detail.

The philosophy of the biosphere assessment was to make estimations of the radiological risk for humans and the environment as realistic as possible, based on the knowledge of present-day conditions at Forsmark and the past and expected future development of the site. This was achieved by using the best available knowledge, understanding and data from extensive site investigations from two sites. When sufficient information was not available, uncertainties were handled cautiously.

A systematic identification and evaluation of features and processes that affect transport and accumulation of radionuclides at the site was conducted, and the results were summarised in an interaction matrix. Data and understanding from the site investigation was an integral part of this work, the interaction matrix underpinned the development of the radionuclide model used in the biosphere assessment.

Understanding of the marine, lake and river and terrestrial ecosystems at the site was summarized in a conceptual model, and relevant features and process have been characterized to capture site specific parameter values. Detailed investigations of the structure and history of the regolith at the site and simulations of regolith dynamics were used to describe the present day state at Forsmark and the expected development of the site. The hydrodynamics in the coastal areas was characterized in the field and combined with the bathymetry of the future landscape to forecast the turnover of water in future coastal basins. The surface and near surface hydrology was described at the site and dynamic models were applied on the future landscape to predict vertical and horizontal transport under different climatic conditions. Historical and present human settlement at the site was used to characterize the utilisation of natural resources in a landscape perspective, and the productivity of food items was described and evaluated. The collection and analysis of multi-elemental chemistry data from different environmental media and a wide array of organisms were used to the estimate a unique parameter set describing sorption and biological uptake at the site.

A continuous and iterative effort to improve the site characterisation and the site modelling during the investigations resulted in a refined collection of data, in parallel with detailed understanding of the processes that affects transport and accumulation in the surface ecosystems. This interdisciplinary and synchronously large scale collection and analysis of site data makes Forsmark one of the most extensively investigated sites used in risk or environmental assessments.

By combining predicted discharge of deep groundwater from the repository and landscape geometries, the areas most likely to be affected by a potential release of radionuclides were identified and outlined, i.e. *biosphere objects*. The properties and temporal development of these discharge areas were described, developing from a coastal sea basin to a terrestrial ecosystem. The identified biosphere objects represent a considerable variation in size, timing of succession and object-specific properties.

An ecosystem-based approach was used to dynamically model transport and accumulation of radionuclides in biosphere objects. The simulations with the model covered a 70,000 year ice free period between two glaciations. The radionuclide model used in SR-Site has been improved in several important ways since previous safety assessments conducted by SKB. For example, the aquatic and terrestrial ecosystems are handled in the same model, which gives a continuous transition from the sea stage to the lake and terrestrial stages. Transport and accumulation in till (lower regolith) is represented in the model. The uptake by plants is included in the mass-balance, and it is related to biomass growth. Moreover, parameter values including hydrological flows, sedimentation and resuspension rates, biomass growth rates, gas exchange rates, as well as element specific distribution coefficients and concentration rations, were as far as possible based on site data.

One endpoint from the simulations with the radionuclide model was the landscape dose conversion factors (LDFs). The LDF represents the mean annual effective dose over lifetime for an individual living in the most contaminated area, assuming a constant unit release rate (1Bq/y). In the safety assessment, the maximum LDF for each nuclide have been selected from the biosphere object at the time yielding the highest unit release dose, and consequently LDFs from different nuclides does not necessarily match the same group of exposed individuals with respect to point in time or location in the landscape. In the SR-Site main report, the resulting dose is presented when the maximum LDF is multiplied by a release.

The potential effect of a radionuclide release on non-human biota in Forsmark is also assessed. For this analysis maximum release under the central corrosion case was multiplied with the maximum environmental concentrations (per unit release) from the radionuclide model. The resulting environmental activity concentrations were used to calculate dose rates for representative species in Forsmark with the ERICA tool. Calculated dose rates were far below the screening no-effect dose rate of 10 $\mu Gy\ h^{-1}$ for all investigated organisms, demonstrating that a potential release from the repository is highly unlikely to cause detrimental effects on the survival and reproduction of organisms. Thus, from this assessment it is concluded that neither negative effects of the repository on biodiversity, nor sustainable use of natural resources in the Forsmark area are of concern.

In the final chapter the effects of uncertainties on the LDF that are used to calculate the final risk are examined. The analysis showed that the handling of system, model and parameter uncertainties is balanced, and that the effects of quantified uncertainties are limited. Consequently, identified uncertainties are not expected to have a significant effect on the assessment endpoint, and it is concluded that the maximum LDFs used in SR-Site are robust estimates for a representative individual of the most exposed group, reflecting process understanding and the best available description of the site.

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1 Introduction

Radioactive waste and spent nuclear fuel from Swedish nuclear power plants are managed by the Swedish Nuclear Fuel and Waste Management Co, SKB. Both waste and spent fuel are planned to be placed in a geological repository. According to KBS-3, copper canisters with a cast iron insert containing spent fuel are to be enclosed by bentonite clay and deposited at approximately 500 m depth in granitic bedrock. Approximately 12,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme, corresponding to roughly 6,000 canisters in a KBS-3 repository.

Between 2002 and 2008, SKB performed site investigations with the intention on finding a suitable location for a repository. Investigations were focused on two different sites along the eastern coast of southern Sweden; Forsmark in the municipality of Östhammar and Laxemar-Simpevarp in the municipality of Oskarshamn. Data from the site investigations have been used to produce comprehensive, multi-disciplinary site descriptions for each of the sites. The resulting site descriptions were reported in /SKB 2008/ (Forsmark) and /SKB 2009/ (Laxemar-Simpevarp). Based on available knowledge from the site descriptions and from preliminary safety assessments of the planned repository, SKB decided in June 2009 to put forward Forsmark as suggested site for the repository. The location of Forsmark is shown in Figure 1-1. An application for the construction of a geological repository for spent nuclear fuel at Forsmark is planned to be filed in 2011.

According to the regulations from the Swedish Radiation Safety Authority, SSM, a safety assessment of the planned repository has to be performed before the construction of the repository starts /SSM 2008/. The assessment should focus on potential developments that may lead to the release of radionuclides. SKB launched the project SR-Site to conduct the safety assessment, which is summarised in the **SR-Site main report**. This report summarises and gives a synthesis of the biosphere part of SR-Site and constitutes a supporting document to the application.

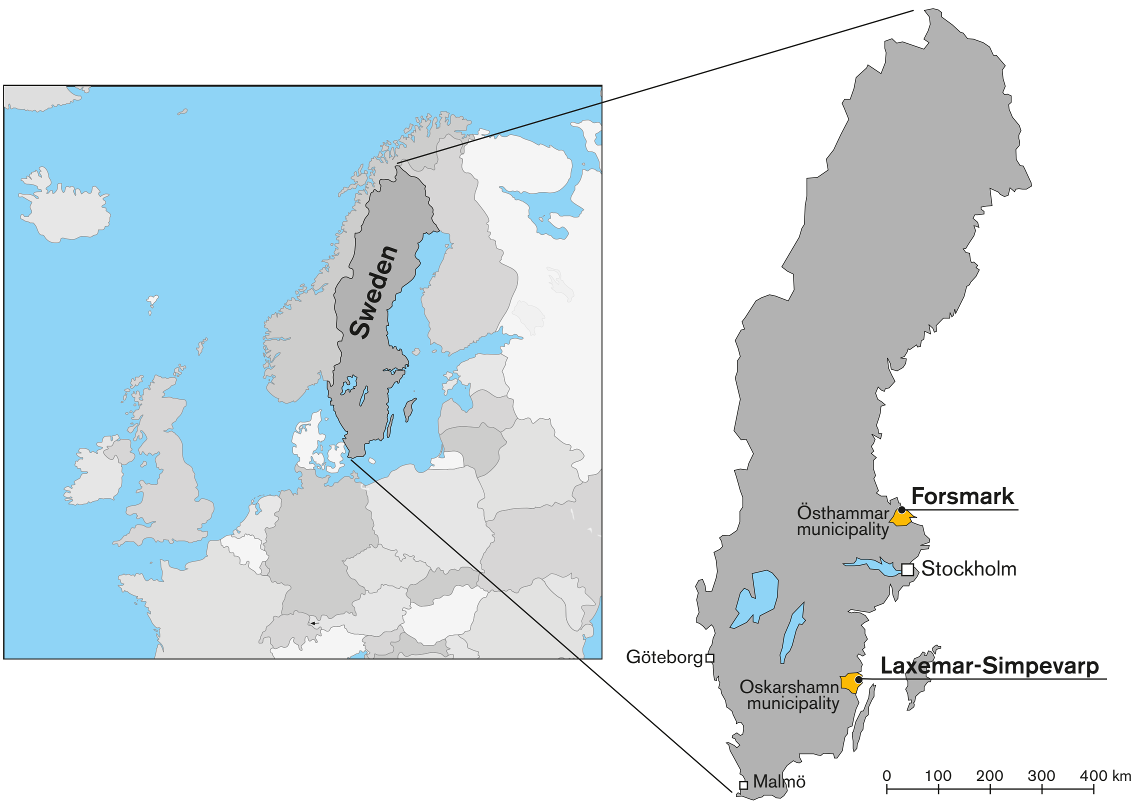

Figure 1-1. *Location of the Forsmark and Laxemar-Simpevarp sites.*

The safety assessment SR-Site focuses on three major fields of investigation: performance of the repository, the geosphere and the biosphere. The biosphere part of SR-Site, SR-Site Biosphere, provides estimates for human exposure given a unit release, expressed as *landscape dose conversion factors* (LDFs). Multiplying these factors with modelled release rates from the geosphere results in estimates of the annual doses used to assess compliance with the regulatory risk criterion. The effects on the environment of a potential release from the repository are also assessed in SR-Site Biosphere.

The work done within the biosphere assessment in SR-Site has been conducted by a number of people. The major part of the group has been involved from the beginning of the site investigation, via the site characterisation and modelling tasks, and in this final synthesis for the safety assessment SR-Site. The project members in alphabetic order, their role and affiliation are listed below:

Eva Andersson**, Studsvik Nuclear AB	process descriptions and limnic ecosystems
Karin Aquilonius, Studsvik Nuclear AB	marine ecosystems
Rodolfo Avila, Facilia AB	radionuclide modelling and dose assessment
Sten Berglund, SKB	hydrology and near-surface radionuclide transport
Emma Bosson, SKB	surface hydrology and near-surface hydrology
Lars Brydsten, Umeå University	regolith dynamics and lake development and GIS analysis
Anders Clarhäll, SKB	editorial work
Per-Anders Ekström, Facilia AB	numerical modelling
Anders Engqvist, KTH	oceanography
Sara Grolander, Facilia AB	site specific chemical data
Anna Hedenström, SGU	regolith
Ulrik Kautsky*, SKB	overall biosphere assessments project leader, scientific and method development
Tobias Lindborg*, SKB	site modelling and landscape development
Angelica Lorentzon af Ekenstam, SKB	process description and project administration
Anders Löfgren, EcoAnalytica	terrestrial ecosystems and synthesis
Sara Nordén, SKB	radionuclide and element specific properties
Peter Saetre, SKB	data evaluation, synthesis and review of results, editor of this report
Mona Sassner, DHI	surface hydrology
Gustav Sohlenius, SGU	regolith and future land use
Mårten Strömgren, Umeå University	GIS analysis, landscape development
Björn Söderbäck, SKB	site descriptions and historical development
Jesper Torudd, Facilia AB	non-human biota assessment
Mats Tröjbom, MTK AB	biogeochemistry and mass balances
Per-Gustav Åstrand, Facilia AB	numerical modelling

* project leader SR-Site Biosphere
** assistant project leader SR-Site Biosphere

2 This report

This report is the main document for reporting the biosphere analysis for the SR-Site safety assessment (**SR-Site main report**), and as such it provides the background information for conclusions on the biosphere communicated in the **SR-Site main report**. This report gives the context of, and the philosophy behind, the biosphere assessment. It describes the methodologies used and summarises the most important results. The findings are synthesised and discussed, and the effects of assumptions and uncertainties on the final results is evaluated. All information necessary for a detailed review and for a reconstruction of the work done can be found in the subordinate reports, which communicate primary analysis and results (Figure 2-1).

To make the safety assessment of the planned repository possible, the SR-Site Biosphere project is divided into a number of subtasks.

1. identify features and processes of importance for modelling radionuclide dynamics of present and future ecosystems in Forsmark,
2. describe the site and predict its future development with respect to identified features and processes,
3. identify and describe areas in the landscape that may be affected by release of radionuclides from the planned repository,
4. calculate radiological exposure to a representative individual of the most exposed group in the future Forsmark landscape, and radiological exposure to the environment.

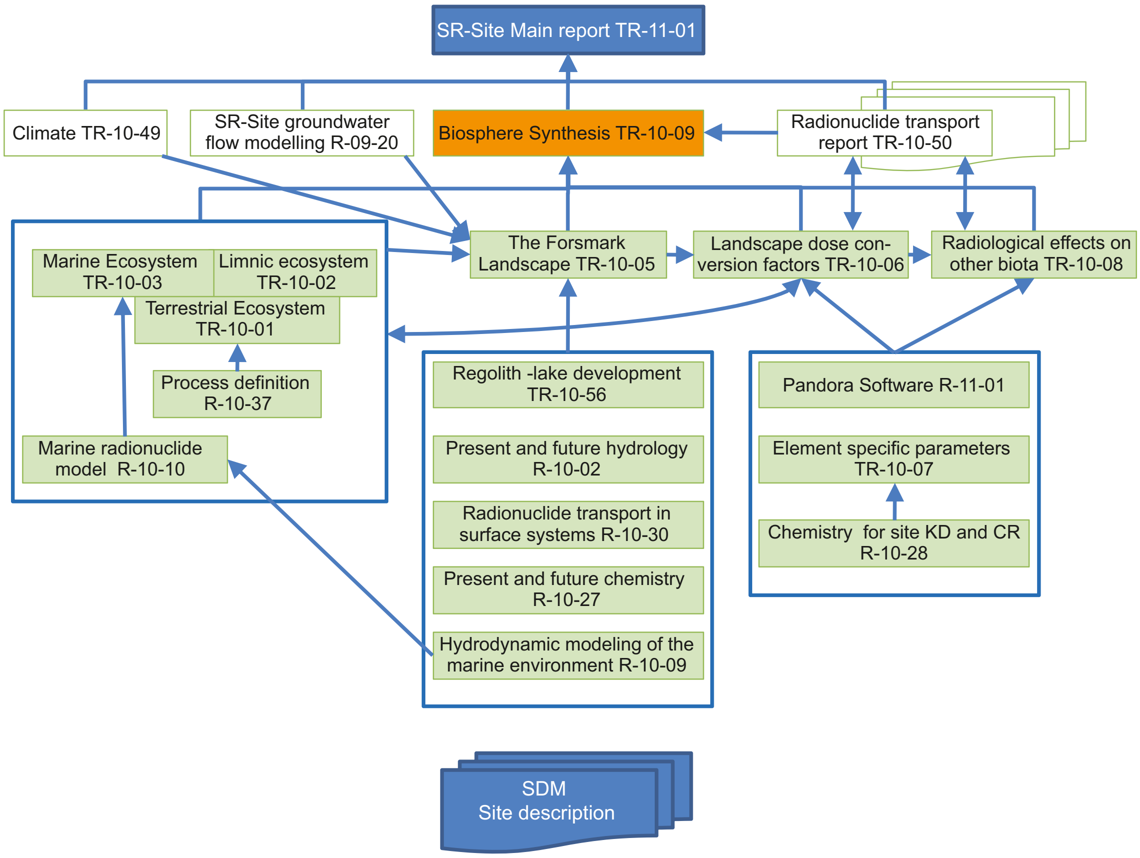

Figure 2-1. *The hierarchy of reports produced in the SR-Site Biosphere project. This report (market orange) and its dependencies on information from subordinate biosphere reports (green) and other reports within SR-Site. Arrows indicates major interactions during project work flow of analysis and results, but interactions have been substantial between most parts of the project throughout the process. The sources of data should be searched for in subordinate reports if not explicitly pointed out. SDM refers to the site descriptive model /Lindborg 2008/.*

2.1 Report hierarchy

In line with other SR-Site reports, main references sited in this report are written in abbreviated form when they occur in the text. Table 2-1 lists these main references and defines the abbreviations by which they are identified in the text hereinafter.

As indicated in the previous section, several of the steps carried out in the SR-Site biosphere assessment result in specific reports that are of central importance for the conclusions and analyses in this synthesis report. Sections below presents a summary of all SR-Site biosphere reports in the context of the subtasks listed in Section 2.0. The content in most reports spans over several of the listed subtasks.

Table 2-1. Main references sited in this report. All these reports are available at www.skb.se.

Full title	Abbreviation used when referenced in this report	Text in reference list (Chapter 13)
Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main Report of the SR-Site project.	**SR-Site Main report**	**SR-Site Main report, 2011.** Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main Report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.
Long-term safety for KBS-3 repositories at Forsmark and Laxemar - a first evaluation. Main report of the SR-Can project.	**SR-Can Main report**	**SR-Can Main report, 2006.** Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can project. SKB TR-06-09, Svensk Kärnbränslehantering AB.
Climate and climate related issues for the safety assessment SR-Site.	**Climate report**	**Climate report, 2010**. Climate and climate related issues for the safety assessment SR-Site. SKB TR-10-49, Svensk Kärnbränslehantering AB.
Radionuclide transport report for the safety assessment SR-Site.	**Radionuclide transport report**	**Radionuclide transport report, 2010.** Radionuclide transport report for the safety assessment SR-Site. SKB TR-10-50, Svensk Kärnbränslehantering AB.
Data report for the safety assessment SR-Site.	**Data report**	**Data report, 2010**. Data report for the safety assessment SR-Site. SKB TR-10-52, Svensk Kärnbränslehantering AB.
FEP report for the safety assessment SR-Site.	**FEP report**	**FEP report, 2010**. FEP report for the safety assessment SR-Site. SKB TR-10-45, Svensk Kärnbränslehantering AB.

2.1.1 Process understanding

The identification and handling of features and processes that are important for transport and accumulation of radionuclides in the environment is of importance to assessment of human health and safety of the environment. Understanding of the site and its development over time is crucial for a successful identification and handling of relevant features and processes. Thus, SKB has updated the description of biosphere features and processes for the SR-Site safety assessment to reflect the current understanding of ecosystem processes and radionuclide behaviour at the investigated site /Andersson 2010, Aquionius 2010, Löfgren 2010, SKB 2010/.

2.1.2 Description of the site and its development

The past and present biosphere at Forsmark has been thoroughly described in a number of SKB reports and articles published in peer-reviewed scientific journals. This knowledge, which constitutes the foundation for future development scenarios of the Forsmark site, is summarised and synthesised in /Lindborg 2008/ and /Söderbäck 2008/.

SR-Site have refined descriptions of the site and its proposed development during non-glacial conditions. Emphasis was put on improving the understanding of features and processes where uncertainties are likely to have a large influence on estimates of exposure. This includes expanded descriptions on landscape development /Brydsten and Strömgren 2010, Lindborg 2010/, and present and future hydrology and hydrodynamics /Bosson et al. 2010, Karlsson et al. 2010/. Transport and retention of radionuclides has been simulated with high resolution in present marine and terrestrial ecosystems /Erichsen et al. 2010, Piqué et al. 2010/. Finally, the SR-Site have improved characterisation of element pools and their turnover rates in the present landscape /Tröjbom and Grolander 2010/.

2.1.3 Identification and characterization of discharge areas

The discharge of deep groundwater in future landscapes has been used to identify areas that may be directly affected by released radionuclides from a repository /Lindborg 2010/. These areas are referred to as biosphere objects, and extensive work has been invested on detailed description of the ecosystems that are likely to develop in these areas /Andersson 2010, Aquionius 2010, Löfgren 2010/, and of their successional development /Brydsten and Strömgren 2010/. Transport within and between biosphere objects have been modelled /Bosson et al. 2010, Karlsson et al. 2010/ and the present retention in regolith and in biota from similar environments at the site has been characterised /Tröjbom and Nordén 2010, Nordén et al. 2010/. The focused description of the biosphere objects and their development in time has been the foundation for a site specific parameterisation of the models used to assess human safety and the protection of the environment (Section 2.1.4).

2.1.4 Radionuclide modelling

Transport and accumulation of potentially released radionuclides to biosphere objects was simulated with the radionuclide model /Andersson 2010/ implemented in the Pandora software /Ekström 2011/. The model is based on process understanding from the site, incorporates the development of discharge areas at the site, and has been parameterised primarily from site data. The exposure of the most exposed group was calculated for a constant release rate of radionuclides to the biosphere and for a pulse release /Avila et al. 2010/. Environmental activity concentrations were used to assess the radiological impact on the environment /Torudd 2010/.

2.2 Overview of contents

The report is divided into chapters and sections that will guide the reader through the work flow that have resulted in quantitative estimates of exposure for humans and other organisms as follows:

Chapter 1 gives a short *background* to the SR-Site safety assessment and a list of the persons involved in SR-Site Biosphere.

Chapter 2 (this chapter) is an *introduction* to the SR-Site Biosphere work. It gives a brief description of the framework and workflow of the project and of the use of the end results.

Chapter 3 puts the biosphere analysis into *the context of the SR-Site safety assessment*. The chapter describes the legal requirements related to the assessment of long-term safety of a repository for radioactive waste, and reviews conclusions of previous SKB safety assessments. The SR-Site safety assessment is put in relation to international recommendations and to corresponding work in countries with similar plans for storage of used nuclear fuel.

Chapter 4 lists identified *features and processes* that are important for transport and accumulation of radionuclides, and for the subsequent exposure of humans and the environment. The identification of features and processes is based on the current understanding of the site.

Chapter 5 provides a description of the present-day conditions at Forsmark. *The site description* focuses on features and process that are important for transport and accumulation of radionuclides. The chapter is structured on descriptions of the Forsmark landscape with respect to climate, topography, regolith, near-surface hydrology, coastal oceanography, chemistry, ecology and utilisation of the landscape by humans.

Chapter 6 describes long-term *site development* at Forsmark based on climate development according to the *SR-Site reference glacial cycle* and the *SR-Site global warming climate case*. The structure follows that of Chapter 5 (see above). Lakes, streams and wetlands render special attention as they are the potential discharge areas for deep groundwater. Site development under prolonged warmer global temperatures is described in the last section.

Chapter 7 identifies the areas in the landscape that are most likely to be affected by a potential release of radionuclides from the repository, i.e. *biosphere objects*. The chapter starts with identifying discharge points for deep groundwater to the surface, followed by a presentation of the principles for delineating biosphere objects. Finally, positions, properties and temporal development of biosphere object are described.

Chapter 8 gives a brief presentation of the mathematical model, assumptions and how the model calculates transport and accumulation of radionuclides in the biosphere. *The radionuclide model* simulates activity concentrations in environmental media (regolith, water, air), and in natural and agricultural food crops, and from these quantify human exposure through relevant pathways. All biosphere objects and their temporal development during a full period of non-glacial conditions are considered in the simulations. This chapter also describes the procedures used to assure quality of data, codes and results.

Chapter 9 presents the *input parameters* that are needed to calculate radiological exposure. The chapter describes the principles and methods used to select parameter values that represent the site, and the procedures used to assure data quality and traceability. Emphasis is put on descriptions of parameters that serve as input to the radionuclide model.

Chapter 10 describes how the results from the radionuclide model were used to calculate *landscape dose conversion factors* (LDFs) for a constant unit release rate and for a unit pulse release (LDF pulse). The results are presented assuming human land use in climate conditions corresponding to the SR-Site reference glacial cycle or to the SR-Site global warming climate case. Effects of parameter and conceptual uncertainties on the results are numerically quantified in the last section of the chapter.

Chapter 11 summarises the assessment of the *radiological impact on non-human biota*. Doses to reference organisms and representative species from the site are presented assuming a release of radionuclides that corresponds to the SR-Site advection/corrosion base case. Results are assessed in the light of regulations and requirements of the Swedish Radiation Safety Authority concerning protection of the environment.

Chapter 12 synthesises and discusses the results of the biosphere analysis, including evaluation of assumptions and how they may affect the final results. Starting point for the discussion is identification of radionuclides that are likely to pose greatest risk for human health, followed by discussion on assumptions and uncertainties regarding activity concentrations in the environment and potential food resources. The discussion considers human behaviour and land use, configuration and long-term-changes that may affect LDF values.

3 Assessment context

This chapter gives a presentation of the background to the biosphere part of the SR-Site assessment. It points out the assessment purpose and the constraints that are placed on the assessment. This is followed by a section describing the legal requirements in Sweden related to the assessment of long-term safety of a repository for radioactive waste. After that, a description of how the SKB biosphere analysis and dose assessment relates to international expertise and to corresponding work in other countries is given, followed by some main conclusions from previous SKB work. The chapter concludes with a short account of the assessment philosophy.

3.1 Assessment purpose

The main purposes of the safety assessment SR-Site are:

- to assess the safety of a potential KBS-3 repository at Forsmark in order to support the licence application,
- to provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.

The overall objective of the SR-Site project is to investigate whether the KBS-3 method has the potential of fulfilling regulatory safety criteria at the Forsmark site, given the level of knowledge on important conditions and processes in the host rock and in the surface system after completion of the surface-based site investigations. The assessment is based on a reference design of the engineered parts of the repository, including reference methods to achieve the specified design, taking into account methods of ensuring that the specifications of the reference design have been achieved. The intention is, however, not to finally establish the technical system for disposal, but rather to investigate the safety of the system as it is specified at this stage, and to give feedback for further developments to that specification. For the biosphere part of the assessment, the general purpose is to determine the radiological significance of potential future releases of radionuclides from a KBS-3 repository into the biosphere at Forsmark, and to consider such releases in relation to Swedish regulatory requirements for solid radioactive waste disposal.

3.2 Preconditions for the SR-Site safety assessment

3.2.1 Repository system

The repository system is based on the KBS-3 method, in which copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in granitic bedrock (see Figure 3-1).

The facility design, with rock caverns, tunnels, deposition positions, is based on the design originally presented in the KBS-3 report /SKBF/KBS 1983/ which subsequently has been developed and described in more detail. The deposition tunnels are linked by tunnels for transport and communication, and shafts for ventilation. One ramp and five shafts connect the surface facility to the underground repository. The ramp is used for heavy and bulky transport and the shafts are for utility systems and for transport of excavated rock and backfill material. The different parts of the final repository are sketched in Figure 3-2.

Spent nuclear fuel with an initial weight of uranium or heavy metal of around 12,000 tonnes is forecast to arise from the Swedish nuclear power programme, corresponding to roughly 6,000 canisters in the repository. These figures are based on a reference scenario for the operation of the nuclear power plants with assumed reactor operational times of 50 years for the facilities at Forsmark and Ringhals and 60 years for the Oskarshamn reactors (**SR-Site main report**).

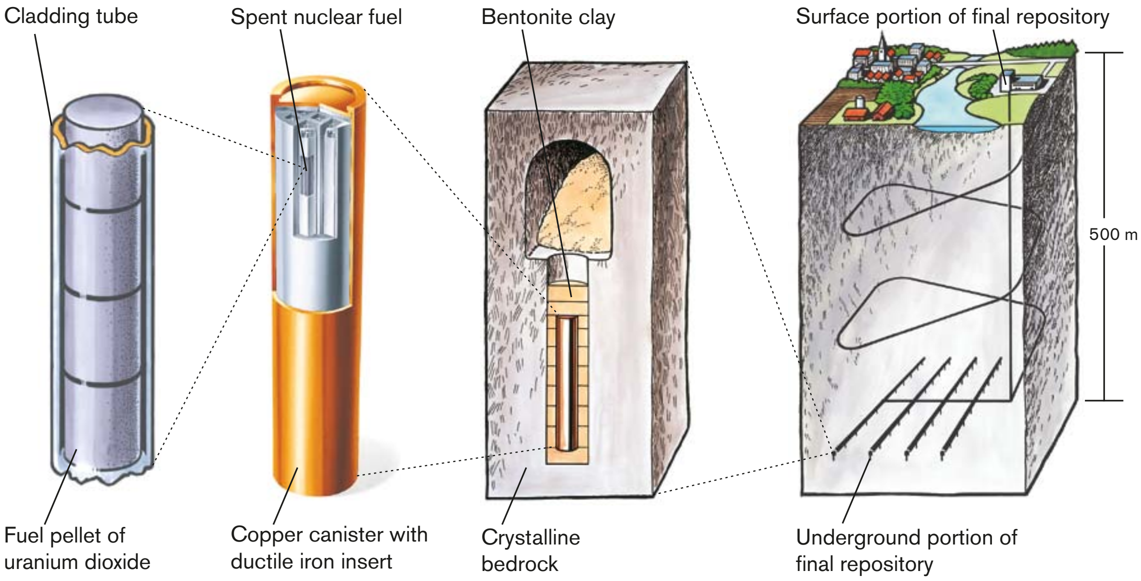

Figure 3-1. *The KBS-3 concept for storage of spent nuclear fuel.*

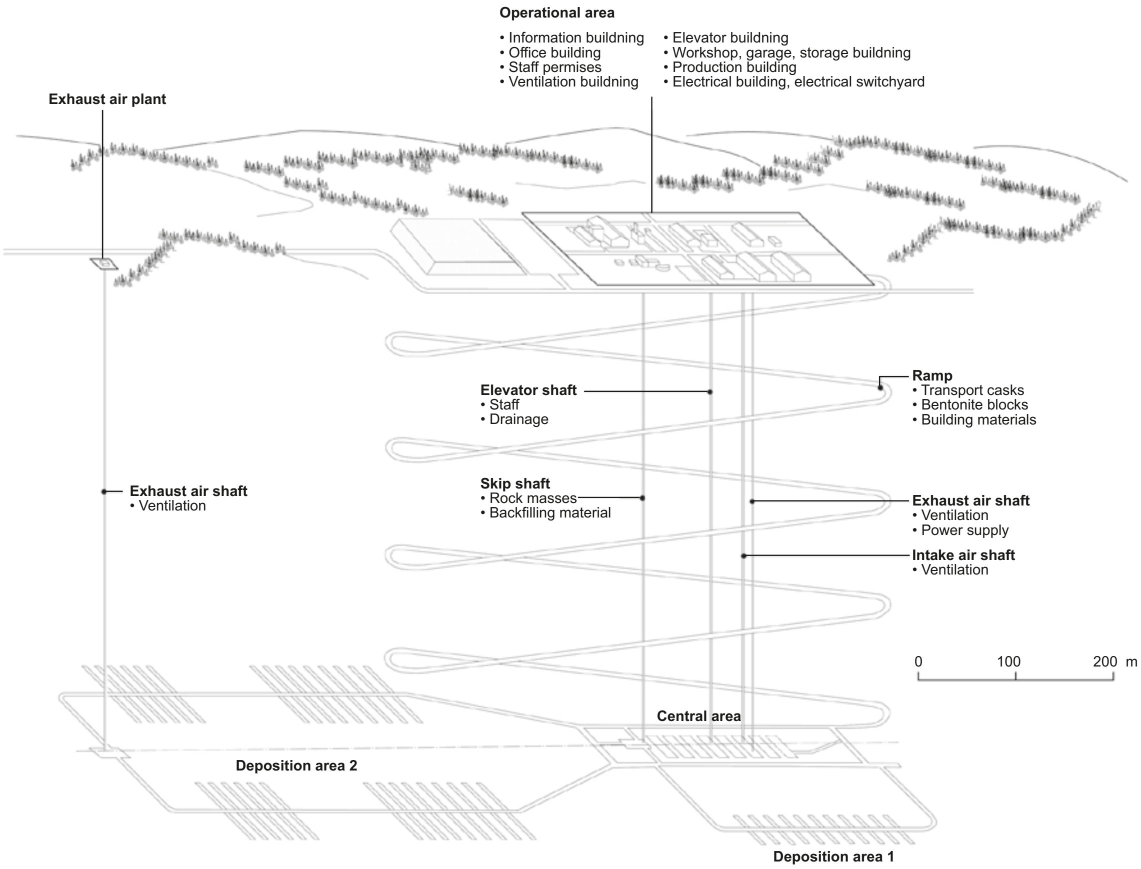

Figure 3-2. *Generic example of repository layout.*

3.2.2 Site context

This section gives a short summary of the site context. More detailed descriptions are given in Chapter 5 (Site description) and Chapter 6 (Site development). The Forsmark site is located on the coast of the Baltic Sea in the county of Uppland within the municipality of Östhammar, about 120 km north of Stockholm, Sweden (Figure 1-1). The planned repository area covers approximately 2·2 km, and is situated immediately southeast of the Forsmark nuclear power plant close to the present-day shoreline. The surroundings show small-scale topographic variations of less than 20 metres.

Post-glacial uplift, in combination with the flat topography, implies fast shoreline displacement. This has resulted in a young terrestrial system that contains a number of recently isolated lakes and wetlands, and new lakes are continuously formed as a consequence of the regressing shoreline (Figure 3-3). The coastline consists of sheltered shallow bays and small islands in an archipelago setting. The seabed in the coastal areas is dominated by erosion and transport bottoms with heterogeneous sediments, consisting mainly of sand and gravel with varying fractions of glacial clay.

The major part of the landscape is covered by a thin regolith layer, dominated by till. The mean regolith depth in the Forsmark area is c. 4 m /Hedenström et al. 2008/. Exposed bedrock and bedrock with only a thin regolith layer (<0.5 m) occupy c. 9% of the area /Lindborg 2008/. The underlying bedrock consists of crystalline rock that formed between 1,850 and 1,890 million years ago during the Svecokarelian orogeny, and it has been affected by both ductile and brittle deformation /Söderbäck 2008/. The ductile deformation has resulted in large-scale ductile high-strain zones and the brittle deformation has given rise to large-scale fracture zones. Tectonic lenses, in which the bedrock is much less affected by ductile deformation, are enclosed between the ductile high strain zones.

Today the Forsmark site has no permanent inhabitants and the surroundings are sparsely populated (see Chapter 5). Land use is dominated by forestry, including hunting. The major food supply for humans around Forsmark is, as in the rest of society, obtained primarily from general dealers, which means that it is produced at distant farms. Historically, the land use at the site has been dominated by forestry for supply to the ironworks at Forsmark, and by small-scale farming. Before that, from the last deglaciation until c. 500 BC, the whole area was submerged below the sea /Söderbäck 2008/.

Figure 3-3. *The coastal area in Forsmark, characterised by small altitudinal differences, shallow coastal bays and recently isolated small lakes and wetlands.*

3.2.3 Release scenarios and source terms

The release of radionuclides from damaged canisters and the transport from the repository to the biosphere is not included in the SR-Site biosphere analysis. The chain of calculations that results in the source term is described in detail in the **SR-Site main report**. Below follows a brief description of the scenarios that could contribute significantly to the release of radionuclides into the biosphere.

The scenario that results in the largest predicted release of radionuclides to the biosphere is canister failure as a result of enhanced corrosion due to advective conditions in the deposition hole following the loss of buffer through erosion (**SR-Site main report**). For this failure mode, both the canister and the buffer are bypassed. The rock retention is small since substantial copper corrosion after buffer erosion only occurs in deposition holes with high flow rates, and these are associated with low retention flow paths to the surface. Under this scenario, radionuclides from the repository are unlikely to reach the biosphere within the first 100,000 years.

The probability of canister failure due to rock shear in the event of a large earthquake is very small during the initial 1,000 years. However, the probability for a canister failure increases cumulatively with time, and in a perspective beyond 100,000 years this scenario contributes significantly to the risk for release of radionuclides to the biosphere.

Under both the corrosion and the shear load scenarios, the most likely outcome is that only one canister will fail. Contaminated groundwater from a failed canister may reach the biosphere at different times: the instantaneously accessible fraction of radionuclides from fuel dissolution may reach the biosphere in a pulse within years or tens of years after failure, whereas the release from the fuel matrix and corroded metals will result in a continuous release of radionuclides during very long time spans (> million years).

In SR-Site, radionuclide transport and dose consequences have been calculated by a sequence of models (Figure 3-4). The near-field model describes radionuclide release and transport in the canister interior, in the buffer, in the backfill of the deposition tunnel and it handles also the exit pathways from the near-field. The far-field model is used to describe transport in the water phase from the repository to the biosphere. In the assessment, groundwater flow is primarily modelled through a discrete fracture network (DFN) where individual fractures are represented explicitly.

The discharge points (exit points in Figure 3-4), which are simulated in the hydrogeological analysis, describes where in the landscape the discharge of deep groundwater from the repository could be expected and during which time periods. Accordingly, the analysis of discharge points includes both a spatial and a temporal dimension. However, it contains no information on the transport of radionuclides and when they might appear in the biosphere. The far-field transport model delivers radionuclide fluxes varying over time, however, the results contain no information on where in the surface system radionuclides are released or on the simultaneous flux of water. Thus, the discharge points are decoupled from the far field release. Finally, the requirement from the calculation chain is that an *a priori* conversion constant without temporal or spatial dimensions is used for calculating dose.

For the assessment of human safety, the radionuclide releases from the geosphere are multiplied by a *Landscape dose conversion factor, LDF* (see Chapter 10). The LDF describes transport, accumulation and consequences of the subsequent exposure of inhabitants in the biosphere, given a unit release rate per year of each considered radionuclide. The maximum LDF, taken over all potential discharge areas and times, is the endpoint of the biosphere assessment. By multiplying the maximum LDF with a release rate, the mean annual dose is obtained. Thus the biosphere assessment provides a conversion constant, which is used without any spatial or temporal connection to the release. The dose is scaled with a risk conversion factor (see below) to obtain the mean annual risk, which is the main endpoint in the SR-Site safety assessment, see **SR-Site main report**.

For the assessment of radiological effects on the environment, the release from the geosphere is used as input into the Radionuclide model for the biosphere (Chapter 8) to calculate activity concentrations in different environmental media. From these activity concentrations, internal and external exposure is assessed and the calculation endpoints are incremental dose rates for reference organisms and for representative species occurring at the site (μGy h^{-1}).

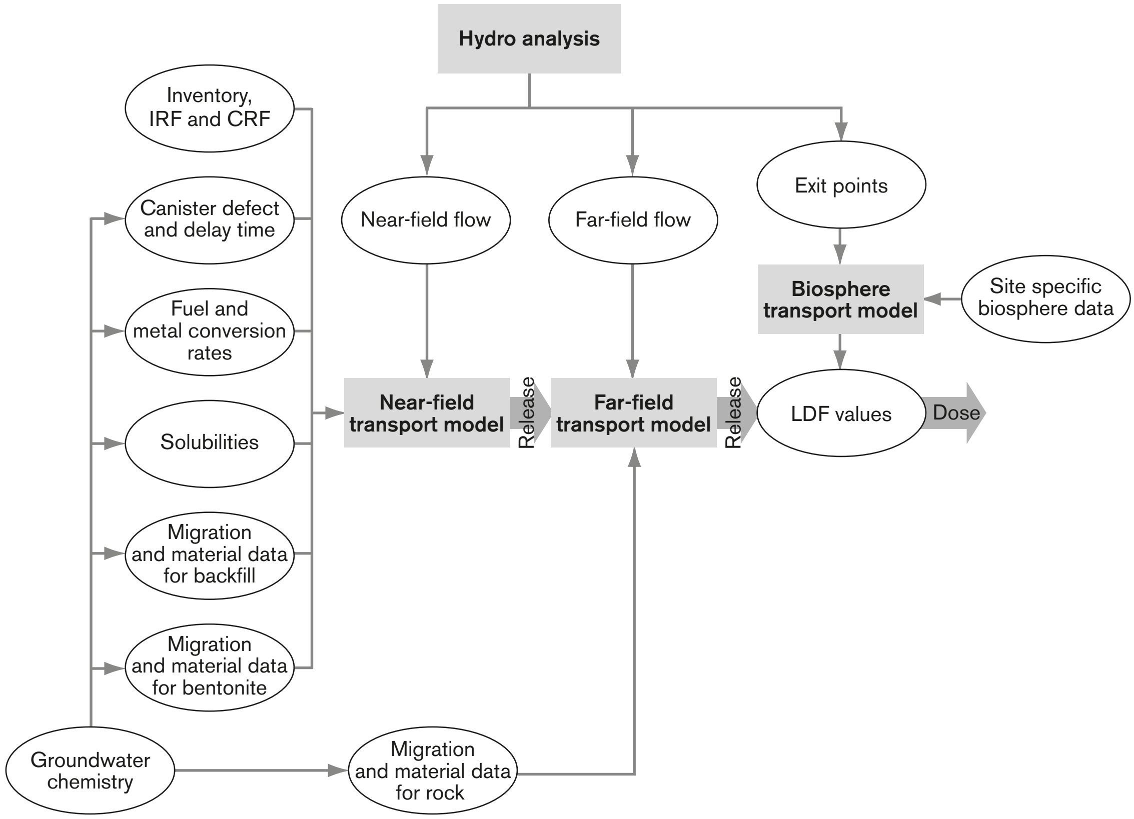

Figure 3-4. *Models and data for the SR-Site consequence calculations (cf. Section 13-4 in SR-Site main report /SKB 2010/).*

3.3 Regulatory requirements on post closure safety

The form and content of a safety assessment and the criteria for judging the safety of the repository are defined in regulations issued by the Swedish Radiation Safety Authority, SSM. The regulations are based on various pertinent components of framework legislation, the most important being the Nuclear Activities Act and the Radiation Protection Act. Guidance on radiation protection matters is provided by a number of international bodies, and national legislation is often, as in the case of Sweden, influenced by international rules and recommendations. There are two more detailed regulations and guidelines of particular relevance for the long-term safety of nuclear waste repositories:

- "The Swedish Radiation Safety Authority's regulations concerning the protection of human health and the environment in connection with the final management of spent nuclear fuel or nuclear waste"(SSMFS 2008:37) /SSM 2008a/.
- "The Swedish Radiation Safety Authority's regulations concerning safety in final disposal of nuclear waste" (SSMFS 2008:21) /SSM 2008b/.

According to the Swedish regulations, human health and the environment should be protected from the harmful effects of ionising radiation from the repository. The risk and dose criteria for protection of human health and environment, which are given in SSMFS 2008:37, are summarised below.

3.3.1 Time frames

The Swedish regulations require that the assessment of potential harm from the repository covers a period of 1 million years. Moreover, the regulations place stricter requirements on details of the assessment during the earlier parts of the period, i.e. during the first 1000 years after repository closure and during a period representing a glacial cycle (c. 100,000 years).

In SR-Site, the assessment is divided into four main periods; the initial period after closure, including the buffer resaturation phase, the first 1,000 years after closure of the repository, a complete glacial cycle (exemplified by Weichsel), and the period up to one million years after closure of the repository. Note that SR-Site covers only the post-closure assessment of the repository; assessment of human and environmental impacts during the operation phase can be found in the environmental impact assessment /SKB 2011/.

3.3.2 Risk criteria for protection of human health

The regulations state that “A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk” /SSM 2008a/. Moreover, it is stated that the recommendations of the International Commission on Radiological Protection (ICRP) Publication 60 /ICRP 1991/ are to be used for calculation of the harmful effects of ionizing radiation. According to ICRP Publication No. 60, the factor for conversion of effective dose to risk is 7.3% per Sievert.

3.3.3 Most exposed group

The most exposed group is not possible to describe in an unequivocal way. /SSM 2008a/ states that “One way of defining the most exposed group is to include the individuals that receive a risk in the interval from the highest risk down to a tenth of this risk. If a larger number of individuals can be considered to be included in such a group, the arithmetic average of individual risks in the group can be used for demonstrating compliance with the criterion for individual risk in the regulations. One example of such exposure situation is a release of radioactive substances into a large lake that can be used as a source of drinking water and for fishing”.

/SSM 2008a/ also states that “If the exposed group only consists of a few individuals, the criterion of the regulations for individual risk can be considered as being complied with if the highest calculated individual risk does not exceed 10^{-5} per year. An example of a situation of this kind might be if consumption of drinking water from a drilled well is the dominant exposure path. In such a calculation example, the choice of individuals with the highest risk load should be justified by information about the spread in calculated individual risks with respect to assumed living habits and places of stay”.

It should be noted that there are no prescriptions in the Swedish regulations concerning assumptions on future human behaviour and land use.

3.3.4 Effects on the environment

For the protection of the environment, no Swedish risk criteria exist. However, /SSM 2008a/ states: “The final management of spent nuclear fuel or nuclear waste shall be implemented so that biodiversity and the sustainable use of biological resources are protected against the harmful effects of ionising radiation”.

With reference to the assessment of protection of the environment, the guidance part of the regulations points out that (unofficial translation from Swedish):

“The organisms included in the analysis of the environmental impact should be selected on the basis of their importance in the ecosystems, but also according to their protection value according to other biological, economic or conservation criteria. Other biological criteria refers, among other things, to genetic distinctiveness and isolation (for example, presently known endemic species), economic criteria refers to the importance of the organisms for different kinds of obtaining a livelihood (for instance, hunting and fishing), and conservation criteria refers to if they are protected by current legislation and local regulations. Other aspects, for instance cultural history, should also be taken into consideration in the identification of such organisms.

The assessment of effects of ionising radiation in selected organisms, deriving from radioactive substances from a repository, can be made on the basis of the general guidance provided in the International Commission on Radiological Protection’s (ICRP) Publication 91 /ICRP 2003/. The applicability of the knowledge and databases used for the analyses of dispersion and transfer of radioactive substances in ecosystems, and for analysing the effects of radiation on different organisms, should be assessed and reported on.”

3.4 Relationship to international experience

The Swedish programme for handling and storage of spent nuclear fuel has a substantial history of working with international organisations and other national agencies with interests and responsibilities for radioactive waste management. This international cooperation gives the international community feedback from practical assessments, as well as feedback to the development of the safety assessment. Thus, the assessment context is dependent on the current international views of assessments.

3.4.1 Background to international cooperation in biosphere assessments

The Swedish programme has offered a willingness for peer review aspects of its safety assessment methods, going back as far as 1984 /Swedish Ministry of Industry 1984/. The reviews presented included contributions from the IAEA, the NEA-OECD, a Technical Advisory Committee of AECL (Canada), the French Institute of Protection and Nuclear Safety, the Atomic Energy Research Establishment (UK), the National Radiological Protection Board (UK), the US National Academy of Sciences, and the British Geological Survey. The reviews specifically included consideration of the biosphere, as illustrated in /Hill et al. 1984/. Shortly after that peer review process, the Swedish Radiation Protection Institute promoted and helped to maintain an international cooperation programme called BIOMOVS with the primary objectives to

- test the accuracy of predictions made by environmental assessment models for selected contaminants and exposure scenarios,
- explain differences in model predictions due to structural deficiencies, invalid assumptions and/or differences in selected input data, and
- recommend priorities for future research to improve the accuracy of model predictions.

The programme considered, among others scenarios, a range of very long-term radionuclide releases to the environment, as might arise as a result of solid radioactive waste disposal in repositories. The work focussed on scientific issues and the best use of data, allowing specialists to explore and develop assessment methods relevant to these long-term situations.

The participants included experts from 22 organisations from 14 countries. One of the model tools that was applied to the model testing exercises was BIOPATH, the biosphere model tool used in the 1983 KBS-3 study, which was subject to review in 1984 /Swedish Ministry of Industry 1984/. Following a programme running from 1985 to 1990, in which various exposure situations were evaluated, a final technical report was issued /BIOMOVS 1993/ and a second phase of cooperation, BIOMOVS II, was started.

The BIOMOVS II programme was similar in scope and also had wide international participation. Consideration was given to identification of critical Features, Events and Processes (FEPs), and the corresponding relevant model features and data requirements. Results from extensive quantitative model inter-comparisons were used to identify which processes could be important in which exposure circumstances, and what the implications might be of alternative representations of these processes. The BIOPATH model, in use at the time by SKB, was among the ten models tested in the comparison exercises under the heading of Complementary Studies /BIOMOVS II 1996b/.

In addition, consideration was given to the development of so-called reference biospheres. The initial idea had been to identify a few key sets of biosphere situations (reference biospheres) and assess the radiological implications of releases in these situations. The intention was to avoid endless speculation about the environmental conditions that might arise by the time of release. The results would be used as a measuring stick, or point of reference, by which to compare the performance of alternative disposal systems. However, it was apparent that a limited set of conditions, or reference biospheres, could not address the range of assessment contexts arising in all the different countries. Apart from the geographical and other physical conditions at different sites, it was recognised that the stage in the development of a repository programme largely determined the necessary and appropriate level of detail. However, it was agreed that a common approach should be developed internationally to solve the problem of identifying and justifying appropriate assumptions for environmental conditions and human behaviour in the long term when addressing a specific site. An outline methodology was developed, along with a corresponding structured list of FEPs and recommendations for methodology enhancement /BIOMOVS II 1996a/.

With the objective of addressing the BIOMOVS II recommendations, the International Atomic Energy Agency (IAEA) set up a "Reference biospheres" project within its BIOMASS Coordinated Research Programme. The project was completed over the period from 1996 to 2001 and built on the modelling and assessment experience within existing programmes, such as that on-going at SKB, as well as the evolution of international recommendations on radiological protection objectives for disposal of radioactive waste. Work was carried out under six Task Groups, including the participation of SKB experts and support organisations.

3.4.2 Biosphere analysis and dose assessments in other countries

Many countries are developing deep repositories for radioactive waste. They are at different stages of development; some are at a conceptual stage, some are investigating the scope for disposal according to assumptions related to geology type and corresponding design options, but are non site-specific, and yet others, like SR-Site are site specific. 'Reference biospheres', as discussed above, will be fit for purpose in the early stages, such as the well scenario described in /Vieno 1994/. Examples of geology-specific cases are given by /NAGRA 2002/ and /JNC 2000/, with biosphere assumptions relevant to the region being investigated. Later stage assessments require substantially more information /Haapanen et al. 2009/ and more detailed assessment /US DOE 2008/, so as to meet regulatory objectives as the programme approaches the licensing stage.

A common feature of the biosphere assessments is the use of assessment biospheres according to /IAEA 2003/, either in its draft forms or the final version, as a methodological basis for organising and structuring relevant information, and then identifying and justifying the specific assessment assumptions.

3.4.3 Current international projects and related research

A number of international projects that support or have relevance for the biosphere part of a waste repository performance assessment have been completed or are on-going. A common feature of the modern programmes of research has been the focus on site-specific assessments, which reflects the progress in stages of repository development.

Among the most substantial international collaboration projects has been the BIOPROTA programme. The project was initiated in 2002 and continues today involving a wide range of operators, regulators technical support organisations and research institutes from North America, Europe and Asia. Participants include operators, regulators and their technical support organisations, as well as research establishments. BIOPROTA is 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.

SKB has been pleased to participate in the project, given the clear focus on scientific evaluation of the science and site investigation work that can support environmental safety cases and related safety assessments. SKB has been among those organisations formally publishing the BIOPROTA output e.g. /Bergström et al. 2006/.

3.4.4 Application of the BIOMASS methodology in SR-Site

The BIOMASS methodology provides a formal procedure for the development of assessment biospheres in general /IAEA 2003/. An assessment biosphere is defined as:

"The set of assumptions and hypotheses that is necessary to provide a consistent basis for the calculations of the radiological impact arising from long-term releases of repository derived radionuclides into the biosphere."

The methodology is based on a staged approach in which each stage introduces further detail so that a coherent biosphere system description and corresponding conceptual, mathematical and numerical models can be constructed. The steps are as follows:

- Define the assessment context
- Identify and justify the biosphere systems to be evaluated
- Biosphere system description
- Consideration of potentially exposed groups
- Model development
- Calculation
- Iteration

This subsection provides a commentary on how those steps are matched within SR-Site. Since the start of the SKB s program the iteration has affected all parts in the program and thus the steps indentified in /IAEA 2003/ are not necessarily taken in the same order, but rather in parallel. It is also noted that the methodological steps are developed through serial investigation of potential sites and site selection, leading to selection of the Forsmark site for investigation within SR-Site.

Define the assessment context

This chapter sets out the assessment context for the biosphere within SR-Site. The overall objective is to:

- Set out what is to be assessed and why.
- Set out the initial premises which provide the boundary conditions to the assessment.
- Define the components of the context, e.g. purpose, assessment endpoints, and societal assumptions, generally issues which are resolved by scientific investigations, but which are needed to make the assessment coherent.
- Provide a clear record of the purpose of making the calculation.

Identify and justify the biosphere systems to be evaluated

A key issue in identifying biosphere systems is the fact that they are changing with time. SKB have placed great emphasis on this issue, because the sites of interest will be subject to substantial environmental change, and this change is explicitly recognised in regulatory guidance.

Environmental changes, primarily driven by climate change and isostatic changes in sea-level at Forsmark, are addressed in Chapter 6. These changes have substantial implications for the information needed to address the assessment endpoints, and include the importance of various biosphere processes and potentially relevant exposure pathways (Chapter 4), the identification of discharge areas and the development of these over time (Chapter 7), and model assumptions (Chapter 8), taking into account previous assessment experience.

Biosphere system description

/IAEA 2003/ offers suggestions for structuring biosphere system descriptions, and these have been taken into account in developing the description of Forsmark as it is today (Chapter 5) and how it is expected to develop as a result of environmental change (Chapter 6). In developing these descriptions, SKB has decided to take a thorough approach to the collection of information about the site, in order to develop an in depth bottom-up understanding of the ecosystems and their evolution, /see /Lindborg 2008/.

Consideration of potentially exposed groups

This is a difficult topic because one cannot reliably predict human behaviour so far into the future as is required for the safety demonstration. /IAEA 2003/ proposes the following approach:

- review exposure modes and routes relevant within the ecosystems of interest,
- identify and describe coherently human activities within those ecosystems, and
- combine human activities and exposure modes to identify those that are most likely to result in the highest doses.

Taking account of the assumptions for societal behaviour set out in this chapter, the same approach is taken by SKB. Human activities relevant within the ecosystems are set out in Chapter 4, and human utilization of resources in the area is described in Chapters 5 and 6. From this, reasonable and cautious assumptions on future human behaviour are developed in Chapter 8, and the most exposed group with respect to all potential discharge areas during a full interglacial is in Chapter 10 used to assess the consequences of a release from the repository.

Model development

/IAEA 2003/ suggests the following steps in model development.

- Identify conceptual model objects, i.e. distinct environmental media potentially influencing dose to the candidate exposure groups.
- Construct the conceptual model by considering the interactions between the conceptual model objects.
- Ensure that no potentially important Features, Events and Processes (FEPs) are omitted from the conceptual model.
- Identify data sources, define a mathematical model taking account of available data sources and scientific understanding, and derive relevant parameter values according to the data protocol.
- Incorporate the exposure group information.

SKB has taken the same steps, critically noting first the locations of possible release into the biosphere and describing the biosphere objects at those locations in chapter (Chapter 7). Similar to /IAEA 2003/, interaction matrices were used to develop an understanding of how these objects exist together over the area and ecosystems of interest (Table 4-2). A systematic approach was used to check the inclusion, or justified exclusion, of potentially FEPs. Two stages were then adopted to model development, first the development of potential discharge within the Forsmark landscape was modelled (Chapter 6 and 7), then the movement of radionuclides within the evolving biosphere objects was modelled (Chapter 8).

The calculation step in the biosphere assessment of SR-Site includes description of the selection and application of appropriate data to the mathematical formulations set out previously, in Chapters 7 and 8. similar to the /IAEA 2003/ protocol for parameter selection. This selection of data and data quality assurance are described in Chapter 9 and 8, respectively.

Iteration

The same methodological steps have been taken through serial investigation of potential sites and site selection, leading to selection of the Forsmark site for investigation within SR-Site. As increasing focus has been given to fewer, now a single, site, it has been both appropriate and possible to give greater consideration to particularly critical matters of the site, such as the details of the connection between the geophere with the surface ecosystems, the bio-geochemical features of soils and other important features of the biosphere.

3.5 Conclusions from earlier SKB work

The methodology for assessment of radiological effects on humans and the environment from a repository for spent nuclear fuel has developed considerably during the last few decades and SKB are deeply involved in this development. A number of biosphere assessments have been performed by SKB, starting with the KBS-3 assessment. The development has regularly been reported in the RD&D Programme, where /SKB 2010/ is the latest. A review of the first c. 25 years work with biosphere assessements is found in /Edlund et al. 1999/.

3.5.1 KBS-3

Already when the KBS-3 report was presented, the biosphere assessment was state of the art in terms of the consideration that it gave to current trends and knowledge in radioecology and systems ecology. In contrast to most other contemporary work it focussed on a real site. This work also inspired the implementation of the BIOMOVS international collaboration and its successors, as described in Section 3.3.

3.5.2 SR-97

With the SR-97 assessment, a spatially distributed model was introduced and site-specific data were used to parameterise the model. The biosphere was subdivided into different ecosystems, and ecosystem-specific dose conversion factors (EDFs) were calculated. Several important issues were identified. One of them was the gap in spatial vertical resolution between geosphere models and surface hydrology, i.e. the geosphere and biosphere interface was inadequately represented. Also, the importance of being able to communicate across the disciplines covering the repository, the geosphere and the biosphere in a coherent way was recognised. This was particularly highlighted by the large ranges of spatial and temporal scales of relevance in repository safety assessment.

It was also recognised that site-specific data regarding the biosphere was lacking in the previous SKB programmes, which led to the initiation of a collection of biosphere data that was the embryo of the site investigation programme for the biosphere. It was also apparent that a biosphere assessment must be flexible enough to handle a multitude of radionuclides and configurations, thus requiring a more flexible assessment tool. The results clearly showed that the use of a well for domestic water use as a main indicator in biosphere assessments had several drawbacks, mainly because higher doses where obtained from other sources. The lack of understanding of forest ecosystems contaminated by groundwater discharge was identified.

3.5.3 SAFE

SR-97 was followed by the renewed assessment of the SFR facility called SAFE, in which the geosphere-biosphere gap was eliminated and instead substituted by an overlap. However, some of the tools had difficulties in handling the resolution of the model domain, and there was a need for expanded site data. These insights contributed to the setup of the SKB site investigation programme, in order to collect better site data, and resulted also in the use of new numerical modelling tools for surface hydrology, such as MIKE-SHE. Studies of the surface hydrology indicated that discharge points seemed to be concentrated to low-lying areas, i.e. lakes, rivers, shorelines, a conclusion that has been further confirmed in SR-Site. The implication of this is that discharge points are not randomly distributed among the surface ecosystems, but are instead concentrated to specific ecosystems.

The biosphere assessment was in SAFE made directly on the discharge flux, in contrast to the use of a unit release rate as in the other assessments. The landscape was allowed to change with shoreline displacement and lake succession. This gave a temporal and spatial connection to the biosphere for the discharge. There was also an opportunity to collect some more site data that had been identified as crucial. A large effort was put into a systematic review of potential processes in the biosphere, resulting in the development of an interaction matrix that has been the basis for all following assessments.

An important insight was that there is a local biosphere around the repository that interacts with an external biosphere. This small concept adjustment has large implications on the use of e.g. concentration factors and other concepts commonly used in the assessment. Moreover, it was recognised that a concentration factor model is not very useful for addressing C-14, the most important radionuclide in this case, and a programme was initiated to substitute concentration factor models with models describing fluxes of organic matter and which also can handle point sources. In the assessment, a new flexible tool for simulation of the C-14 fluxes, implemented in Matlab/Simulink, was tested. This was the embryo of the tool used today, PANDORA. Moreover, a detailed oceanographic model with high discretisation was used to estimate water turnover. This assessment also developed a shoreline displacement model and the first versions of models for sedimentation and lake succession, models that have been further developed for SR-Site.

The SAFE assessment was also the first time when the draft version of the SSM regulations were applied and discussed. Especially, the concept of "today's biosphere" was clarified in the authorities' review, which criticised SKB's interpretation that it was the biosphere at the moment, i.e. the Bothnian Sea, which gave very high dilution and thus low doses. Moreover, the authorities asked for evidence that downstream accumulation gives lower doses than the doses at the point of discharge into the biosphere. In the SAFE assessment, SKB identified the need for a forest model for the assessment, and this conclusion was reinforced by the authorities. The SAFE project was the foundation for the biosphere group that has since then continued and extended its work for SR-Can and SR-Site.

3.5.4 SR-Can interim assessment

The development of the safety assessment for the HLW repository included several preparatory steps. One was a test safety assessment "SR-Can interim". This was then followed by SR-Can and now by SR-Site.

In SR-Can interim, the first version of the landscape model was implemented using a new developed toolbox for Matlab/Simulink called TENSIT. Exposure models were essentially the same as in SR-97 and SAFE, as there were no more site data available. The lessons learnt, besides those resulting in improvements of the modelling tool which resulted in PANDORA, was that with the models used the highest exposure was obtained in the first object in a chain or network of objects in a landscape. It was also realised that data handling and representation increased markedly when addressing a landscape with about 20 objects over 20 time steps. This required improved traceability and error checking, and to obtain this, new tools for filing and version handling were implemented. It was also realised that a full probabilistic treatment of a landscape was not a fruitful exercise.

Simultaneously, a large effort was made to implement a site investigation programme which, among other things, was designed to improve the knowledge database for the surface ecosystems, as well as providing data on several parameters used in SR-Site.

3.5.5 SR-Can

The SR-Can assessment aimed at presenting the methodology to be used for the application to construct a HLW repository and to demonstrate the role of the copper canister. In SR-Can, the PANDORA tool was used extensively and the landscape models were developed further. Site data were still sparse, but the understanding from the sites had improved substantially. From the transport modelling it was obvious that discharge from the repository will likely be limited to a restricted number of objects situated at the lowest points in the landscape, thus mainly lakes, mires, rivers and the sea. Moreover, it was concluded that forests, located in the more elevated areas, are unlikely recipients of a release from the repository.

A major step forward was that ecosystem models provided data on the sizes of groups that potentially will receive doses of different magnitudes. The landscape dose conversion factor (LDF) was calculated as the maximum dose conversion factor from all objects in a landscape over time. The risk to a representative member of the most exposed group was calculated with a log-normal distribution fit to the spectrum of persons receiving the highest dose to one tenth of the highest dose. The effects on non-human biota were evaluated with the ERICA tool (see description in Chapter 11) and it was demonstrated that the potential levels of environmental contamination from a repository were below screening levels discussed for tier 1 (the lowest screening level assessment in the ERICA tool). Furthermore, the concepts for representing the biosphere under conditions of permafrost and greenhouse warming were sketched out. In the simulations, the landscape changed at 1,000 year intervals and this resulted in artefacts in the calculations. Moreover, the land use at a given time in an object was either agricultural or "natural", which introduced conceptual misunderstandings, contradicting the well-based observations from the sites showing a gradual continuum of land use in time and space.

The international review by SSM pointed out several issues. Major concerns were about discretisation of the biosphere, the distribution of the discharge points, and the assessment of potential impact on non-human biota, which was not regarded as sufficient. Moreover, errors in calculations and parameter values were pointed out, as well as difficulties in traceability of data and results. The authorities also requested a presentation of the process understanding. The review comments have been taken into account in this safety assessment. For instance, some of the more important issues have been addressed through improved documentation of processes, and use of a clearer hierarchy of reports (outlined in this report). Traceability in the handling of review issues has been improved with the tools Subversion and Trac (Section 8.10).

3.6 Assessment philosophy

The assessment context includes what should be assessed, requirements set by the authorities, the international discussions and the history of the SKB biosphere assessment, as well as the constraints that are imposed by the assessment chain in SR-Site (Figure 3-4, see also below). Additionally, there are our own ambitions and goals how to solve the assessment, which we call the assessment philosophy.

The philosophy of the biosphere assessment has been to make estimations of the radiological risk for humans and the environment as realistic as possible, and as far as possible based on conditions measured at the site. The use of real site data means that assumptions and parameter values can easily be traced back to the site model and data. The assessment is based on a representative data set where the measured parameters are sampled at the same site during the same time period, which means that correlations and dependencies are taken into account. Thus, it is possible to make a scientifically underpinned and realistic assessment.

The assessment is based on substantial knowledge of present-day conditions at Forsmark and its past Holocene history. For the current situation, the uncertainty in assumptions and parameter estimates is relatively low (Chapter 5). For future situations, uncertainties in the societal development and biosphere properties are larger, and therefore some cautious assumptions have to be introduced in the assessments (Chapter 8 and discussion in Chapter 12). The only constraints on the future human land use in the SR-Site assessment are given by what humans reasonably can do in order to (unintentionally) maximise their exposure to potentially released radionuclides.

In Section 3.2.3, the assessment context for the calculation chain is described. The calculations chain set the frames and constraints for the biosphere assessment in several ways. Since there is no information on actual releases in time and space available for the biosphere assessment, we assume that all biosphere objects are equally likely to receive a release, and the release is assumed to be more or less constant over long periods. The results from the hydrogeological analysis (Figure 3-4) are only used only to identify biosphere objects in the biosphere assessment (Chapter 7) where potential releases might occur at any time, and, equally important, to screen out areas which never will get any release. This step reduces the number of potential biosphere objects and helps to concentrate the work on specific areas and ecosystem types for further considerations (Chapter 7)

Moreover, because an *a priori* conversion factor has to be estimated before the results from far field calculations are available, the dose conversion factor for a unit release rate (LDF) is estimated (Chapter 10). The maximum LDF value over time and across all biosphere objects is used to cautiously reassure that the worst instance in time and space is taken into account, regardless of the likelihood of radionuclide release into that specific object. This maximum LDF, which has no spatial or temporal dimension (even if detailed temporal and spatial calculations have provided it), is used as the conversion factor in the calculation chain. Since the maximum LDF is an *a priori* estimate, no further considerations are made on whether radionuclides are saturated in the environment or organisms.

The landscape dose conversion factors obtained from the biosphere assessment are best estimates for the most exposed group from deterministic simulations. These deterministic simulations are the combined result of process understanding, the most precise description of the site available and relevant assumptions on societal development. In addition, the effects of parameter uncertainties, assumptions and conceptual uncertainties on the estimated LDFs have been addressed through probabilistic simulations, alternative models and informed assumptions. This approach is consistent with recommendations from the ICRP /ICRP 2006/ and with the guidelines from SSM /SSM 2008/. We conclude that the current approach is cautious and sufficient to demonstrate compliance with the regulations, but that detailed consideration of the temporal and spatial scales in the assessment can potentially reduce the LDF.

4 Biosphere features, processes and pathways

This chapter provides a description of processes that are important for transport and accumulation of radionuclides within ecosystems. The knowledge of important processes is used in all aspects of the safety assessment, i.e. from site investigations and site description (Chapter 5) to radionuclide models (Chapter 8) and estimations of exposure (Chapter 10). In addition, exposure pathways for humans and other organisms are given in this chapter.

4.1 Evaluation of important biosphere processes

4.1.1 Identification of processes for transport and accumulation of radionuclides in the biosphere

The identification and handling of features, events and processes that are of significance for transport and accumulation of radionuclides in the environment is important in the assessment of human health and the safety of the environment. Ecosystems are complex with a large number of structures and functions, and the number of interactions within an ecosystem is unlimited. Thus, a systematic approach is needed to identify the ecosystems that are likely to receive discharge of contaminated groundwater, the compartments where radionuclides may potentially accumulate within these ecosystems, and the processes that affect the transport, accumulation and exposure of organisms and humans that live in or utilize the ecosystem. For the time frames of a deep geological repository, the effects of landscape development and ecosystem succession on transport, accumulation and exposure also need to be considered.

The interaction matrix (IM) is a practical tool to display identified components and pathways that may potentially affect radionuclide accumulation and exposure. When constructing an IM the major components of the system (in the case of the biosphere, an ecosystem), are listed along the lead diagonal of the matrix. The dynamics of the system is then described by processes acting between the major components. Processes are displayed as off-diagonal elements in the matrix, and represent direct interactions between two components that will result in a change in at least one of the components. Thus, an IM transparently documents compartments and processes considered in the safety assessment, and can be used to list the rationale for dismissing identified processes as being of little or no quantitative importance in a particular safety assessment /Avila and Moberg 1999, Velasco et al. 2006, Harrison and Hudson 2006/.

SKB has been working with IM to describe the effects of a potential release of radionuclides from deep repositories since the early 1990s /Eng et al. 1994, Skagius et al. 1995, Pers et al. 1999/. An early version of the IM for the biosphere was presented in 2001 /Kautsky 2001, SKB 2001/. SKB produced the IM for the biosphere with the aid of experts from several scientific disciplines including geology, oceanography, hydrology, soil science, chemistry, physiology and ecology. For the SR-Site safety assessment, the original IM has been updated to reflect the current understanding of ecosystem processes and radionuclide behaviour at the investigated site /SKB 2010/. The understanding reflected in the IM has been used as help to guide the planning of site investigations, the modelling of the site and its development, and the development of the radionuclide model.

The International Atomic Energy Agency (IAEA) has produced a database of features, events and processes (FEPs) that is used in safety assessments of repositories for radioactive waste by a number of countries. IAEA features and processes associated with the biosphere are included in SKB's biosphere IM unless they are clearly irrelevant to Swedish conditions. Definitions of IAEA FEPs and how they correlate to the process names used by SKB can be found in SKB's database of FEPs (FEP report).

4.1.2 Major components and processes identified in the biosphere assessment of SR-Site

15 components and 51 processes have been identified and described in total in the biosphere IM for SR-Site /SKB 2010/ (Figure 4-1). The identified components primarily represent different environmental media (geosphere, regolith, soil water, surface water, and atmosphere) and organism groups that are exposed, directly or indirectly, through these media (primary producers, decomposers, herbivores, carnivores, and humans). In addition, water chemistry, released radionuclides, temperature and external conditions were also included as separate components in order to increase matrix resolution and to make the IM more useful for radionuclide pathway analysis.

If the number of leading diagonal components increases, then the number of possible process interactions and the matrix resolution also increase. To keep the number of diagonal elements manageable they represent broad categories and there will be processes acting within these categories, i.e. within the diagonal elements. However, the diagonal elements have been selected in such a way that as many binary interactions as possible are placed in off-diagonal elements. As an example, it is possible to include water composition in soil water and surface water. However, that would lead to many process interactions occurring within diagonal elements and the IM would not sufficiently illustrate important radionuclide pathways.

Not all processes between the components in the IM are expected to be quantitatively important for transport and accumulation of radionuclides from a deep repository in Forsmark. Thus, of the 51 identified processes, 34 were considered to be relevant and sufficient for assessing the safety of human health and the environment (Table 4-1). To illustrate the nature of these processes they have been grouped into six broad categories, namely 1) biological processes, 2) processes related to human behaviour, 3) chemical, mechanical and physical processes, 4) transport processes, 5) radiological and thermal processes and 6) landscape development processes. In the text below, these process categories are described, and key processes are briefly described. A detailed description of all processes is given in /SKB 2010/, and the rationale for why some of these processes are not relevant in the safety assessment is provided in /Andersson 2010, Aquilonius 2010, Löfgren 2010/.

Biological processes

Biological processes are processes that are dependent on organisms. One way of exposure of radionuclides is via intake of water and food and thus the distribution of biota and food-web interactions is important to consider. In addition, biota may influence the distribution of radionuclides in abiotic pools by e.g. disturbing sediment or affecting water composition. The biotic processes are general and may involve both humans and other organisms. Processes that are strictly related to humans are categorised as processes related to human behaviour (see below). Consumption, decomposition, excretion, food supply, growth, habitat supply, primary production, stimulation/inhibition, and uptake are biotic processes that influence the distribution of radionuclides in biota and transport of radionuclides in food webs.

The processes bioturbation and particle release/trapping are biotic processes that influence the abiotic compartment of the environment. Bioturbation influences the properties of the regolith and thereby affects the accumulation of radionuclides in the regolith. Particle release/trapping influences the amounts of particles in water and air, which is important for the transport of radionuclides adhering to particles.

Processes related to human behaviour

Human behaviour may have large effect on the biosphere, e.g. by introducing species of biota or chemical elements or by disturbing or removing material in large quantities. Water use, anthropogenic release, and species introduction/extermination are processes related to human behaviour that are necessary to consider in a safety assessment.

Chemical, mechanical and physical processes

These are processes that result from interactions at varying degree of strength: strong interactions (physical, including mechanical) follow physical laws, chemical laws regulate weaker interactions.

Chemical, mechanical and physical processes can influence the state of elements and compounds, which can be important for the transport of radionuclides. For example, in some states elements are tightly bound to particles and in other states they may be easily dissolved and transported by water. Chemical, mechanical and physical processes necessary to consider in the safety assessment are, for example, element supply, phase transitions and sorption/desorption. Element supply is the amount of elements available to use for biota and a low element supply may limit the production. The process phase transition is important, among others, for transport of C-14 from water to air. The process sorption/desorption determines whether radionuclides are bound to surfaces or dissolved in water and is crucial to consider when determining the transport and biological uptake of radionuclides.

Transport processes

Transport processes are processes whereby elements and substances are transported from one point to another in a system. Transport processes important to consider in the safety assessment are convection, deposition, import, resuspension, relocation and saturation.

Convection includes surface water flow, and groundwater discharge and recharge. Discharge and recharge are important for the transport upwards from a repository to surface systems and the pattern of discharge and recharge is important for understanding why transport of deep groundwater occurs. Surface water flow is also important for relocation of radionuclides, since relatively fast transport through the landscape can take place in surface waters compared with groundwater and may affect the retention time in water bodies. In addition, flooding may cause a redistribution of radionuclides in the landscape. Radionuclides that have reached the surface system can, via flooding and recharge, go back to the groundwater system again.

Import is the transport of radionuclides from surrounding ecosystems. This process may be of importance for the amounts of radionuclides in an ecosystem. The processes resuspension, relocation and deposition are important for the transport from sediment to water column and vice versa. Deposition is, in addition to sedimentation, also used to describe meteorological precipitation, which is important for water balances and surface water flow. Saturation refers to changes in water content of the regolith, which is important for the properties of the regolith, which in turn, affect convection as well as living conditions for biota.

Radiological and thermal processes

Thermal and radiological processes are those processes that concern temperature, solar insolation and radionuclides. Thermal and radiological processes important to consider in safety assessments are decay, exposure, light-related processes, and radionuclide release. Radionuclide-specific characteristics influence the transport of radionuclides and are, for obvious reasons, important to consider in the safety assessment. The amount of radionuclides released, decay and exposure are crucial for the safety analysis.

The process heat storage has a great influence on both biotic and abiotic components of aquatic ecosystems influencing e.g. distribution of biota, mixing of the water column, and occurrence of ice cover preventing exchange across the air-water interface. Light-related processes include insolation, light absorption, light reflection and light scattering, which influence primary production. Radionuclide release is the release of radionuclides from the repository and is for obvious reasons important to quantify in the safety assessment.

Landscape development processes

Type of ecosystem influences transport and accumulation of radionuclides. Landscape development processes important to consider in the safety assessment are change in rock-surface location, sea-level change, terrestrialisation, and thresholding. Terrestrialisation is the process that turns lakes to mires. Thresholding is the occurrence and location of thresholds that delimit water bodies like lakes and sea basins. The processes change in rock surface location, sea level change, terrestrialisation and thresholding determine the size and type of ecosystem at the site.

Necessary for dose assessment	Not necessary for dose assessment	No interaction

	1	2	3	4	5	6	7	8
1	**GEOSPHERE (B.C.)**	a) Change in rock surface location b) Weathering						a) Material supply
2	a) Consolidation b) Loading	**Regolith**	a) Element supply b) Habitat supply c) Light related processes d) Relocation	a) Element supply b) Food supply c) Habitat supply	a) Food supply b) Habitat supply	a) Habitat supply	a) Habitat supply	a) Food Supply b) Habitat supply c) Material supply
3	a) Intrusion	a) Bioturbation b) Death	**Primary producers**	a) Habitat supply b) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Habitat supply b) Stimulation/inhibition	a) Food supply b) Material supply c) Stimulation/inhibition
4	a) Intrusion	a) Bioturbation b) Consumption c) Death d) Decomposition	a) Stimulation/inhibition	**Decomposers**	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	a) Food supply b) Material supply c) Stimulation/inhibition
5	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Habitat supply c) Stimulation/inhibition	a) Consumption b) Habitat supply c) Stimulation/inhibition	**Filter feeders**	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition	a) Food supply b) Material supply c) Stimulation/inhibition
6	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Stimulation/inhibition	a) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	**Herbivores**	a) Food supply b) Stimulation/inhibition	a) Food supply b) Material supply c) Stimulation/inhibition
7	a) Intrusion	a) Bioturbation b) Death	a) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	**Carnivores**	a) Consumption b) Food supply c) Material supply d) Stimulation/inhibition
8	a) Intrusion b) Material use	a) Death b) Material use c) Relocation	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination e) Stimulation/inhibition	**Humans**
9	a) Change of pressure b) Convection c) Weathering	a) Relocation b) Saturation	a) Habitat supply b) Water supply	a) Habitat supply b) Water supply	a) Water supply	a) Water supply	a) Water supply	a) Water supply
10	a) Change of pressure b) Convection c) Loading d) Weathering	a) Relocation b) Resuspension	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Water supply	a) Habitat supply b) Water supply
11	a) Convection b) Weathering	a) Deposition b) Phase transition c) Weathering	a) Element supply b) Food supply c) Light-related processes d) Stimulation/inhibition	a) Element supply b) Food supply c) Habitat supply d) Stimulation/inhibition	a) Element supply b) Food supply c) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition	a) Stimulation/inhibition
12	a) Convection	a) Reactions	a) Element supply b) Stimulation/inhibition	a) Element supply	a) Element supply	a) Element supply	a) Element supply	a) Deposition b) Element supply c) Stimulation/inhibition
13	a) Convection b) Weathering	a) Physical properties change b) Weathering	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition
14	a) Radionuclide release	a) Deposition b) Irradiation	a) Exposure	a) Exposure	a) Exposure	a) Exposure	a) Exposure	a) Exposure
15	a) Change in rock surface location	a) Change in rock surface location b) Import c) Saturation d) Terrestrialisation	a) Import b) Light-related processes	a) Import	a) Import	a) Import	a) Import	a) Import

Figure 4-1. *The interaction matrix used in the SR-Site biosphere assessment. The diagonal elements (grey) are key components of an ecosystem. The off-diagonal elements (coloured boxes) represent processes where by the components interact. The matrix is read clockwise, so that the effect of e.g. Regolith (2:2) on Primary Producers (3:3) through e.g. supply of nutrients and trace elements is found above the diagonal in box (2:3), whereas the effects of Primary Producers on the Regolith through e.g. plant Senescence ("death") is found below the diagonal in box (3:2). An off-diagonal element is empty when two ecosystem*

9	10	11	12	13	14	15
a) Convection	a) Convection	a) Convection	a) Convection	a) Convection	a) Radionuclide release	
a) Convection b) Thresholding	a) Acceleration b) Convection b) Thresholding	a) Phase transition b) Reactions c) Resuspension d) Sorption/desorption	a) Reactions	a) Convection b) Heat storage c) Light-related processes d) Pressure change	a) Phase transition b) Sorption/desorption	a) Export b) Thresholding
a) Excretion b) Uptake	a) Acceleration b) Covering c) Excretion d) Interception e) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Acceleration b) Excretion c) Particle releas/trapping d) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Decomposition b) Excretion c)Uptake	a) Acceleration b) Decomposition c) Excretion d) Movement e) Uptake	a) Consumption b) Death c) Decomposition d) Excretion e) Particle release/trapping f) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
	a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
	a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-relaetd processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
	a) Excretion b) Movement c) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Uptake c) Water use	a) Acceleration b) Antropogenic release c) Covering d) Excretion e) Movement f) Uptake g) Water use	a) Anthropogenic release b) Death c) Excretion d) Uptake e) Water use	a) Acceleration b) Anthropogenic release c) Excretion d) Uptake	a) Anthropogenic release b) Convection c) Light-related processes d) Reactions	a) Anthropogenic release b) Excretion c) Growth d) Sorption/desorption e) Uptake	a) Export
Water in regolith	a) Convection	a) Convection b) Physical properties change c) Relocation	a) Phase transition	a) Convection b) Heat storage	a) Convection	a) Export
a) Convection	**Surface water**	a) Convection b) Physical properties change	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Convection c) Heat storage d) Light related processes	a) Convection	a) Export b) Import
a) Convection	a) Convection	**Water composition**	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Light-related processes c) Reactions	a) Phase transition b) Sorption/desorption	a) Export
a) Convection b) Phase transition	a) Convection b) Deposition c) Phase transition d) Wind stress	a) Deposition b) Phase transition c) Wind stress	**Local atmosphere**	a) Change of pressure b) Convection c) Heat storage d) Phase transition e) Light-related processes f) Reactions	a) Convection b) Sorption/desorption	a) Export
a) Phase transition	a) Convection b) Phase transition	a) Convection b) Physical properties change c) Reactions	a) Change of pressure b) Convection c) Phase transition	**Temperature**	a) Reactions b) Phase transition	a) Export
		a) Decay b) Radiolysis c) Reactions	a) Phase transition	a) Decay	**Radionuclides (*)**	a) Export
a) Import	a) Convections b) Import c) Sea level change d) Terrestrialisation	a) Import	a) Import b) Reactions	a) Import b) Light-related processes	a) Import	**External conditions**

components do not interact. Interactions that were considered in detail in the biosphere assessments are marked in orange, whereas interactions that were judged to have a minor or insignificant effect on the transport and accumulation of radionuclides are marked in yellow. The details of the biosphere interaction matrix, and the underlying matrices for the sea, lake and terrestrial ecosystems are presented in /SKB 2010, Andersson 2010, Aquilonius 2010, Löfgren 2010/.

Table 4-1. Short definitions of the 34 processes that are included in the safety assessment for spent nuclear fuel in Forsmark. A fuller description of the processes is given in /SKB 2010/. * denotes biological processes that may concern humans in some interactions.

Biological processes	
Bioturbation	The mixing of elements and particles in both aquatic and terrestrial regolith by organisms.
Consumption*	When organisms feed on solid material and/or on other organisms.
Death	The generation of dead organic matter by organisms.
Decomposition	The breakdown of organic matter.
Excretion*	The excretion of water or elements to the surrounding media by humans and other organisms.
Food supply	The fraction of produced biomass that can be used as a food source for humans and other organisms.
Growth*	The generation of biomass by organisms
Habitat supply	The providing of habitat for organisms by abiotic elements or other organisms.
Particle release/trapping	Organisms release particles (for example by fragmentation, spawning and pollen release) or trap particles (for example with gills, feathers and slime).
Primary production	The fixation of carbon by primary producers in photosynthesis.
Stimulation/inhibition*	When one diagonal element positively or negatively influences another diagonal element. The extreme of inhibition prevents an interaction completely and leads to exclusion from the model domain (e.g. primary production is not possible below the photic depth in lakes and sea).
Uptake*	The incorporation of water or elements from the surrounding media into humans and other organisms.
Processes related to human behaviour	
Anthropogenic release	Release caused by humans of substances, water or energy into the local biosphere. (For example irrigation of vegetables).
Species introduction/ extermination	Introduction or extermination of species from the model area by human activities (e.g. introduction of crayfish in lakes).
Water use	Water used by humans for other purposes than drinking, e.g. washing, irrigation and energy production. This process may affect the water table.
Chemical, mechanical and physical processes	
Element supply	The availability of elements and substances for use by organisms.
Phase transition	Changes between different states of matter: solid, liquid and gas.
Physical properties change	Changes in volume, densities and/or viscosity.
Sorption/desorption	Dissolved substances adhere to surfaces or are released from surfaces.
Wind stress	A mechanical force generated by wind.
Transport processes	
Convection	The transport of a substance or a conserved property with a fluid or gas.
Deposition	Vertical transfer of a material or element to a surface of any kind due to gravitation, e.g. sedimentation, rainfall, and snowfall.
Import	Transport into the model area.
Relocation	Transport of solid matter and sessile organism from one point to another.
Resuspension	The stirring up of previously settled particles in water or air.
Radiological and thermal processes	
Decay	The physical disintegration or transformation of radionuclides to other radionuclides or stable elements.
Exposure	The act or condition of being subject to irradiation. Exposure can either be external exposure from sources outside the body or internal exposure from sources inside the body.
Heat storage	The storage of heat in solids and water.
Light-related processes	Processes related to the light entering the biosphere (insolation), e.g. absorption, attenuation, reflection and scattering.
Radionuclide release	Release of radionuclides from the repository for spent nuclear fuel.
Landscape development processes	
Change in rock surface location	Changes in the location of the rock surface due to isostatic rebound or repository-induced changes.
Sea level change	Alteration in the level of the sea relative to the land.
Terrestrialisation	Infilling of a lake or shallow sea basin with mire vegetation.
Thresholding	The occurrence and location of thresholds delimit water bodies like lakes and sea basins.

4.2 Exposure pathways

Man and other organisms can be exposed to radionuclides both externally and internally in the environment. Exposure pathways identified as significant from an analysis of a diverse use of natural resources that can be observed today have been included in this safety assessment /Avila et al. 2010/. These pathways are briefly described below whereas a fuller description and a discussion of exposure pathways considered but found to be insignificant (e.g. the use of contaminated peat) are presented in /Avila et al. 2010/.

Based on earlier assessments /Bergström et al. 1999, Avila and Bergström 2006, **SR-Can main report**/ it is concluded that the major long-term risk for human exposure to radionuclides from a repository is from internal exposure. The internal exposure is always preceded by incorporation of radionuclides into the human body. This can occur mainly by ingestion of contaminated water and food or inhalation of contaminated air.

The internal exposure will, among other things, depend on the fraction of contaminated food and water consumed and the level of activity in the food and water. In this methodology, it is assumed that all water and food is contaminated, but other situations can easily be addressed by introducing corrections to account for the fraction of consumed water and food that is not contaminated. The dietary composition can also have an impact on the internal exposure, as different foods can have different contamination levels. However, for long-term assessments it is difficult to postulate a particular dietary composition, as the human habits and choices may change. Food intake and food production are important processes that will affect the potential exposure of humans to radionuclides derived from the repository. The assumptions on human food consumption are discussed in more detail in Chapter 12.

The exposure via inhalation of contaminated air can occur both outdoors and indoors. However, exposure indoors may be lower than outdoors due to the filtering effects of buildings. In SR-Site, only outdoor exposure (hundred percent of time) was considered, which in most cases gives a conservative estimate, as the radionuclide contamination of the air comes from resuspension of soil particles. The situation could, however, be different for isotopes of elements that can exist in gas form in the environment. No separate biosphere assessment is carried out for such radionuclides. However, isotopes that are likely to enter the gas phase to any significant extent are assessed in Section 13.8 in the SR-Site Main Report. Other pathways for radionuclide penetration into the human body, for example through the skin, are of little significance in comparison with the pathways that are assessed /Avila et al. 2010/.

The external exposure comes from radiation emitted by the radionuclides in surrounding environmental media, comprising air, water, soils and sediments. Previous safety assessments of planned geologic repositories /Bergström et al. 1999, Karlsson and Bergström 2000, **SR-Can main report**/ have shown that, for most radionuclides of interest, external exposure gives a minor contribution to the total dose. Thus, in most cases, external exposure contributes only marginally to total risk.

5 Site description – present-day conditions at Forsmark

This chapter provides a brief description of the present-day conditions at Forsmark, based on available knowledge from the site investigations. More detailed descriptions of the site can be found in the site description report for Forsmark /SKB 2008/ and in the report describing the surface systems at Forsmark /Lindborg 2008/.

Understanding of surface systems at the Forsmark site needs a combination of information from several scientific disciplines in order to give an overall picture of factors forming the conditions in the present landscape. Moreover, the present conditions could not be understood without a historic perspective that forms a basis for understanding of the continuously transforming landscape. Abiotic factors set the limits and create prerequisites for the formation of ecosystems, which in turn affect the physical environment via feedback mechanisms.

The chapter starts with a presentation of the abiotic characteristics of the Forsmark area which sets the physical and chemical limits for the formation of ecosystems (Section 5.1), and continues with an overview of the present-day ecosystems of the site and of the utilisation of the landscape by humans (Section 5.2).

5.1 Abiotic characteristics

Abiotic characteristics like topography and climate, as well as physical properties of the bedrock, regolith and water, set the limits for development of ecosystems and human utilization of the landscape. Abiotic factors, the development of ecosystems and the resulting chemical environment are interdependent; the formation of ecosystems influences abiotic factors such as soil properties, as well as hydrochemical characteristics of the surface water, whereas the chemical environment in turn gives prerequisites for the formation of specific ecosystems. The abiotic factors and conditions described in this section are important for the understanding of the present-day Forsmark area and constitute important input parameters in the radionuclide transport modelling.

5.1.1 Topography

The topography of the Forsmark area is characterised by a low relief (Figure 5-1). In terrestrial areas, elevation differences are usually less than 20 metres. Prominent topographical features of the landscape are the relatively small glacial landforms like eskers. The relief is more pronounced west and south of the Forsmark area, where the relative relief reaches 50 metres in a landscape characterised by bedrock lineaments and fracture zones oriented largely in the directions of N-S and NW-SE (Figure 5-2) /Olvmo 2010/.

SKB has developed a *digital elevation model* (DEM) to describe the topography of the area (Figure 5-3). The DEM, which covers an area of approximately 30 km · 30 km serves as input to other models for projection of both past and future conditions. The DEM is a central data source for the site characterisation, and is used as input to most of the descriptions and models produced for the surface system. Detailed descriptions of the DEM are provided in /Brydsten and Strömgren 2004/ and /Strömgren and Brydsten 2008/.

5.1.2 Regolith

The term regolith refers to all loose material overlying the bedrock. The major portion of regolith at Forsmark is glacial deposits, reworked during multiple glaciations and relocated by subsequent glacial and post-glacial processes. The upper part of the regolith is affected by deposition and decomposition of organic material, and in terrestrial areas also by weathering of the original material, thus forming soil in terrestrial areas and sediments, often rich in organic matter, in aquatic areas. Data describing regolith properties is an important input when modelling the hydrology and transport of elements and various compounds within the geosphere and between the biosphere and the geosphere. Soil properties are also strongly associated with classification of vegetation types and land use in the terrestrial ecosystem, and regolith data therefore contribute to the prediction of future vegetation types when the present-day sea floor becomes parts of the terrestrial system following isostatic rebound.

Figure 5-1. The Forsmark area seen from south-east, with the only larger arable land area, Storskäret, in the foreground.

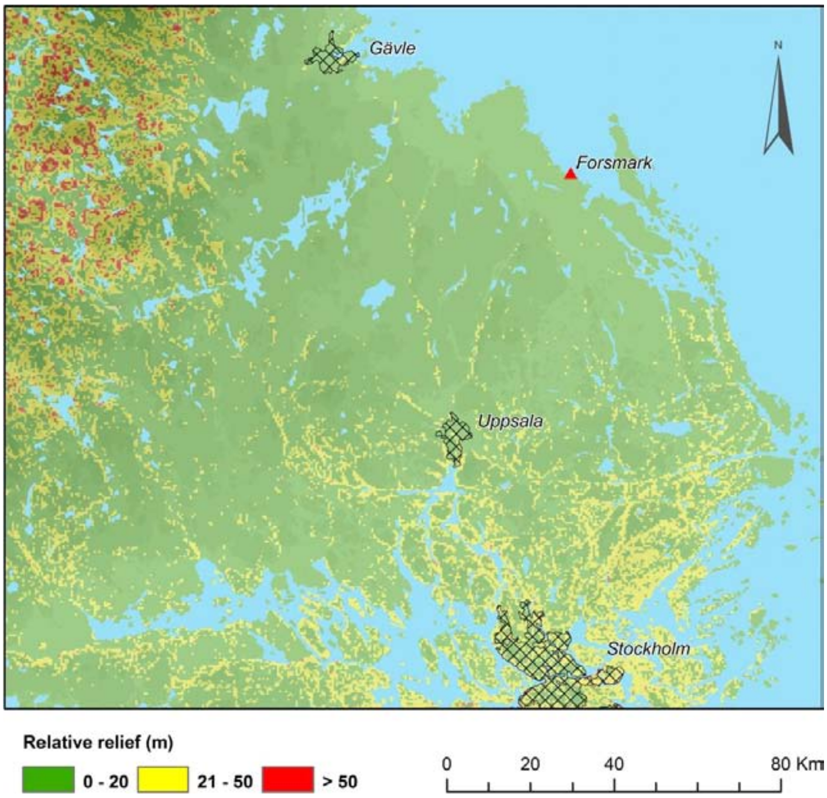

Figure 5-2. Topography of the region around Forsmark illustrated by relative relief, in this case calculated as maximum elevation range within grid cells of 300 x 300 metres. The relative relief is less than 20 metres in most parts of the area, which makes glacial landforms like eskers (north-south trending lines of yellow pixels north of Uppsala) protrude more than bedrock hills. Figure from /Olvmo 2010/.

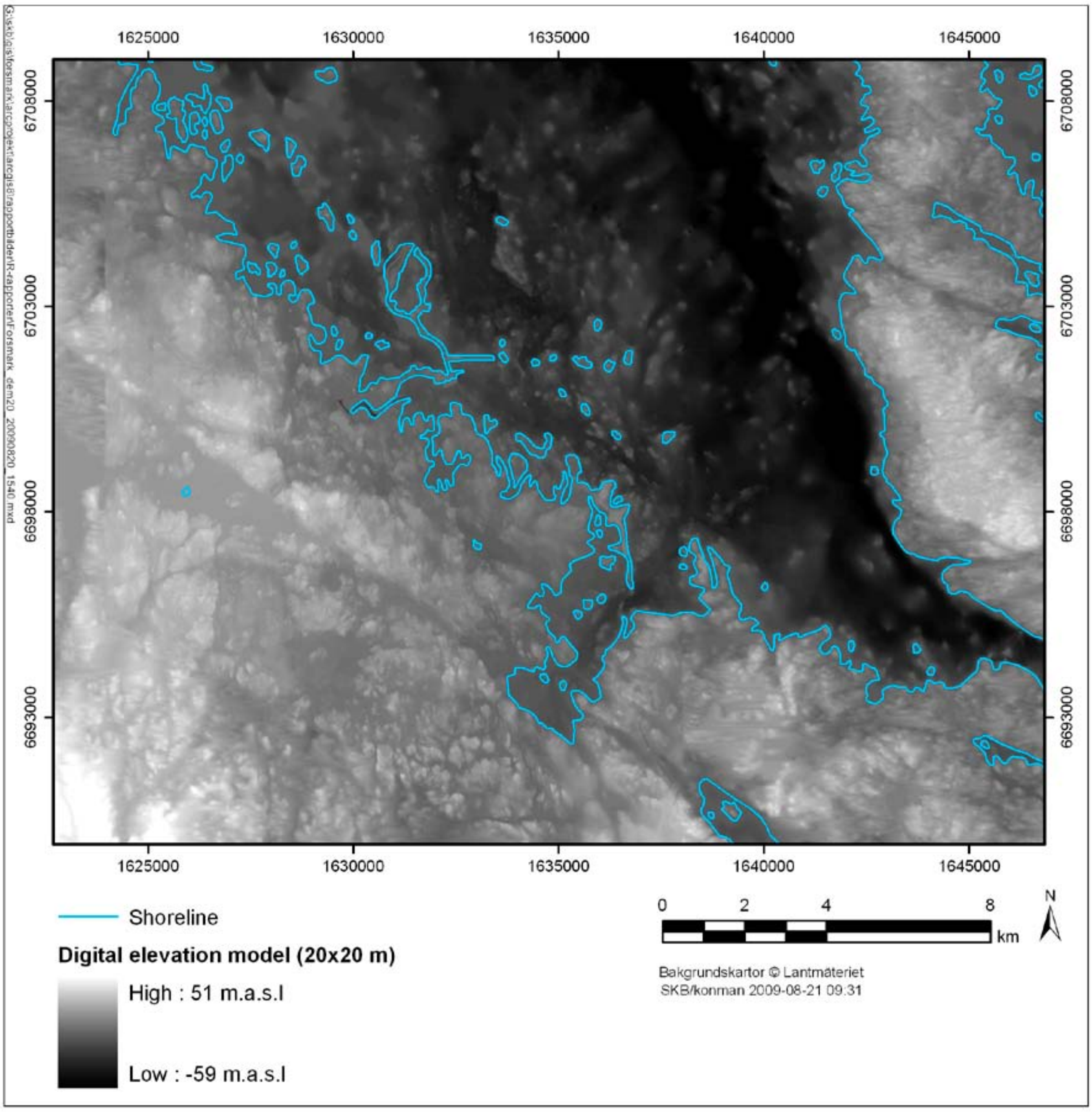

Figure 5-3. *The digital elevation model (DEM) for the Forsmark area describes the topography (including the present-day bathymetry). The current shoreline is illustrated by a light blue line. Figure modified from /Strömgren and Brydsten 2008/.*

Regolith distribution and properties

Approximately 90% of the ground surface in the Forsmark area consists of regolith that originates from the last glaciation when the ice sheet reworked and redistributed sediments of earlier Quaternary glaciations. The distribution of regolith, shown in Figure 5-4, follows the general pattern for areas in Sweden below the highest postglacial coast-line. Elevated parts of the terrain are dominated by till or exposed bedrock and valleys have a higher percentage of clay and postglacial redeposited fine-grained material. Till constitutes the dominant regolith exposed at the ground surface, occupying approximately 65% of the terrestrial surface areas and 30% of the area currently submerged by the sea. Generally, the till is thicker in depressions, thus levelling out some of the bedrock relief. The till in the Forsmark area is subdivided into 1) a sandy till with medium frequency of superficial boulders (dominant), 2) a clayey till with low boulder frequency, and 3) a sandy till with high boulder frequency /Hedenström and Sohlenius 2008/. Clay, gyttja clay, sand and peat occur frequently but scattered, mainly covering smaller patches. Peat accumulation occurs in all Forsmark wetlands, but deposits thicker than 0.5 m are restricted to the south-western part of the investigated area. This is the most elevated part of the Forsmark area and has therefore experienced terrestrial conditions and peat accumulation for the longest time /Fredriksson 2004/.

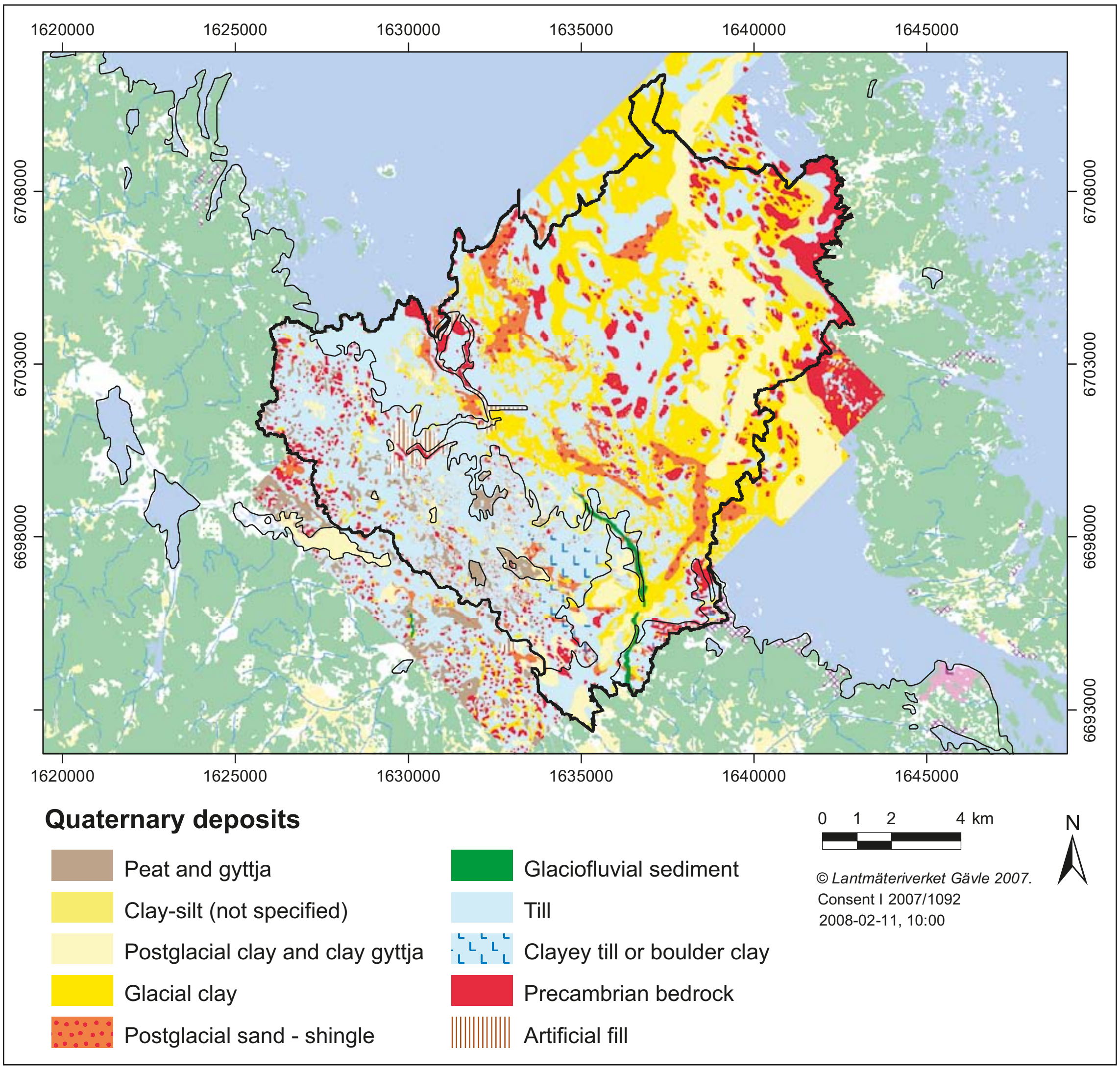

Figure 5-4. *The distribution of regolith at Forsmark, characterised at 0.5 m depth /Hedenström and Sohlenius 2008/. It should be noted that the areas presently submerged by water (limnic and marine environments) are presented without water. The black line shows the extension of the regolith depth model (Figure 5-5). Figure from /Hedenström and Sohlenius 2008/.*

Table 5-1. The proportions (%) of areas covered with different Quaternary deposits (characterised at 0.5 m depth) and bedrock exposures, overall and in subareas of the Forsmark area. The subareas are described in /Figure 2-3 in Hedenström et al. 2008/. Terrestrial refers to all areas not submerged by the sea.

	All areas	Terrestrial	Marine area
Bedrock exposures	9	13	6
Glacial clay	25	4	41
Postglacial clay (including gyttja clay and gyttja)	11	4	17
Postglacial sand and gravel	4	2	6
Till total (sandy/clayey)	48.5 (46/2.5)	65 (58/7)	30
Glaciofluvial sediment	0.5	1	0
Peat	1	8	–
Artificial fill	1	3	–

A high content of calcium carbonate ($CaCO_3$) is recorded in a majority of the glacial deposits /Hedenström and Sohlenius 2008/. The carbonates originate from Palaeozoic limestone on the bottom of the Bothnian Sea, brought to Forsmark by glacial transport. Due to continuous weathering, the $CaCO_3$ affects shallow groundwater and soil conditions by increased concentrations of calcium and bicarbonate /Tröjbom and Söderbäck 2006/. The soil types in the area are typically of low maturity and lacks well developed soil horizons because of the relatively short period of exposure to soil-forming processes /Lundin et al. 2004/.

Regolith depth and stratigraphy

Information on regolith depth and stratigraphy in Forsmark is extensive as a result of drillings, excavations and geophysical measurements during the site investigations /Hedenström and Sohlenius 2008/. This information is used for interpolation in a regolith depth model /Hedenström et al. 2008/ to get a total coverage of estimated regolith vertical distribution (Figure 5-5). Regolith in the model is subdivided into seven layers and three generalised lake sediment lenses. The total regolith depth in the model varies between 0.1 and 42 m. Areas with thin regolith and frequent bedrock outcrops are mainly the coastal zone and the islands, including the coastal zone of Gräsö Island. Generally,

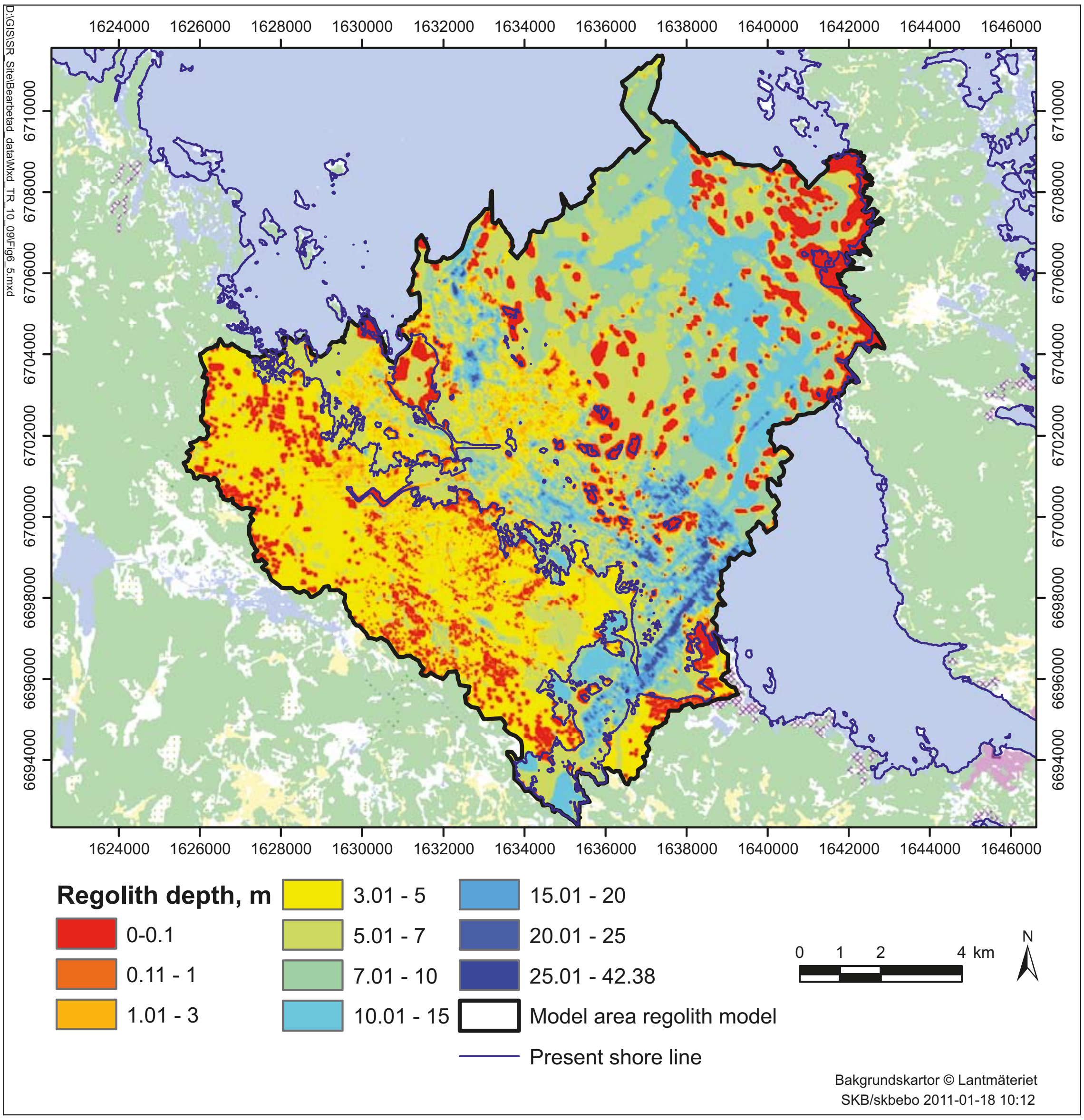

Figure 5-5. *Total modelled regolith depth at Forsmark. Figure from /Hedenström et al. 2008/.*

the regolith is deeper in the marine area where the average regolith depth is c. 8 m, whereas the average regolith depth in the terrestrial area is approximately 4 m. A reason for thicker sediments in the marine areas is the local bathymetry; the submarine N-S trending trough west of Gräsö Island has functioned as a sediment trap, enhancing deposition both due to glacial and postglacial processes.

The stratigraphical distribution of till is homogenous in most parts of the area, however, a more complex till stratigraphy has been observed at some sites. The distribution of sediments in the lakes and ponds is fairly uniform, with generally thin sediment sequences. The total thickness of water-laid sediments is less than 2 metres in the majority of the investigated lakes /Hedenström 2004/. Based on the results from the site investigations, a general stratigraphy for the Forsmark area is shown in Table 5-2.

An inventory of small and shallow basins located in the central part of the investigation area showed that approximately half the investigated sites had a layer of clay under organic sediments /Sohlenius and Hedenström 2009/.

5.1.3 Climate

The mean annual temperature at Forsmark is approximately +7°C (Table 5-3), measured during three subsequent years (Jan. 2004–Dec. 2006) at two meteorological stations in the vicinity of Forsmark. The temperatures are slightly milder at the station closest to the coast. The dominating wind direction in the area is from south-west. The region shows a strong precipitation gradient in the east-westerly direction. The annual corrected precipitation in the Forsmark area during the studied period was 546 mm/y /Johansson 2008/, to be compared with the 30 year long-term mean precipitation of 690 mm/y 15 km west of the Forsmark area, and only 490 mm/y at a similar distance north-east of Forsmark /Larsson-McCann et al. 2002/.

Snow cover in the area has been measured weekly during five seasons (2002/03–2006/07). On average, snow covered the ground for 105 and 80 days/season on forest land and open land, respectively, and the period of snow cover was typically from the end of November until the beginning of April /Löfgren 2008/. The maximum snow depth recorded was 48 cm in forest land and 25 cm in open land, and the maximum snow water content was 144 and 64 mm, respectively. Measurements of ground frost penetration during three seasons (2003/04–2005/06) showed that ground frost was present for 40 and 80 days/season in forest land and open land, respectively. The maximum ground frost depth was 46 cm on open land, and only 8 cm on forest land.

Table 5-2. The general stratigraphical distribution of Quaternary deposits in the Forsmark area /Hedenström and Sohlenius 2008/. It should be noted that not all deposit types are always present at the same site. Gyttja is formed in lakes and consists mainly of remnants from plants that have grown in the lake.

Quaternary deposit	Relative age	Environment
Bog peat	Youngest	Bog
Fen peat	↑	Fen
Microphytobenthos/calcareous gyttja/algal gyttja		Lake
Clay gyttja-gyttja clay	↑	Coastal and lake
Postglacial sand/gravel	↑	Marine
Glacial clay		Glacio-lacustrine
Glaciofluvial sediment		
Till	↑	Glacial
Bedrock	Oldest	

Table 5-3. Some climate characteristics for the Forsmark area. Data are for 2004 to 2007 from Storskäret, Forsmark /Johansson 2008/.

	Forsmark area
Latitude, longitude	60° 22' N, 18° 11' E
Mean annual temp.	+7°C
Min.–max. daily temp.	–14 – +25°C
Mean annual precipitation (mm)	546
Vegetation period	May–September
Length of vegetation period* 2004–2006	204 days

*Starts when 5 consecutive days have a daily mean >+5°.
Ends when 4 consecutive days have a daily mean <+5°.

5.1.4 Surface hydrology

The overall aim of the hydrological description is to describe objects such as lakes, watercourses and aquifers, primarily in terms of their geometries and hydraulic properties. Modelling of the hydrological surface system gives information on interaction between the objects and the integrated hydrological system at the site, and produces an overall water balance for the area. Important results presented within the framework of the site description /Johansson 2008/ include delineations of surface-water catchment areas, hydraulic parameters of the regolith, water balances, cross sections and elevation of streams, and lake turnover times.

In total, 25 lake-centered catchment areas, ranging in size from 0.03 to 8.67 km^2, have been delineated and described within the Forsmark area /Brunberg et al. 2004, Andersson 2010/. The 25 lakes are all small and shallow with mean and maximum depths ranging from approximately 0.1 to 1 m and 0.4 to 2 m, respectively (Figure 5-6). Seawater flows occasionally into lakes close to the sea during events of higher sea level. Wetlands are frequent and cover 25 to 35% of some of the catchments /Johansson 2008/.

Figure 5-6. *Lake Eckarfjärden, one of the larger lakes in the Forsmark area. Eckarfjärden is, like all other lakes in the area, a shallow oligotrophic hardwater lake surrounded by reed.*

No major watercourses flow through the central part of the site investigation area, and most streams in the area dry out during parts of the year (Figure 5-7). Downstream of the lakes Gunnarsboträsket, Eckarfjärden and Gällsboträsket the streams carry water for most of the year, except for dry years such as 2003 and 2006. Many streams in the area have been straightened and deepened in order to increase drainage.

The long-term overall water balance in the area was roughly estimated from measurements of precipitation, surface discharge and water levels during the period April 2004–April 2007 /Johansson 2008/ (Table 5-4). Numerical modelling of the surface water and groundwater flow systems has been performed using the MIKE SHE tool /Bosson et al. 2008/. The modelling results for surface water and groundwater levels and the main water balance components are in agreement with the results from field measurements.

Table 5-4. Longterm water balance for Forsmark, based on statistical calculations and measurements during the period April 2004–April 2007 /Johansson 2008/.

Parameter	
Precipitation (P)	560 mm/year
Actual evapotranspiration (ET)	400–410 mm/year
Runoff (R)	150–160 mm/year

Figure 5-7. The largest stream in the site investigation area in Forsmark, near the inlet to Lake Bolundsfjärden (May 2007).

Direct groundwater recharge from precipitation is the dominant source of recharge. Generally, the lakes are locations for discharge of groundwater for most of the year. During summer, when groundwater levels in the vicinity of the lakes are lowered by plant water uptake, some of the lakes may periodically change from discharge to recharge areas. Due to a high infiltration capacity of the topmost regolith layer, overland flow rarely occurs in unsaturated areas. However, overland flow may occur in saturated areas where the groundwater level reaches the ground surface. The runoff in streams is dominated by water of groundwater origin. During intensive rain-events or snow-melt, overland flow may also contribute substantially to the runoff.

The hydraulic conductivity (K) of the till is typically in the range 10^{-7} to 10^{-4} m/s. The hydraulic conductivity is comparatively high in the uppermost c. 0.5 m of the till, and then decreases with depth in the regolith profile. However, the hydraulic conductivity is again comparatively high in the zone closest to the bedrock /Johansson 2008/. The high hydraulic conductivity in the uppermost till is probably due to the combined effect of several soil-forming processes (e.g. bioturbation by roots and soil organisms and ground frost), which results in increased porosity and permeability.

The small-scale topography of the area gives rise to many small catchments with local, shallow groundwater flow systems in the regolith. This, in combination with the decreasing hydraulic conductivity with regolith depth, means that a dominant part of the near surface groundwater will move along shallow flow paths. Shallow groundwater flow paths imply strong interactions among evapotranspiration, soil moisture and groundwater levels and flow. In Forsmark, the groundwater table in the regolith is very shallow, in general the depth to the groundwater table is less than a metre. The groundwater level in the regolith is highly correlated with the topography of the ground surface. This local flow system in the regolith overlies a larger-scale flow system in the bedrock.

5.1.5 Coastal oceanography

The marine part of the Forsmark area is located in Öregrundsgrepen, a funnel-shaped bay of the Bothnian Sea which is a part of the Baltic Sea with its wide end to the north and the narrow end southwards. The studied area was divided into 28 sub-basins, based on today's bathymetry and the projected pattern of future drainage areas arising in consequence of isostatic rebound /Brydsten 2006/. The sub-basins are presented in Figure 5-8, together with the DEM for the marine area at Forsmark. The major part of the area is shallow and most sub-basins show a mean depth shallower than 10 m. The only exception is the N-S trending deeper channel west of Gräsö Island, exceeding depths of 40 m. The salinity stratification in Öregrundsgrepen is generally weak. Local freshwater runoff produces slightly lower salinities in the area compared with the Bothnian Sea /Aquilonius 2010/. The direction of the flow through Öregrundsgrepen varies from time to time, but on an annual basis there is a net flow directed from north to south /Karlsson et al. 2010/.

Marine sub-basins in the area were identified from the DEM /Strömgren and Brydsten 2008/ (Figure 5-8). The water retention time in the 28 sub-basins varies between 13 and 34 days (22 on average) /Karlsson et al. 2010/. The more rapid water turnover is found in the deeper areas close to the open Bothnian Sea and the longest retention in the partly isolated shallow sub-basins 117 and 118.

5.1.6 Chemistry

The present chemical characteristics at Forsmark are a consequence of the past landscape development, together with the abiotic and biotic factors acting today. The description presented below is based on extensive studies reported in /Sonesten 2005, Tröjbom and Söderbäck 2006, SKB 2008, Tröjbom et al. 2007, Hedenström and Sohlenius 2008, Andersson 2010, Löfgren 2010, Aquilonius 2010, Tröjbom and Nordén 2010, Tröjbom and Grolander 2010/.

Fresh surface waters and shallow groundwater in the Forsmark area are generally characterised by high contents of marine ions, high pH and high alkalinity, as well as very high concentrations of calcium compared with the general conditions in Sweden. These site-specific characteristics can be explained by marine remnants left by a regressing Baltic Sea, together with glacial remnants in the form of the calcite-rich till layer deposited during the Weichselian glaciation /Sonesten 2005, Tröjbom and Söderbäck 2006, Tröjbom et al. 2007/.

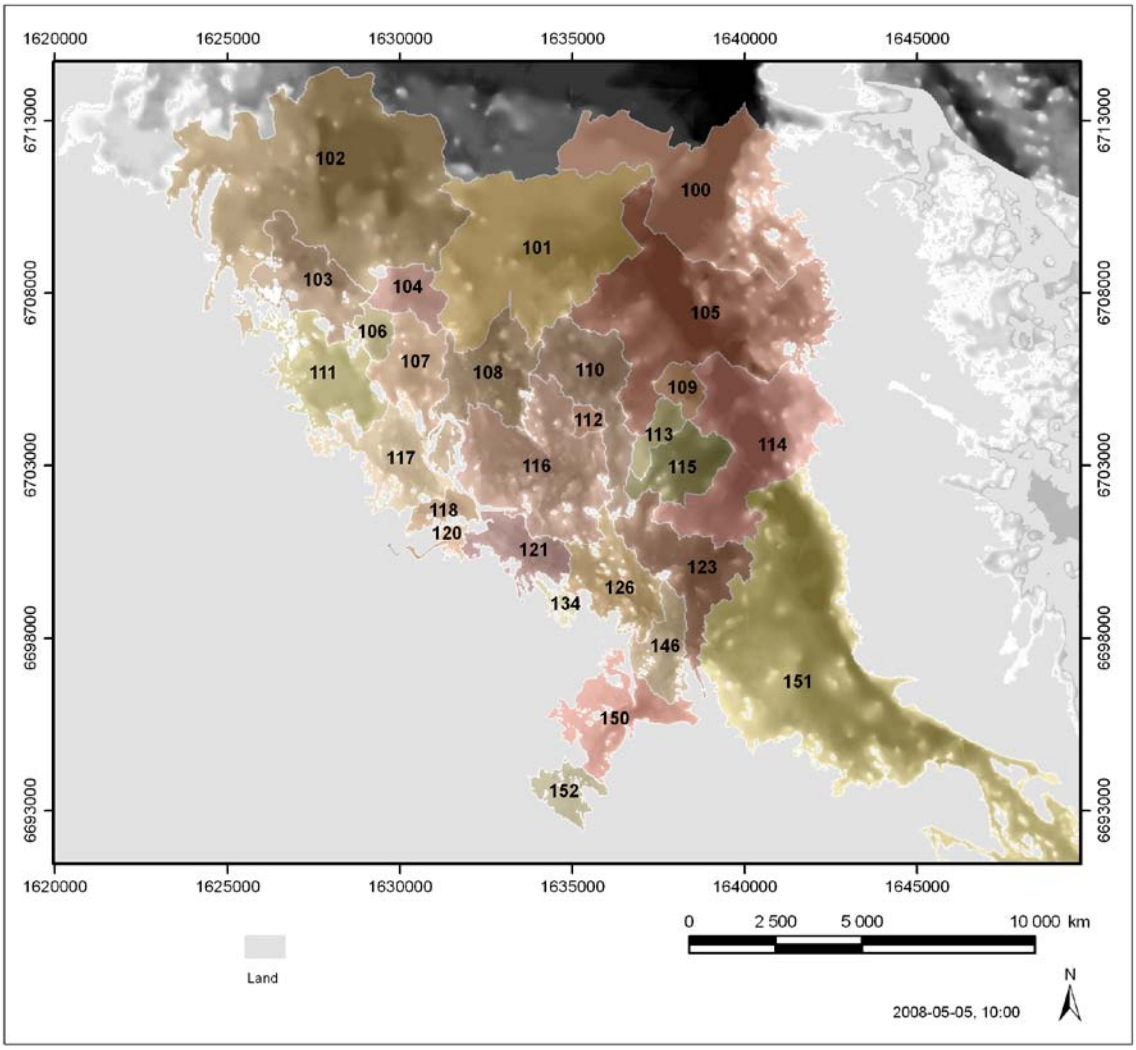

Figure 5-8. Marine sub-basins used in the SR-Site assessment, projected on the bathymetric map of Forsmark. Numbers are identification numbers of the sub-basins. Figure from /Aquilonius 2010/.

The influence from calcite has had a strong effect on the development of the terrestrial and limnic ecosystems in the Forsmark area. Secondary precipitation of calcite, with co-precipitation of dissolved phosphorus, mediates the development of the nutrient-poor oligotrophic hardwater lakes which are typical of this region (Section 5.2.2). In comparison with other parts of Sweden, lakes in the Forsmark area are characterised by low concentrations of phosphorus and high concentrations of nitrogen and dissolved organic carbon /Brunberg and Blomqvist 1999, Tröjbom and Söderbäck 2006/. The rich supply of calcium also influences soil formation and the development and structure of the terrestrial ecosystems /Löfgren 2010/.

The distribution of different elements among biotic and abiotic pools gives, together with estimates of element fluxes in to and out of the pools, an overall picture of major sources and sinks of elements in the landscape. Based on measured element concentrations in a large number of organisms, in different parts of the regolith and in lake water /Löfgren 2008, Nordén et al. 2008/, the amounts of different elements in major terrestrial and limnic ecosystems pools have been estimated at the landscape level /Tröjbom and Grolander 2010/. The results show that the completely dominating fraction for most elements in both terrestrial and limnic ecosystems is found in the regolith pools, i.e. in soils and sediments. The only pools in the landscape that are not negligible in comparison with the total regolith pool are those of nutrients and essential trace elements found in organisms in terrestrial ecosystems. The terrestrial biota pools in Forsmark are usually much larger than the corresponding limnic pools.

Major element fluxes in the Forsmark landscape have been quantified by the use of a simple mass balance model /Tröjbom and Grolander 2010/. This model couples major sources of elements released in the system (i.e. atmospheric deposition, fixation of gases, weathering of regolith and bedrock and flushing of relict sea water) to major sinks (i.e. accumulation in the terrestrial and limnic systems, export via surface water and emissions to the atmosphere) at the landscape level. The mass balance indicates large differences among elements in terms of transport and retention in the landscape, depending on their properties and biological functions (Figure 5-9). For a number of metals in the upper part of the figure, input from the atmosphere is equal to or exceeds the known sinks, which implies that a significant fraction is retained in the terrestrial system. In the lower part of this figure, atmospheric deposition balances only a minor fraction of the known sinks, which means that weathering reactions and other processes in the terrestrial system are the main sources of these elements.

5.2 Ecosystems

This section presents a general description of the ecosystems in the Forsmark area. Detailed information on biomass, production, chemical composition, and turnover of tissue and carbon content used in the ecosystem models can be found in the ecosystem reports; terrestrial ecosystems /Löfgren 2010/, limnic ecosystems /Andersson 2010/ and marine ecosystems /Aquilonius 2010/.

5.2.1 Terrestrial ecosystems

Terrestrial vegetation is strongly affected by the topography, regolith characteristics and human land use. In Forsmark, 73% of the terrestrial area is covered by forests, dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), which are the dominating tree species in the boreal forests of Scandinavia. The relative large portion of a variety of deciduous trees is both a consequence of the previous or present human land use and of the location by the coast. The field layer is characterised by herbs and broad-leaved grasses, along with a number of orchid species, favoured by the calcareous soils. The area has a long history of forestry, in recent times generally managed by clear-cutting.

Wetlands occur frequently and cover 10–20% of the area, locally reaching a coverage of 25–35% in some sub-catchments /Johansson et al. 2005/. A major part of the wetlands in the Forsmark area consists of coniferous forest swamps and open mires (Figure 5-10). The less mature wetlands consist of moderatly to extremely rich fens /Jonsell and Jonsell 1995/, which is a consequence of the high calcareous content of the local regolith (Section 5.1.2). Arable land and pastures are found close to settlements, including settlements now abandoned. The grasslands were earlier intensively managed, but a majority are no longer managed following the nation-wide general regression of cultivated land. The spatial distribution of different vegetation types is presented by /Löfgren 2010/.

The most common larger mammal species in the Forsmark area are roe deer and moose. Wild boar occurred sparsely at the start of the site investigations in 2002, but the population has increased at an amazing rate during subsequent years, similar to many other parts of the country /Truvé 2007/. In total, 96 bird species have been found in the Forsmark area /Green 2004/. The most common species in Forsmark are, as in the rest of Sweden, Chaffinch and Willow Warbler.

A conceptual model of important fluxes

Ecosystem characteristics, such as biomass, net primary production, consumption and accumulation of soil organic matter, have been in focus because of their direct implication to food web transfer and long-term accumulation of elements in the landscape. The largest carbon flux in terrestrial ecosystems is the uptake of carbon by primary producers. This net primary production creates a demand of a number of macro- and micronutrients that are incorporated into the biomass according to more or less well-described stoichiometric relationships /Sterner and Elser 2002/. Consequently, NPP will set the upper limit to the potential uptake of different elements into biomass. In turn, this will set limits to what extent further propagation up in the food web is possible. Biomass does eventually reach the soil compartment as litter, where it is mineralized. The balance between litter production and heterotrophic respiration determines to what extent organic material (and incorporated elements) may be accumulated in the soil.

Figure 5-11 is a compilation of important processes that have been identified from the descriptions of ecosystems at the site and from the interaction matrix (Chapter 4) for a mire ecosystem at a given point in time. These ecosystem characteristics are further described for Forsmark in /Löfgren 2010/.

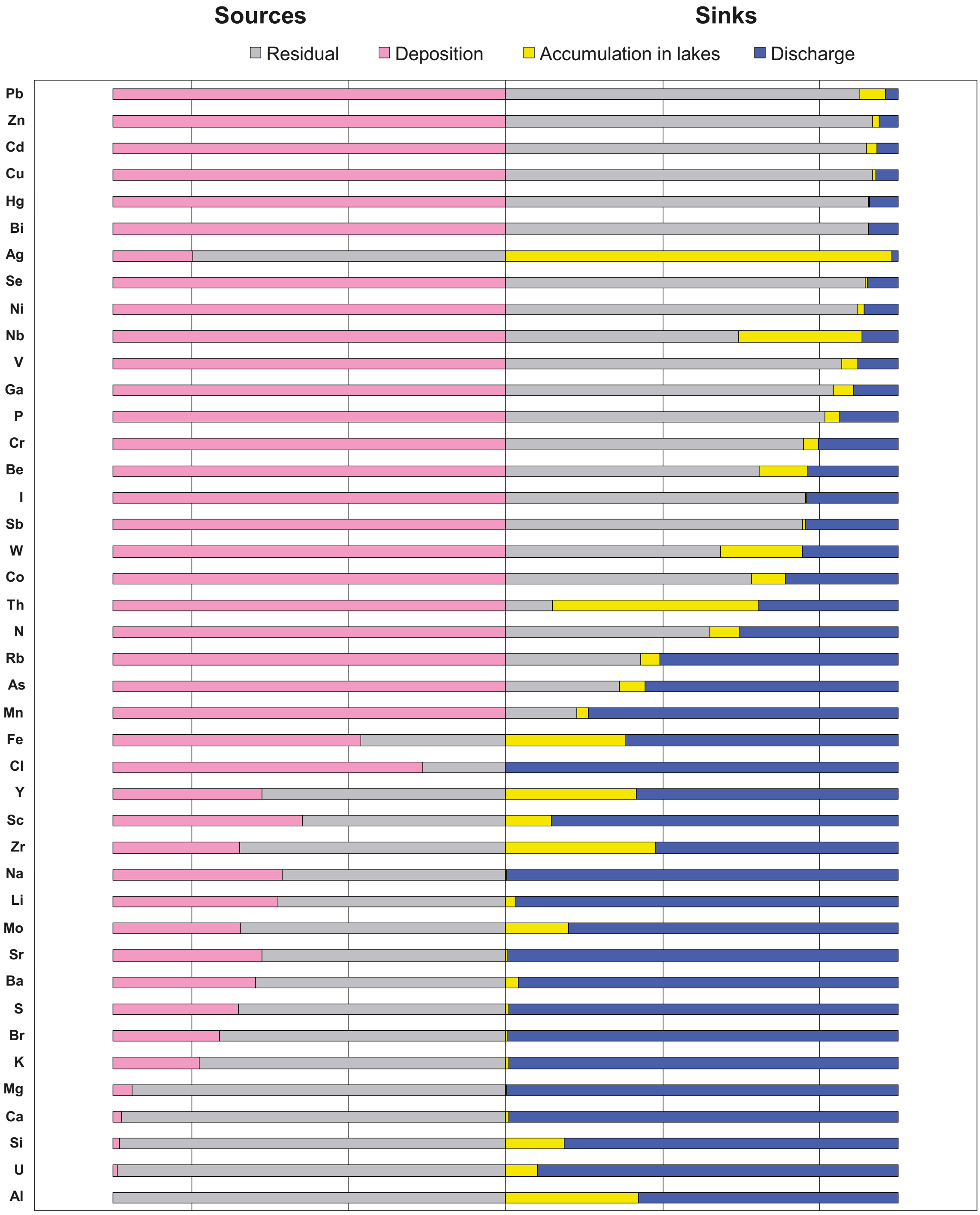

Figure 5-9. *Relative element fluxes at the landscape level in the Forsmark area, based on a mass balance model /Tröjbom and Grolander 2010/. Exchange with the atmosphere is consistently treated as a source (i.e. atmospheric deposition). The major sinks are accumulation in lake sediments and discharge via watercourses. The residual (i.e. the difference between the above mentioned fluxes) may either be positive or negative. If positive, it represents the additional supply via weathering in the terrestrial system that is needed to obtain balance (grey bar at the left side). A negative residual represents an additional sink in the terrestrial system where elements supplied via atmospheric deposition are accumulated (grey bar at the right side). Figure from /Tröjbom and Grolander 2010/.*

Figure 5-10. A wetland in Forsmark dominated by Reed (Phragmites australis).

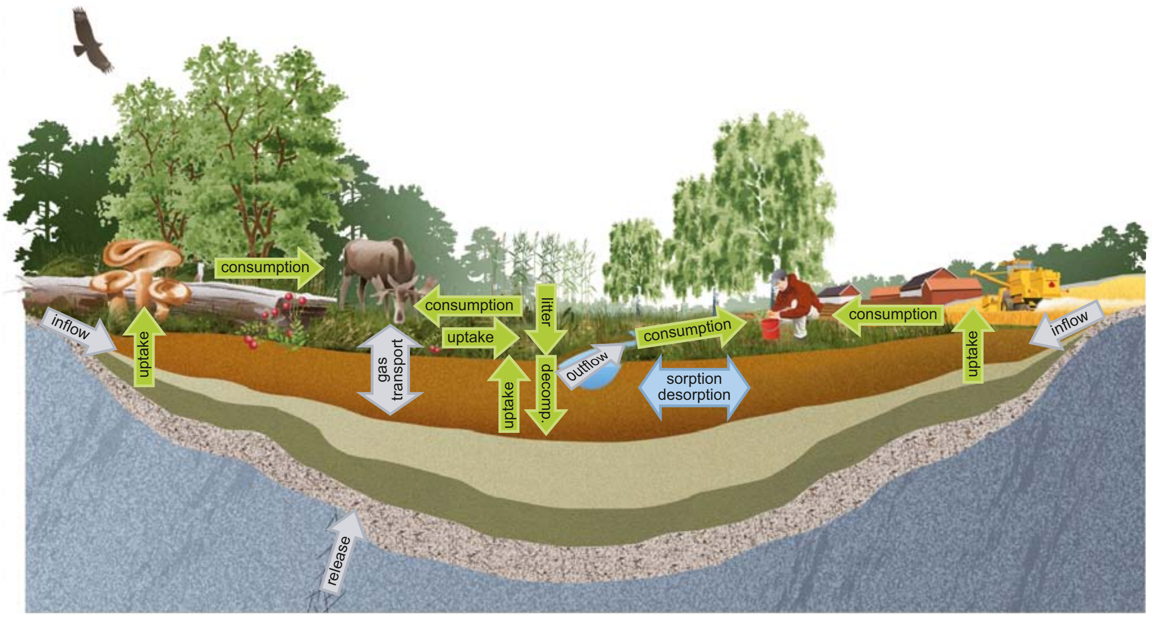

Figure 5-11. *A conceptual description of important fluxes affecting the transport and accumulation of elements in a wetland ecosystem and in an arable land on a drained part of a mire, where the human exposure in a safety assessment is in focus. Green arrows are fluxes mediated by biota, grey arrows are water and gas fluxes, blue arrow represents sorption/desorption processes, consumption also includes water for drinking. The mire was preceded by a lake and a marine stage in which gyttja/clay and postglacial clay were deposited prior to the peat.*

5.2.2 Aquatic ecosystems

Limnic

All present-day lakes in the Forsmark area are small and shallow, and are characterised as oligotrophic hardwater lakes /Andersson 2010/. The shallow depths and relatively clear water of the lakes permit photosynthesis in the entire benthic habitat of the lakes, and the bottoms are covered by dense stands of the macroalgae *Chara* sp. Moreover, many of the lakes also have a thick (>10 cm) microbial mat, consisting of cyanobacteria and diatoms, in the benthic habitat.

The large amounts of macroalgae and microphytobenthos give rise to high primary production in the benthic habitat, whereas primary production in the water column is modest. Modelling of limnic ecosystems within SR-Site indicates that only minor parts of the primary produced carbon are consumed by other organisms and transported upwards in the food chain /Andersson 2010/. Instead, much of the produced carbon is circulated within the microbial food web and transferred back to abiotic pools or sequestered in the sediment.

The fish community in the lakes is dominated by species resistant to low oxygen concentrations, mainly due to poor oxygen conditions during the winter. As described above (Section 5.1.4), the streams in Forsmark are all very small and long stretches of the streams are dry during summer (Figure 5-12). The downstream parts of some of the streams may function as passages for migrating fish, and extensive spawning migration between the sea and a lake has been observed.

Figure 5-12. *Many of the small streams in the Forsmark area dry out during summer (photo from July 2003).*

Marine

Shallow waters, a subdued bathymetry and restricted light penetration characterise the marine ecosystems in Forsmark. Together, these factors result in high primary production in the near-shore zone, were the highest biomasses and primary production are found. In deeper areas, where primary production is restricted to the pelagic zone, the production is lower. The marine system of the Forsmark area is a relatively productive coastal zone in a region of otherwise fairly low primary production. This is due to upwelling along the coast /Eriksson et al. 1977/. Like in the rest of the Bothnian Sea, the fauna consists of mixed freshwater and saltwater species. The benthic fauna occurs in the highest densities in association with vegetation. In offshore areas, herring and sprat are the dominating fish species, whereas perch and pike are the most common species in the inner bays /Aquilonius 2010/.

Conceptual model of important fluxes in aquatic ecosystems

Both abiotic and biotic process influence transport and accumulation of elements in aquatic ecosystems and are thus of interest in the safety assessment. Of the biotic processes identified in Chapter 4, primary production, growth, death, consumption, uptake, excretion and particle release/trapping are the major biotic processes that may affect the transfer and accumulation of elements in aquatic ecosystems (Figure 5-13). In lakes, these processes often involve larger fluxes of matter than abiotic processes such as convection (influx and outflux of matter via inlets and outlets). Advective flux (i.e. water turnover) is often the overall dominating factor affecting the transfer and accumulation of chemical elements in the sea, especially in open and more offshore basins. In comparison, biotic processes are less important. In general, the abiotic processes sedimentation, resuspension and sorption/desorption of radionuclides to particles and sediments are important for the transport and accumulation of radionuclides in aquatic ecosystems.

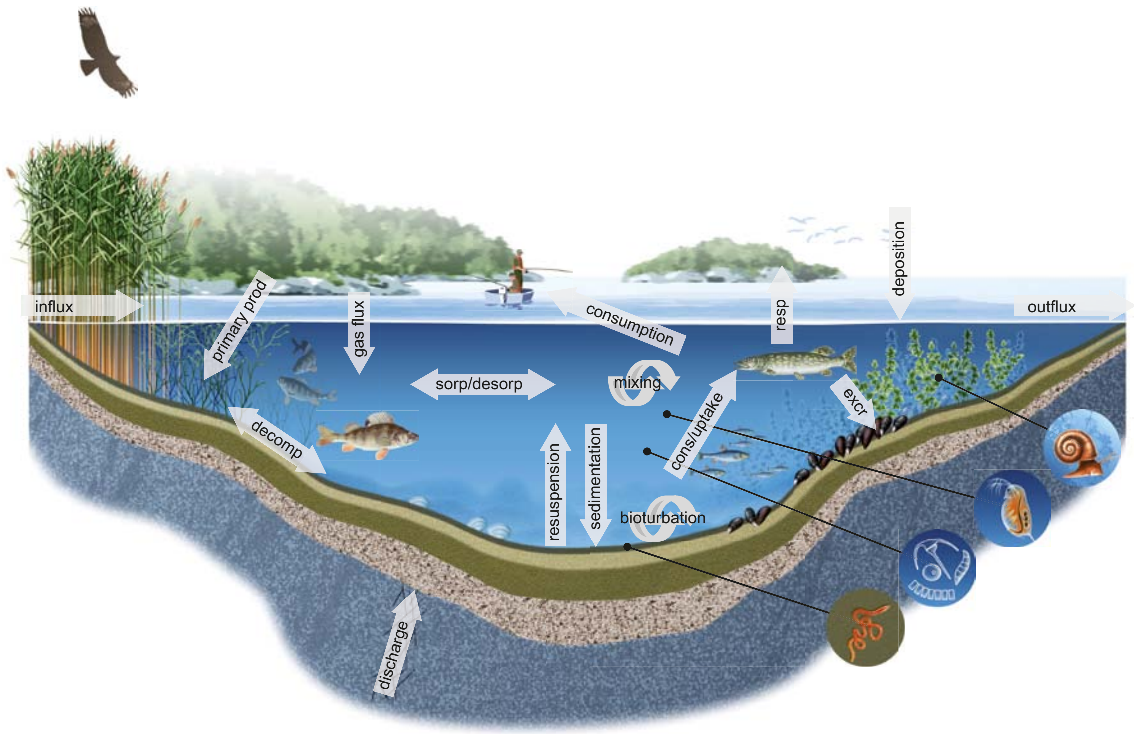

Figure 5-13. *A conceptual model of aquatic (i.e. both limnic and marine) ecosystem processes.*

5.2.3 Human utilization of natural resources

Today, the Forsmark area has no permanent residents, but there are five holiday houses and three farms situated within the area /Miliander et al. 2004/. The only agricultural enterprise operating today is situated at Storskäret. It is focused on meat production and the cattle graze outdoors during the vegetation periods. The area used for agricultural purposes (pastures, meadows and fields) comprises 4% of the total area. The land use is dominated by forestry, and wood extraction is the only significant outflow of biomass from the area. The dominant leisure activity is hunting. Besides this, the area is only occasionally used for leisure as a result of the small local population, the relative inaccessibility of the locality and the distance from major urban areas. The area contains one large industrial plant, the Forsmark nuclear power plant, with more than 700 employees. Besides these, there are only a few work places within the area /Miliander et al. 2004/.

6 Site development

6.1 Main factors affecting site development

The long-term landscape development in the Forsmark area is determined by two main and partly interdependent factors, *climate variations* and *shoreline displacement*. These two factors in combination affect a number of processes, which in turn determine the development of ecosystems. Some examples of such processes are erosion and sedimentation, groundwater recharge and discharge, soil formation, primary production, and decomposition of organic matter. The shoreline displacement is mainly a secondary effect of climate variations. It is caused by the interplay between glacially induced isostatic rebound on the one hand, and eustatic sea level variations (Section 3.3 in **Climate report**). Periodically, shoreline displacement has strongly affected the Forsmark area, both before and after the latest deglaciation, and it is likely that the area repeatedly has been situated below the sea level for long periods /Chapter 3 in Söderbäck 2008/.

Many of the analyses of surface systems within SR-Site are focused on the development of today's landscape, influenced by the transgressing shoreline (Figure 6-1) which divides the area into a submerged and a terrestrial part. The shoreline is of course a place of special attention since it is a highly dynamic part of the landscape system. It is along the shoreline where coastal processes determine the development; unconsolidated sediments are eroded and transported to deeper areas, waterborne nutrients create a productive littoral zone were flooding regularly occurs, and much of the marine primary production is concentrated to the shallow waters in the vicinity of the shoreline.

This coastal zone migrates continuously as a consequence of the isostatic rebound, which means that traces of coastal processes ascend with the land and can be found higher up from the current shoreline. Furthermore, as soon as land emerges from the sea, other types of processes start to dominate landscape development; terrestrial processes create a zonation as a consequence of exposure. Areas on higher altitudes have been exposed to these transforming processes during a longer period than have areas at lower altitudes. For example, land higher up is more weathered, soil-forming processes have created soils with a higher degree of maturity, and wetlands have accumulated more gyttja and peat. Studies of these terrestrial environments in different successiv stages constituted a fundamental part of the SR-Site surface systems programme. Lower lying land, i.e. of a younger terrestrial age, is assumed to develop in the same direction as the older parts of the terrestrial landscape, and the development of older land higher up in the terrain is assumed to continue along the same successional path until shifts in climate regimes are projected to alter the dominant processes of transformation. Such a concept of "space-for-time substitution" is used in all disciplines of SR-Site surface systems as described in this chapter. It is applied to knowledge from the site investigations, but also in numerical models and studies of analogue areas currently experiencing climate regimes different from today's Forsmark.

Lakes, streams and wetlands are given special attention in the following sections because they are the most likely recipients for potentially released radionuclides. This is because lakes, streams and wetlands often coincide with topographic depressions, which in turn are probable locations of deep groundwater discharge reaching the surface /Joyce et al. 2010/.

6.2 Long-term site development

The following sections (6.2.1 through 6.3.3) describe the long-term site development at Forsmark based on the *SR-Site reference glacial cycle* (Section 4.5 in **Climate report**), which presupposes the global climate system to be continuously characterised by repeated mid-latitude glaciations interrupted by warmer periods in cycles of approximately 100,000 years (Section 6.2.1). Site development under prolonged global mean temperatures higher than those existing today is described in Section 6.4, which is based on a development according to the *SR-Site global warming climate case* (Section 5.1 in **Climate report**).

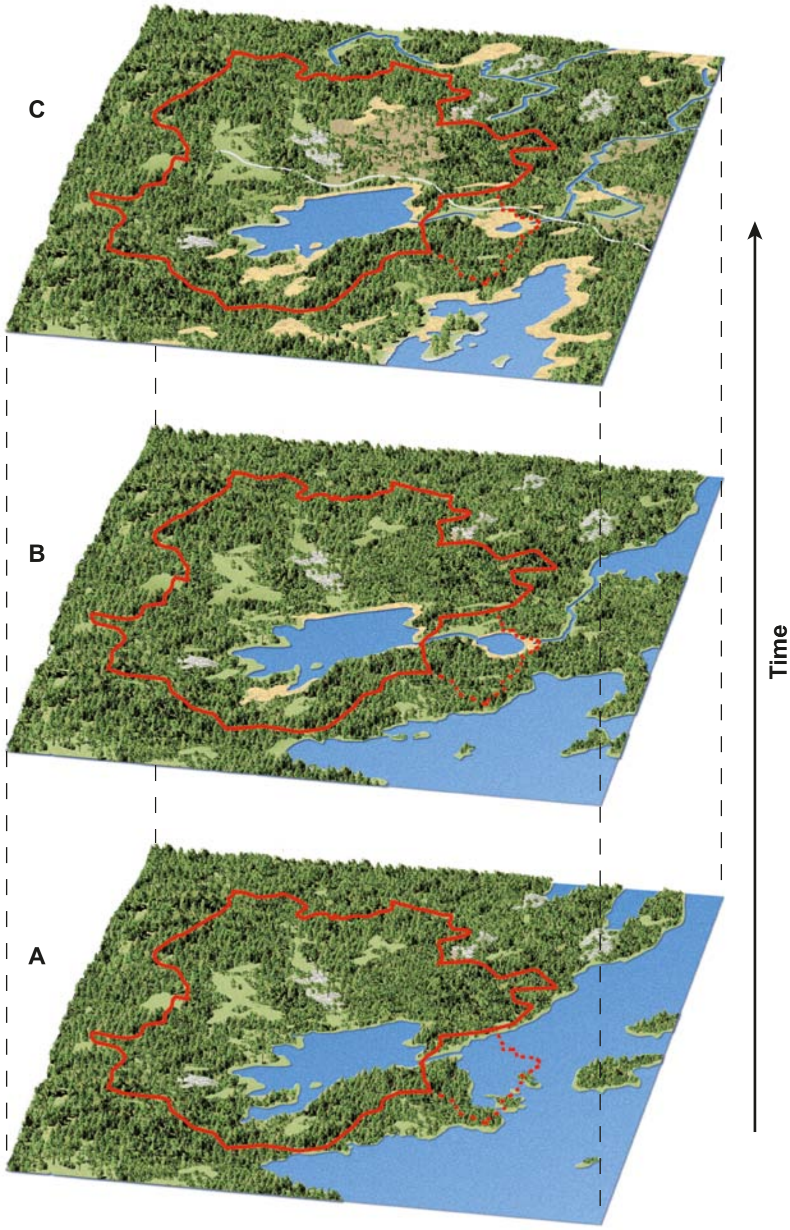

Figure 6-1. Potential development of a coastal area with two delineated sub-catchments (red solid and red dotted line, respectively) in east-central Sweden over approximately 800 years (A-C). Following the shoreline transgression, the smaller area (red dotted line) goes from being a shallow marine basin (A), to a lake-centred sub-catchment (B), and the subsequent expansion of reed belts in the littoral zone then transforms the lake into a wetland (C).

6.2.1 Climate and climate-related processes

The SR-Site primary approach of handling the complex issue of future climates is by constructing a *reference glacial cycle*, which constitutes a repetition of the climate reconstructed for the latest glacial cycle, in Europe called Weichsel, and the subsequent warm period, the Holocene (**Climate report**). Covering a period of 120,000 years, the reference glacial cycle provides an example of how climate and climate-related processes are likely to succeed during a future glacial cycle including full glacial conditions, interrupted by several warmer periods (interstadials). The reference glacial cycle gives input on timing, function and feedbacks of climate-related phenomena like ice sheets, permafrost and shoreline displacement (**Climate report**). In SR-Site, the reference glacial cycle is complemented with additional climate cases with potentially larger impact on repository safety (Chapter 5 in **Climate report**).

Figure 6-2 shows how the climate develops at Forsmark in the reference glacial cycle, represented by so called *climate domains*, i.e. areas dominated by certain climate related processes such as for instance ice sheets and permafrost. For a motivation and full description of the climate domains (Chapter in **Climate report**). The Forsmark site is dominated by temperate climate domain (green) for the first ~ 25 thousand years, although shorter periods of the periglacial climate domain (blue) occur around 10 kyrs after present. Subsequently, up to the first period of glacial climate domain (white or light grey), temperate conditions are gradually replaced by periglacial conditions.

The trend with gradually more dominating periglacial conditions is a natural result of the progressively colder climate during the first and major part of a glacial cycle (Section 4.5 in **Climate report**). This progressively cooling trend during the glacial cycle also causes periods with glacial climate domain to increase in length each time glacial conditions appear. The trend is not interrupted until the final deglaciation at the very end of the scenario, when ice-free conditions dominate again in a warm interglacial climate.

At the time of the latest deglaciation of Forsmark around 8800 BC, which corresponds to the last part of the reference glacial cycle (Figure 6-2), the area was covered by approximately 150 m of glacio-lacustrine water /Söderbäck 2008/ and the nearest shoreline was situated some 100 km west of Forsmark. Thereafter, the isostatic rebound has been continuous and slowly declining. The rate of rebound in Forsmark has decreased from c. 3.5 m/100 years directly after the deglaciation to a present rate of c. 0.6 m/100 years, and it is predicted to decrease further to become insignificant around 30,000 AD.

The global warming climate case describes a future climate development influenced by anthropogenic emissions of greenhouse gases and associated perturbations of the natural climate system (Section 6.4). These perturbations may cause the occurrence of air temperatures several degrees warmer than present in central Sweden and Forsmark within the first hundreds to thousands of years after present (Section 5.1 in **Climate report**). Subsequently, following reduction in emissions, temperatures are envisaged to slowly decline for the rest of the long initial period with temperate climate conditions.

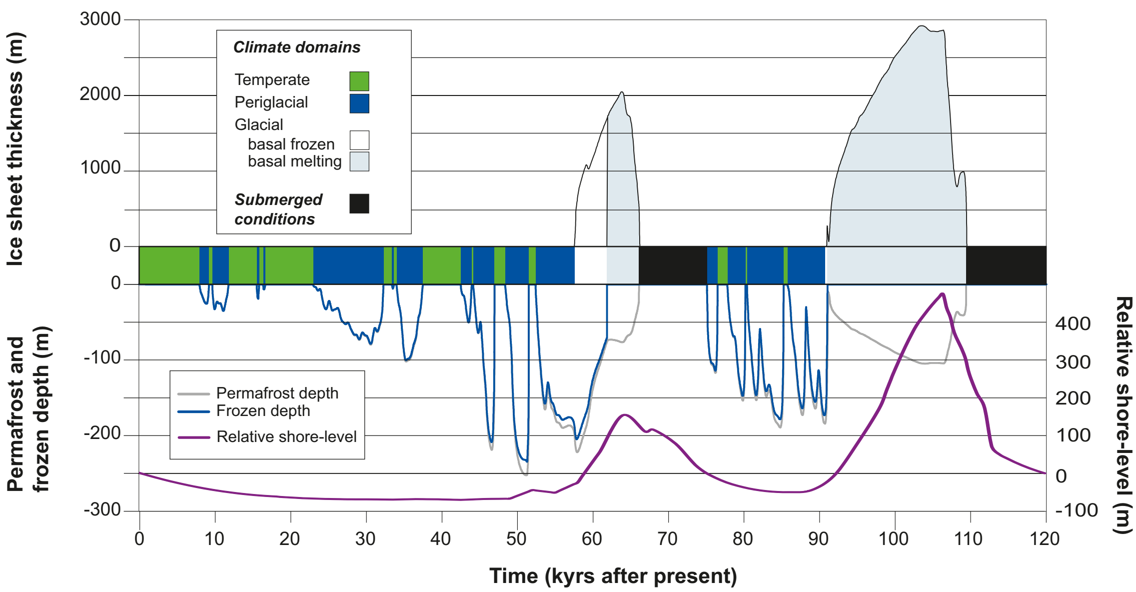

Figure 6-2. *Evolution of important climate-related variables at Forsmark for the coming 120 kyrs in the SR-Site reference glacial cycle. Figure from* ***Climate report****.*

6.2.2 Topography

The obvious glacial origin of dominating regolith and noticeable glacial erosion on exposed bedrock have traditionally resulted in interpretations of ice sheets leaving a significant imprint on today's bedrock morphology in areas once covered by Quaternary glaciations. However, numerous studies during recent decades have shown that glacial erosion under certain conditions may have been very restricted (Section 3.5 in **Climate report**, see also /Kleman and Hättestrand 1999/). Many areas, Forsmark included, do show glacial sediments laid down during the latest glaciation, but even in these cases a likely explanation is that these sediments primarily consist of early Quaternary sediments reworked during several subsequent glaciations /Kleman et al. 2008/. In south central Sweden, including the Forsmark site, the accumulated amount of bedrock erosion from all Quaternary glaciations is likely less than some 10 metres on average /Lidmar-Bergström 1996/.

Considering the bedrock topography in Forsmark to have been fairly stable throughout Quaternary glaciations, there is no reason to believe that future glaciations would leave a significantly different imprint on the bedrock topography /Olvmo 2010/. The future denudation (all erosion and weathering combined) in Forsmark has been estimated to 1–2.6 metres for the coming c. 100,000 years and between 8–21 metres for the coming 1 million years (Section 3.5 in **Climate report**). The landscape that will emerge from a vanishing future ice sheet will not be exactly the same as the landscape we know from Forsmark today, but it will most probably show a similar pattern of glacial sediments and minor bedrock basins occupied by lakes. We assume a future deglaciated landscape to include all relevant processes and features we know from today and the surface system to function in a similar manner.

6.2.3 Regolith

Similar to many other areas covered by Late Quaternary glaciations, Forsmark experienced a complete redistribution and reshaping of unconsolidated deposits during the latest glaciation. Since then, much of the fine-grained glacial sediment has been eroded and relocated to sedimentation basins, within or outside the Forsmark area. Postglacial redistribution of fine-grained material is a continuous process, even though the locations of maximum erosion (primarily by waves in exposed shallow waters) and accumulation migrate as a consequence of a transgressing shoreline.

Postglacial redistribution also occurs on land, where material is transported and settles as sediment in lakes and shallow marine embayments. Growth and decomposition of plants gives rise to organic material in the form of gyttja and peat, further infilling lakes and marine embayments. The ongoing isostatic uplift results in the emergence of new land areas, transforming the coastal basins to sheltered positions that favour the accumulation of clay gyttja and gyttja. Gyttja is formed in lakes and consists mainly of remnants from plants that had grown in the lake. Many of the present and future ponds and lakes in Forsmark are very shallow, often less than 1 m water depth at the deepest, and will have only a short duration as a lake/pond before the basin is infilled and developed into a wetland. In several of the present-day small wetlands, the lacustrine sediments, representing the lake stage of the basin, are missing and peat is formed directly on the marine sediments or till.

The above general description implies that processes controlling regolith distribution are essentially different during glacial and non-glacial periods; glaciations giving a new set of regolith units, partly redistributed during non-glacial periods, with the addition of organic material during non-glacial periods. SR-Site primarily handles the future redistribution of regolith during non-glacial periods by applying the *coupled regolith-lake development model* (RLDM) /Brydsten and Strömgren 2010/. This model is divided into a marine module that predicts the sediment dynamics caused by waves, and a lake module that predicts infilling of lakes. The model forecasts regolith distribution and thickness of different strata at time-steps of 500 years (marine stage) or 100 years (lake stage) from 9000 BC until the sea has withdrawn from the model area (c. 30,000 AD).

The marine module of the model runs from the time when the area has recently been deglaciated at about 8800 BC until 11,500 AD. Inputs to the model are site description data on the current surface distribution of regolith /Hedenström and Sohlenius 2008/ and the regolith depth model (RDM) that shows the stratigraphy and thickness of different sediments /Hedenström et al. 2008/.

Lakes are modelled individually with a module based on equations for net sedimentation rate and vegetation colonisation /Brydsten 2006/. The lake module gives the distribution of regolith, surface elevation and thickness of the marine and limnic postglacial deposits in each time step until the lake is totally infilled.

The RLDM suggests that a major part of the study area was covered by postglacial clay shortly after the area was deglaciated. As the water got shallower following isostatic rebound, much of the postglacial clay was resuspended and exposed glacial sediments underneath. According to the RLDM, the minimum areal extension of postglacial clay occurred at about 2000 BC, mainly in today's marine basin *Gräsörännan* west of the Gräsö Island. Postglacial clay extension increases during the following period, and reaches a local maximum around 2500 AD, and successively decreases until the shoreline reaches a location outside the model area at about 11,500 AD. At that time, the regolith in the model area is, as in present-day conditions, dominated by till, but large areas of the more recently emerged parts are covered by glacial or postglacial clay (Figure 6-3). According to the RLDM, the maximum thickness of postglacial clay in the area (28.6 metres) will be found west of Gräsö Island /Brydsten and Strömgren 2010/.

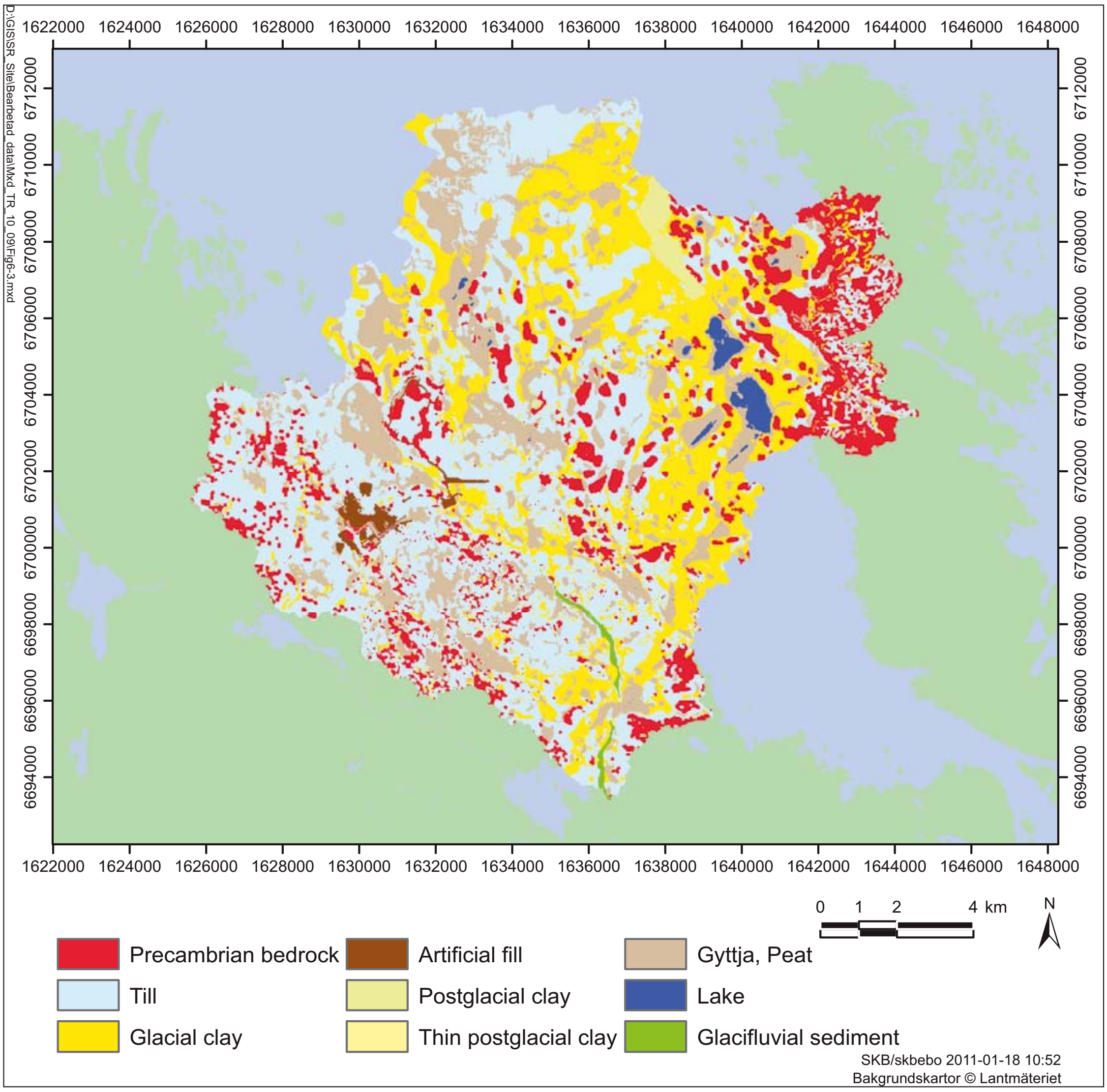

Figure 6-3. *Surface distribution of regolith at 10,000 AD according to the Coupled regolith-lake development model /Brydsten and Strömgren 2010/. Most of the postglacial clay is eroded and transported out of the area. The only larger remaining area of postglacial clay is in the former marine basin Gräsörännan, in the north-central part of the figure. Figure from /Brydsten and Strömgren 2010/.*

6.2.4 Surface hydrology

Hydrological processes play a substantial role in the development of surface systems, primarily by regulating the availability of water for biomass production and by the role of water as a medium for transport of particles and dissolved substances. Since surface hydrology is highly dependent on climate, we can anticipate substantial changes in altered climate domains during a glacial cycle. By using conceptual knowledge and output from hydrological modelling performed within the site description /Bosson et al. 2008/ as a starting point, numerical models describing present and future conditions have been developed and applied in order to answer questions about the future hydrology in Forsmark /Bosson et al. 2010/.

Modelling of future hydrology has been conducted both on a regional spatial scale and on a local scale for two selected sub-catchments. The models were run for different time-slices (2000, 5000 and 10,000 AD) and with input data representing different climate conditions, i.e. a normal temperate climate (based on measured data from the Forsmark area), a temperate climate with increased precipitation (referred to as "wet climate") and a periglacial climate with lower temperatures and permafrost. The three time-slices differ in shoreline position, in the distribution of regolith and vegetation (based on information from the RLDM /Brydsten and Strömgren 2010, Löfgren 2010, Section 6.2.3/).

According to the model results, water balance does not change dramatically during continuous temperate climate at Forsmark. The change of internal distribution of the precipitated water will not exceed 10% of the present water balance at the site, but changes in water balances will be more pronounced during other climate domains. A larger amount of water will contribute to runoff during times characterised by wet conditions, with a faster turnover time as a result. In a periglacial climate regime, infiltration is strongly reduced because of perennially frozen ground, causing large annual variations in hydrological characteristics, since water turnover takes place during a restricted summer season.

The overall pattern of recharge and discharge areas does not change when prolonging a temperate climate to the studied future periods, which confirms that the flow gradient is more dependent on topography than on the distribution of regolith or distance to the shore. However, the results show that regolith stratigraphy and thickness may influence the local distribution of recharge and discharge areas in the near-surface system. Since most of the discharge areas for deep groundwater are concentrated to low-elevation points in the landscape, the distribution of the regolith in these areas can cause local deviations in transport of dissolved substances and particles.

Permafrost has a profound effect on patterns of recharge and discharge in the landscape /Vidstrand et al. 2010/. This is because vertical exchange of groundwater under permafrost conditions is concentrated to areas were thawed conditions prevail from the ground surface all the way down to the unfrozen conditions that underlie the permafrost. These *through taliks* generally occur under lakes and are encased by permafrost on the sides (Section 3.4 in **Climate report**). Some taliks act as recharge areas and some as discharge areas. Thus, the flow paths from a repository in a periglacial climate domain will deviate from flow paths developed under present climate conditions. Many of the areas likely to be taliks are discharge areas also under present conditions, but the funnelling of flow in through taliks might lead to higher concentrations of transported substances where discharge reaches the surface in a periglacial environment /Bosson et al. 2010/.

6.2.5 Coastal oceanography

Of profound importance to marine environment development in Forsmark is the interplay between glacially induced isostatic depression/recovery and eustatic sea level variations. This interplay gives changing local water depths and residence times as well as changing regional circulation and salinity of water bodies in the Baltic basin. Today, the Baltic Sea is a brackish sea with substantial input of freshwater and restricted inflow of saline water via narrow and shallow straits connecting the Baltic Sea to the Atlantic. Isostacy of the straits is today relatively stable and the height of the thresholds will only marginally affect the future salinity of the Baltic Sea /Gustafsson 2004a, b/.

In contrast, isostatic rebound in central and northern Sweden is significant. The Southern Kvark sill is characterised by a maximum water depth of 40 metres and isostatic rebound of about 5 mm per year /Ekman 1996/, which implies large changes in the exchange of water between the Bothnian Sea and the Baltic Proper within the next few millennia /Gustafsson 2004a, b/. Isostatic rebound is most evident even on the local scale. Even though the process is fast enough to make a noticeable difference during a generation, it takes time to complete. It takes about 12,000 years to transfer the entire Forsmark area from fully submerged from just before the first islet emerges above the sea surface (1000 BC), until the last marine embayment is turned into a lake (11,000 AD).

The description of coastal oceanography within SR-Site has focused on hydraulic residence time, because of its importance for transfer and accumulation of radionuclides. According to /Brydsten 2006/, the local development can be divided into three stages; an *open sea stage*, an *open-ended coastal stage* (as the present stage) and a *bay stage* with only one open boundary. These stages will appear in the above mentioned order following deglaciation over the subsequent roughly 15,000 years. Using the shoreline displacement equation /Brydsten 2006/ as input, /Karlsson et al. 2010/ conducted detailed hydrodynamic modelling of marine basins in the Forsmark area. The hydrodynamic model gives outputs of annual mean flows between adjacent basins and a measure of the water retention time for each basin and for the whole area. For the open sea stage, the circulation was simulated using a model for the entire Baltic Sea. For the other two stages, a high-resolution local model was set up for the near-coastal basin Öregrundsgrepen.

During the *open sea stage* the water turnover will be rapid and similar in the whole model area and in the open Baltic Sea. Oceanographic conditions will be fairly homogenous and the water exchange is at its maximum. In the *open-ended coastal stage* a net through-flow of the area is still possible, although the water retention time increases as a result of a complex interplay between a narrower southern boundary, decreasing volumes of the marine basins and decreasing of the cross-sectional areas between adjacent basins. The water turnover during this stage is primarily determined by the wind and fluctuating sea levels, and water retention times will be longest in the shallow basins located far from the boundaries to the Baltic Sea. During the *bay stage,* the southern entrance has closed and Öregrundsgrepen has been transformed into a bay, whereby the water retention time for the whole area increases. The oceanographic conditions will be typical for estuarine circulation in an enclosed bay. The basins gradually become more enclosed and are one by one transformed into lakes. Runoff from land becomes more important for water turnover during this stage and wind still plays an important role.

6.2.6 Chemistry

The chemistry observed in the Forsmark area today is a consequence of past landscape development, present and historic land use, and anthropogenic inputs. The ongoing shoreline regression creates a spatial gradient from the coast in an inland direction, which represents a timeline in landscape maturity. This means that the spatial gradient of today may be extrapolated and translated into a succession of landscape maturation for the future. The present chemical conditions found in the modelled area in Forsmark therefore represent a historic time span of about 10,000 years since the last deglaciation. In Figure 6-4 this is illustrated as a box moving over time from the sea-bottom environment to the terrestrial environment, although the illustration is somewhat limited by the fact that climate, vegetation cover and anthropogenic influence via e.g. atmospheric deposition and land use have varied during the period.

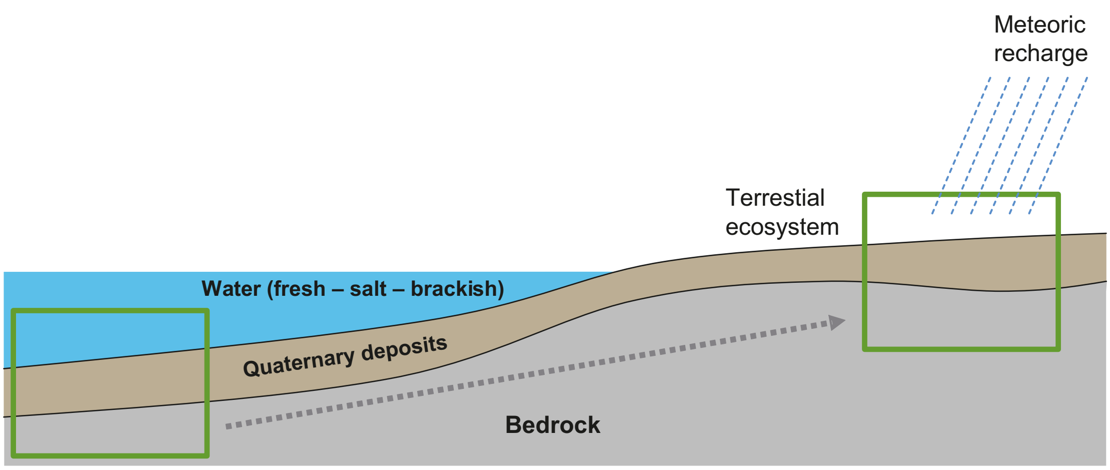

Figure 6-4. *A hypothetical cross-section of the Forsmark area today, illustrating the spatial gradient that can be extrapolated and translated into a succession of landscape maturation for the future. The left box may represent the conditions soon after the deglaciation (8800 BC), whereas the right box represents conditions in the most elevated parts of the area, which have been exposed to meteoric recharge and chemical weathering for several thousands of years. Figure from /Tröjbom and Grolander 2010/.*

The historical development of the chemistry in the surface system at Forsmark can be divided into four stages, based on differing hydrological conditions: (1) Deglaciation of exposed glacial sediments, submerged by the freshwater Baltic Ice Lake. These deposits contained large amounts of limestone. (2) Freshwater conditions were replaced by the brackish Littorina Sea, with increasing salinity, where density turnover infiltrated sea water through the underlying sediments. (3) Close to the emerging coast when a shallow sea still covered the area, the topographical discharge gradient may have transported traces of deep groundwater into glacial and post-glacial deposits. (4) As soon as land emerged, recharge of meteoric water created new hydrological flow patterns recharging through the regolith and discharging in streams and lakes. At this stage, aeration by meteoric recharge, in combination with a supply of organic carbon, altered redox conditions in the shallow groundwater. Increased supply of H^+ ions, mainly supplied through decomposition of organic matter, is the ultimate driving force for weathering reactions that take place in the regolith and bedrock.

Most of the easily weathered calcite in the upper regolith will be dissolved and washed out within a period of some thousands of years /Tröjbom and Grolander 2010/. This means that the strong influence of the calcium-rich deposits on the terrestrial and limnic ecosystems will be reduced over time. For instance, the oligotrophic hardwater lakes that are characteristic for the coastal area in Forsmark will likely be transformed to more dystrophic (low pH, brown-water) and nutrient-rich conditions within some thousands of years after isolation from the sea, if they have not been turned into wetlands before this /Andersson 2010/.

The part of the Forsmark area currently submerged by the sea has larger areas of clay than the currently emerged part, which is dominated by till /Hedenström and Sohlenius 2008/. This implies that weathering rates and area-specific discharge of different elements will increase with a lowering shore-level. This is especially the case if these areas are drained and cultivated in a way similar to comparable land areas in the region today. Area-specific losses of e.g. phosphorus are at least an order of magnitude larger for arable land than for forest land /Tröjbom et al. 2007/, and a greater proportion of arable land could significantly increase the nutrient status and primary production in the freshwater recipients.

6.2.7 Ecosystems

The costal setting of Forsmark supports a large number of diversified ecosystems, such as shallow marine basins with protruding islets, mixed forests with interspersed grasslands and cultivated fields, and freshwater lakes in different stages of succession towards wetlands. The location along a coast characterised by isostatic rebound also makes the distribution of ecosystems highly dynamic; a shoreline regressing at a speed of about 6 mm/year /Ekman 1996/ transforms marine ecosystems into limnic and subsequently to terrestrial ecosystems. Development continues as terrestrial sites are elevated to higher ground and successional processes reorganize both the habitat and the species pool. Successional paths can change into new directions with shifts in climate or human utilisation of the area.

All these environments and their possible development are extensively described in three SR-Site ecosystem reports covering the marine /Aquilonius 2010/, limnic /Andersson 2010/, and terrestrial /Löfgren 2010/ ecosystems. Modelling of potential climate extremes has made it possible to make a sketch of the boundaries that would set the limits to what ecosystems that might occur. Output from such modelling has also been used as input to vegetation modelling in order to describe the vegetation during a prevailing climate /Kjellström et al. 2009/.

As the sea bottom is elevated by the isostatic rebound, deeper off-shore areas become shallow coastal areas. Water turnover becomes slower as a consequence of shallower water and a more secluded position. The marine ecosystem will transform from being net heterotrophic and dominated by pelagic primary production towards a primarily benthic and in general autotrophic ecosystem. A bay turns into a lake ecosystem after isolation from the sea, and gradually matures in an ontogenetic process, including sedimentation in combination with mire growth from the lake edges.

In Forsmark, all present-day lakes have developed into oligotrophic hardwater lakes with high primary production at the sediment surface. The subsequent development into wetland is dominated by the ingrowth of littoral plants and by a gradual infilling with allocthonous sediments. Some stages in peatland development might include sedges, mosses, or flood tolerant trees like pine, birch or alder /Fredriksson 2004/. The richer types of mires, which are typical of the Forsmark area, will undergo a natural long-term acidification when turning into more bog-like mires. A stylised illustration of this temporal development is shown in Figure 6-5.

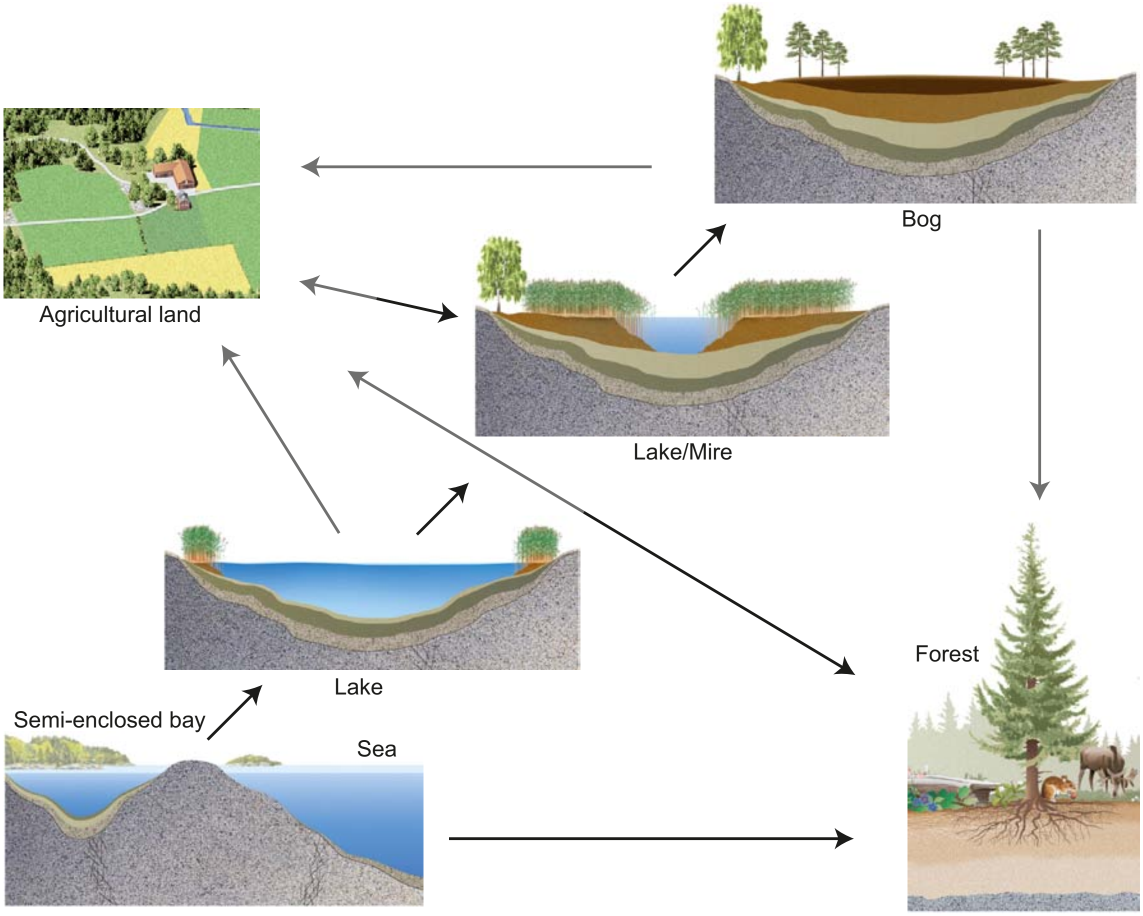

Figure 6-5. *A schematic illustration of the major ecosystems that may be found during a temporal sequence, where the original sea bottom develops to a lake or a terrestrial ecosystem. Black arrows indicate natural succession, whereas grey arrows indicate human-induced changes. Agricultural land may be abandoned and develop into forest or, if the hydrological conditions are suitable, into a fen. Figure from /Söderbäck 2008/.*

Biotic processes will be restricted by a shorter vegetation period during a periglacial climate domain and, consequently, this will lead to lower biomasses and net primary production in both forested taiga and tundra peatlands /Gower et al. 2001, Wielgolaski et al. 1981/. In aquatic ecosystems, the biomass of primary producers is not necessarily lower in periglacial conditions, since periglacial lakes often contain large amounts of macrophytes, microbial algae and mosses, which are less affected by a shorter vegetation period, and lower temperatures in the sea may increase the upwelling of deep nutrient-rich water and thereby alter the production. Biomass and production of higher biota do, however, most likely decrease in aquatic ecosystems under periglacial conditions.

6.2.8 Human utilisation of natural resources

The possibility for future agriculture in Forsmark was studied in /Lindborg 2010/ by classifying the availability of arable land from maps of Quaternary deposits /Hedenström and Sohlenius 2008/ and from the output of the RLDM /Brydsten and Strömgren 2010/, thus giving availability in time steps until 35,000 AD. The classification of land as arable was done by using current regional agriculture practices as a reference. Cultivation in Uppsala County today is mainly occurring on areas with glacial and postglacial clay and sand. Only a small fraction of the cultivated land is situated in areas with peat and till. The limited cultivation of peatlands is because peat decomposes and subsides quickly when drained and cultivated, thus making agriculture possible only for a few tens of years /Section 4.3 in Lindborg 2010/.

Parts of the currently submerged land consists of regolith with a high content of stones and boulders, and is therefore unsuitable for farming even after being elevated to a terrestrial position. There are, however, large areas with fine-grained sediments that potentially may be cultivated (see the north-eastern half of Figure 6-6c below). Since the proportion of land that it is possible to cultivate will increase as new land areas are formed, this means that the potential food productivity in the total area is expected to increase during the period up to 10,000 AD.

6.3 Site development during the reference glacial cycle

According to the regulations, the assessment has to be subdivided into several time periods (Chapter 3). To provide a forecast of what will happen in the future is an impossible task and is not the intention of the safety assessment. The intention is instead to provide a range of likely scenarios or variants of potential future conditions, based on available scientific knowledge, and to examine the effects of a potential release of radionuclides from a repository on humans and other biota under these scenarios or variants. In this section, available knowledge of the present-day properties of the site, and of the processes affecting its future changes, is used in a scientific coherent way to describe a possible and likely development of the site during the reference glacial cycle.

As a combined effect of the ongoing shoreline displacement, redistribution of marine sediments, infilling of lakes and climate variations, the landscape properties and features will continuously change in predictable ways. By combining information from the contemporary DEM /Strömgren and Brydsten 2008/ with the shoreline displacement in the reference glacial cycle (Section 4.5 in **Climate report**), output from the RLDM /Brydsten and Strömgren 2010/ (Section 6.2.3) and biotic information from the ecosystem modelling, a *landscape development model* that describes the long-term development of the site at the landscape level has been developed.

The landscape development model produces a description over time in spatial detail (20 m · 20 m) of landscape properties and features, including topography, location of the shoreline, regolith depth, areas and depths of present and future lakes and sea basins, stream network, and vegetation and land use. This description can in turn be used to extract time-dependent properties of the biosphere objects (Chapter 7) that are input parameters to the radionuclide model that is presented in Chapter 8.

Below follows a short description of the development of the Forsmark site, from present-day and over the complete reference glacial cycle. During the initial period of temperate climate domain, i.e. until c. 10,000 AD, the landscape is highly dynamic due to the moving shoreline and the infilling of lakes, and the description during this period is based mainly on output from the landscape development model. Thereafter, and until the onset of the next glacial loading, the landscape development will be more static and the succession will be determined mainly by climate variations.

6.3.1 Site development during the initial 1,000 years after repository closure

The shoreline displacement, measured as relative sea water-level, is projected to be nearly 6 m during the next 1,000 years, assuming an almost constant isostatic rebound rate of 6 mm/year /Ekman 1996, Hedenström and Risberg 2003/ and a constant absolute sea level. Based on this scenario, a likely development of the site is described below.

The shoreline displacement will result in a horizontal transfer of the coastline to a location c. 1 km east of the repository at 3000 AD, which means that parts of the present seafloor will become land. Also, some of the coastal bays will be isolated and transformed to lakes (see Figure 6-6a). The ongoing shoreline regression causes a succession pattern, where the shore vegetation, dominated by herbs, sedges and grasses, will be replaced by forest vegetation. The types of dominant vegetation communities during this succession are mainly determined by the composition of the underlying Quaternary deposits, which, in turn, depend on the extent of previous wave exposure of the shallow coast.

All present-day lakes in the Forsmark area are small and shallow. This means that large parts of the lakes will be transformed to wetland during the coming 1,000 years /Brydsten and Strömgren 2010/. For example, two of the smaller lakes, Lake Puttan and Norra Bassängen, situated close to the planned repository, are expected to be almost completely transformed to wetland, whereas a minor part of the larger Lake Bolundsfjärden will continue to be open water in the year 3000 AD (see Appendix 1 for a map of the Forsmark area today).

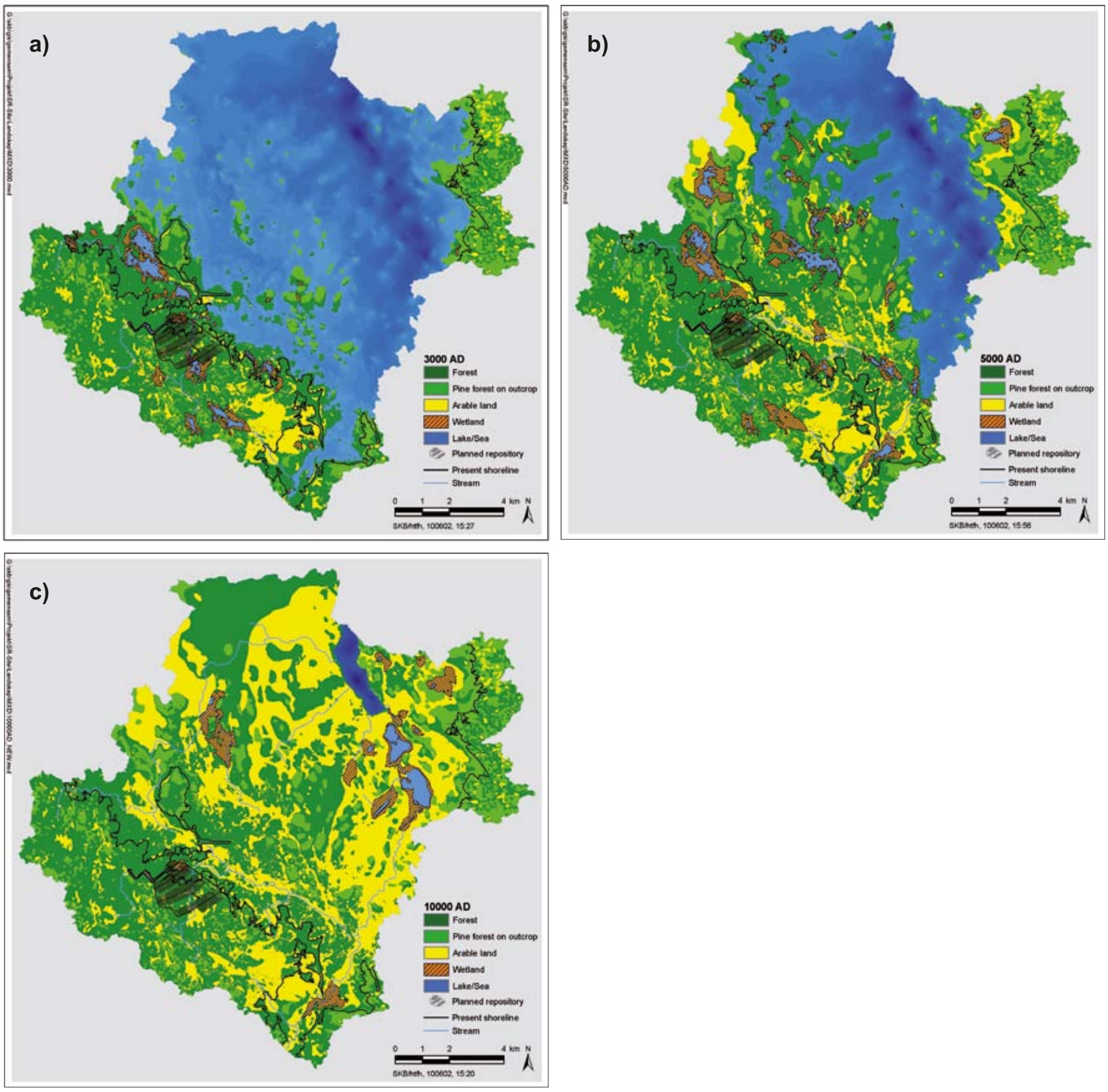

Figure 6-6. *Modelled distribution of different vegetation types and of arable land in Forsmark at a) 3000 AD, b) 5000 AD and c) 10,000 AD. All areas that potentially can be cultivated are represented on the map as arable land /Chapter 4 in Lindborg 2010/. The present shoreline is marked as a black line and darker shades of blue represent deeper sea. Figure from /Lindborg 2010/.*

The man-made, deep inlet canal for cooling water to the nuclear power plants, situated immediately north of the planned repository, will be isolated from the sea around 2500 AD /Lindborg 2010/. If it is left unaltered after decommissioning of the power plants, it will probably remain as a lake far beyond the initial 1,000 years. Moreover, two new, relatively large lakes situated north of the repository and west of the present "Biotest basin", will be isolated from the sea in the latter part of the period.

As the seafloor close to the coast gets shallower, erosion will occur on wave-exposed bottoms. Some sheltered areas inside a developing, denser archipelago will show accumulation for a short period /Brydsten 2009/. The circulation in Öregrundsgrepen is expected to remain essentially the same as today /Karlsson et a*l*. 2010/. The salinity of the Bothnian Sea is expected to decrease slightly to around 4.8‰ during the initial 1,000 years, assuming unaltered runoff to the Bothnian Sea /Gustafsson 2004a/.

The potential for sustainable human exploitation of food resources in the area over the coming 1,000 years is not expected to differ much from the situation today. Only minor parts of the newly formed land will have the potential for cultivation due to the boulder-rich sediments in the former sea and lake areas, but also due to problems with draining the low-elevation new areas /Lindborg 2010/. New areas will, however, be available for grazing by livestock.

The potential water supply for humans is expected to be fairly unaltered during this period. In the future, the deep canal north of the repository has potential as a freshwater reservoir when the salinity decreases, and also the stream through Bolundsfjärden may potentially be used for freshwater supply. New wells may be drilled in the bedrock or dug in the regolith in the area which is land today, whereas the new land will be too young for wells if current practises are sustained /Kautsky 2001/.

In summary, the biosphere at the site during the next 1,000 years is assumed to be quite similar to the present situation. The most important changes are the natural infilling of lakes and a slight withdrawal of the sea with its effects on the near-shore areas and the shallow coastal basins.

6.3.2 Site development until the end of the initial period of a temperate climate domain

During the initial period of a temperate climate domain, the regressive shoreline displacement is assumed to continue, but at a gradually declining rate (Section 4.5 in **Climate report**, see also /Lindborg 2010/). Initially, the coastline will be subjected to a horizontal transfer of approximately 1 km per 1,000 years. This will strongly influence the landscape, especially during the first part of the period, and eventually it will result in a situation where the planned repository will have an inland rather than a coastal setting (Figure 6-6c).

The strait at Öregrund, south of the modelled area, is expected to be cut off about 3000 AD, and Öregrundsgrepen will turn into a bay. This will affect the water circulation, and due to the continued narrowing of the bay, the water turnover will be further restricted /Karlsson et al. 2010, Engqvist and Andrejev 2000/. During the period from 3000 to 5000 AD, a semi-enclosed archipelago is expected to develop northeast of the repository. Around 5000 AD, many straits in this archipelago will close and a number of lakes will be isolated from the sea.

At 5000 AD, the coastline has withdrawn c. 5 km from the repository. A small stream drains the area above the repository, and some small and shallow lakes are expected to be situated along the stream. This small stream will join a large stream to the south-east at about 5000 AD. The large stream consists of the upstream joined Forsmarksån and Olandsån, draining a large part of Northern Uppland (drainage area $1.3 \cdot 10^3$ km^2). During the period from 3000 AD to 10,000 AD, the Öregrundsgrepen bay gradually shrinks to finally form a short and narrow bay along the island of Gräsö (Figure 6-6c).

In the modelled area, a large number of lakes will be isolated from the sea during the period from 3000 AD to 10,000 AD. Most of the new lakes are small and shallow, and are expected to be infilled and transformed into mires within a period of 2,000 to 6,000 years /Brydsten and Strömgren 2010/. Around 10,000 AD, almost all lakes in the area have been infilled and only some initially relatively large and deep lakes near the Gräsö Island are expected to remain (Figure 6-6c).

The salinity of the sea will continuously decrease due to the isostatic rebound of the shallow sills at Åland between the Bothnian Sea and the Baltic Proper. Around 6000 AD, the salinity is expected to have decreased to 3–4‰, which means that an ecosystem similar to that in the Northern Kvark today, with lower abundance of marine species and higher of freshwater species, will develop.

According to /Brydsten 2009/, accumulation of sediments may occur both on bottoms at large water depths and on shallow bottoms that are sheltered from wave exposure inside a belt of skerries. Erosion occurs mainly on shallow bottoms exposed to waves. Transport bottoms can be found in all places between these two extremes, i.e. at intermediate depths with moderate wave exposure. This means that the seafloor in the model area will show a characteristic evolution over time, beginning with a period of accumulation due to large water depth early after deglaciation. Then comes a period with transport, after which erosion dominates when the water depth decreases even more. Finally, transport and accumulation may occur in sheltered locations during a short period before the sea bottom becomes land. This means that there are very limited parts of the model area that will show continuous accumulation of sediments throughout the whole marine period. The small areas that potentially may show continuous accumulation since the latest deglaciation are situated in the deepest parts of Öregrundsgrepen /Brydsten and Strömgren 2010/.

Much of the newly formed land will be unsuitable for farming due to boulder- and stone-rich deposits /Lindborg 2010/, but there are large areas currently submerged in central Öregrundsgrepen with fine-grained sediments that will be possible to cultivate when exposed on land. Also patches of organic soils on previous lakes/mires may be cultivated, but presumably these soils can be sustainably utilised only for limited periods since compression and oxidation of the organic material will lower the ground surface and cause problems with drainage /Lindborg 2010/.

The food productivity in agricultural areas is several hundred times higher than that in aquatic or non-cultivated terrestrial areas /Andersson 2010, Aquilonius 2010, Löfgren 2010/. Since the proportions of land possible to cultivate will increase as new land areas are formed, this means that the potential food productivity in the total modelled area is expected to increase during the period. However, the number of people that potentially can be sustained by food produced within the Forsmark area is strongly dependent on the degree to which land is used for farming.

The availability of freshwater for human supply is expected to gradually increase. As mentioned above, new lakes and streams will form. These will probably resemble the present-day lakes and streams, and most of the lakes will be short-lived due to their shallowness. New groundwater, potentially useful as drinking water, will be available when the shoreline moves eastwards. Among existing geological formations, the Börstilåsen esker, situated approximately 4 km southeast of the planned repository, may provide groundwater of drinking-water quality, but there are no indications in the hydrogeological modelling results that this aquifer will have contact with discharging groundwater from the repository /Joyce et al. 2010/.

6.3.3 Site development during the remaining part of the reference glacial cycle

As described in Section 6.2.1, SR-Site uses a reconstruction of the last glacial cycle to give one example of possible future changes in climate and climate-related processes. This reconstruction covers, in a realistic way, all relevant climate-related changes that can be expected in a 120,000-year perspective (**Climate report**). The reconstruction divides the period into distinct climate domains, but in reality when looking at the entire modelled area at Forsmark, changeover from one climate domain to another is a smooth transition (Section 4.4.4 in **Climate report**). In addition, it takes time for the environment and its predominant processes to adapt to an abrupt change in climate /Chapter 3 in Lindborg 2010/.

For the modelled area at Forsmark it obviously takes time for a change in environmental conditions to propagate from one end to the other. For instance, this is true for the changeover after the deglaciation, from submerged conditions to an entirely terrestrial and temperate domain. This transition is caused by shoreline displacement, which takes 12,000 years to transfer the whole area from fully submerged just before the first islet emerges from the sea (1000 BC), until the last marine embayment is turned into a lake (around 11,000 AD). During two periods in the later part of the reference evolution, Forsmark is covered by an ice sheet (Figure 6-2). The site will be submerged by water directly after deglaciation and thereafter the transfer from submerged conditions to an entirely terrestrial area is assumed to be repeated. For further descriptions of transitions between climate domains (Section 4.5 in **Climate report**).

Temperate climate domain

The temperate climate domain corresponds to 26% of the reference glacial cycle. After the initial temperate period, which according to the reference glacial cycle ends around 9400 AD, a relative short period of periglacial conditions will follow, and thereafter temperate conditions will dominate again until c. 23,000 AD. Another temperate period that will last for about 5,000 years occurs around 40,000 AD.

During future periods of temperate conditions before the next glaciation, Forsmark is assumed to show biosphere characteristics similar to those of the later parts of the initial temperate period, i.e. the landscape will consist of terrestrial ecosystems, mainly forests and mires, with few or no lakes and no sea. Parts of the area, especially those with fine-grained sediments in central Öregrundsgrepen, can potentially be used for long-term agriculture (Figure 6-6c). Patches with mainly organic soils may also be cultivated for restriced periods. Higher altitude areas with outcrops of bedrock will likely be forested with pine. Also the pattern for discharge of deep groundwater, as well as the conditions determining transport and accumulation of radionuclides in the landscape, are expected to be similar to those prevailing during the late part of the initial temperate period /Chapter 4 and 5 in Lindborg 2010/.

Periglacial climate domain

Periods of periglacial conditions, which are characterised by tundra vegetation and permafrost features, correspond to 34% of the reference glacial cycle. Although the periglacial domain constitutes the largest proportion of the reference glacial cycle, it often occurs during relatively short periods interrupted by other climate domains. The longest uninterrupted period of periglacial conditions starts around 23,000 AD and continues for another 10,000 years. Below follows a generalised description of conditions during the periglacial climate domain. It should, however, be noted that the conditions may vary considerably within this climate domain, from a situation not very different from temperate conditions but with shallow permafrost, to a harsh arctic climate with deep permafrost and very sparse vegetation.

The annual vegetation period of the periglacial domain is short. Nevertheless, primary production may be high in some environments, e.g. in shallow lakes /Andersson 2010/. The terrestrial vegetation consists of sedges, herbs and shrubs. At more exposed and dryer localities lichens dominate, whereas vegetation on wet ground is dominated by mosses. The precipitation will typically be lower than during temperate conditions, due to the limited evapotranspiration transporting water to the atmosphere, exemplified for periglacial conditions at Forsmark in /Kjellström et al. 2009/. The low evapotranspiration means that wet ground is prevalent, because surplus water is unable to infiltrate into the ground /Bosson et al. 2010, French 2007/. This may result in larger areas of wetlands compared with a temperate climate, but on the other hand the peat formation rate is lower, partly because the terrestrial plant productivity is low.

Even on gentle slopes, the soil creeps downhill. Other processes typical of periglacial conditions are upward migration of stones induced by freeze-thaw processes, so called cryoturbation, causing tundra-polygons and thermokarst phenomena. Thus, there are many periglacial processes disturbing the soil and also exposing it to erosion.

Taliks are unfrozen areas, often occurring under lakes or rivers in the permafrost region /Hartikainen et al. 2010/. The talik features are the only spots in the periglacial landscape where radionuclides released from the repository can be transported up to the biosphere /Bosson et al. 2010/. Given that lakes and streams often are locations for human settlement and land use, taliks can potentially be locations where humans during periglacial conditions are exposed to radionuclides released from a repository.

Glacial climate domain

Forsmark is covered by an ice sheet during 24% of the reference glacial cycle, mainly during its later part. On the ice-surface, microbes, algae and some insects can exist. At the ice-margin, a productive aquatic community may exist, which can sustain fish populations that may be exploited by humans and by animals living on the ice (e.g. birds, arctic foxes, polar bears) and in the sea (e.g. seals and whales).

Any larger vertebrates or humans living on the ice are likely to migrate over large areas due to low food production and severe weather conditions. In most cases, a human population will probably comprise occasional visitors, due to the harsh environment. The only situation under glacial conditions when humans or other biota may be exposed to high concentrations of radionuclides from the repository is when the retreating ice-front is situated near the Forsmark area and the area is submerged. Under these conditions, it is possible that a human population could be present for longer periods and live on fish taken from close to the ice margin.

Submerged conditions

In the reference glacial cycle, two periods of submerged conditions at Forsmark are present, representing 16% of the total reference glacial cycle. These periods always follow directly after the ice sheet has withdrawn as a result of the bedrock being depressed by the ice load. After the last glaciation which ended at 8800 BC in Forsmark, the first terrestrial areas appeared around 1000 BC and the last marine embayment in the modelled area is turned into a lake around 11,000 AD. This means that the submerged conditions in the modelled area may be divided into two phases; one first phase of c. 8,000 years when the whole area is submerged, and another that continues for a further 12,000 years when the sea gradually withdraws and the land area expands accordingly. This description of the temporal succession is not seen in the description in the reference glacial cycle (Figure 6-2) since the latter is valid specifically for a point above the repository target area, but it gives a more realistic picture of the succession for the whole landscape (see also the section on transitions between climate domains in (Section 4.4.4 in **Climate report**).

Submerged conditions are not defined as a climate domain in SR-Site **Climate report**. Instead, it is a state when the processes and properties related to the marine conditions are dominant. The marine ecosystem is not expected to change dramatically from today as a result of changes in climate, except for the long-term variations in salinity and water depth. Therefore, the submerged future landscape is in SR-Site treated in the same way as the historical and present aquatic ecosystems at Forsmark, and the prerequisites for transport and accumulation of radionuclides are assumed to be similar to those in the present marine ecosystem.

6.4 Site development according to the SR-Site global warming climate case

SR-Site handles the possibility of anthropogenic induced global warming by constructing a *global warming climate case* (**Climate report**), describing a future climate development influenced by perturbations of the natural climate system. In this climate case, the perturbations are assumed to cause air temperatures several degrees warmer than present in central Sweden within the first hundreds to thousands of years after present. Subsequently, following reductions in emissions, temperatures are envisaged to slowly decline for the rest of the prolonged period with temperate climate conditions **(Climate report**).

The combined effect of greenhouse-gas emissions and exceptionally small amplitudes of solar insolation variations during the coming 100,000-year period /Berger 1978/, may cause the present interglacial to be exceptionally long /Berger and Loutre 2002/. The global warming climate case follows the proposition by /Berger and Loutre 2002/, and extends the initial period of temperate climate domain by 50,000 years compared with the reference glacial cycle (Section 6.2.1). After this initial 50,000 years of temperate conditions, the global warming climate case follows the same pattern as the reference glacial cycle and the corresponding first period of periglacial domain will occur in about 58 kyrs from now. Consequently, the climate-related processes will be identical in the two climate cases, but displaced by 50,000 years.

As exemplified in the global and regional climate modelling performed by /Kjellström et al. 2009/, a global warming climate may result in the Forsmark region experiencing a mean annual air temperature increase of ~3.5°C and an increase in mean annual precipitation by ~20% as compared with the climate during 1961–2000, which is chosen as reference period in the study by /Kjellström et al. 2009/. These conditions were modelled for a period a few thousand years after present, but similar conditions could arise also within a few hundreds of years. The results by /Kjellström et al. 2009/ are in line with several other climate model simulations assuming similar future atmospheric greenhouse gas concentrations /BIOCLIM 2003, Rummukainen 2003/.

An important question related to future global warming is changing sea level and shoreline position, which may result from melting of present glaciers and ice sheets and from the thermal expansion of sea water. This is of particular importance for Forsmark, being an area of low relief in a coastal position close to the Bothnian Sea. Contradictory predictions regarding the future of the Greenland ice sheet in a warming climate /Lindborg 2010/ have been taken into account in SR-Site by including an assessment of the consequences of a melting ice sheet and its effect on sea level at Forsmark (Figure 6-7). The global warming climate case is therefore designed to allow the Greenland ice sheet to collapse and melt completely during the next thousand years.

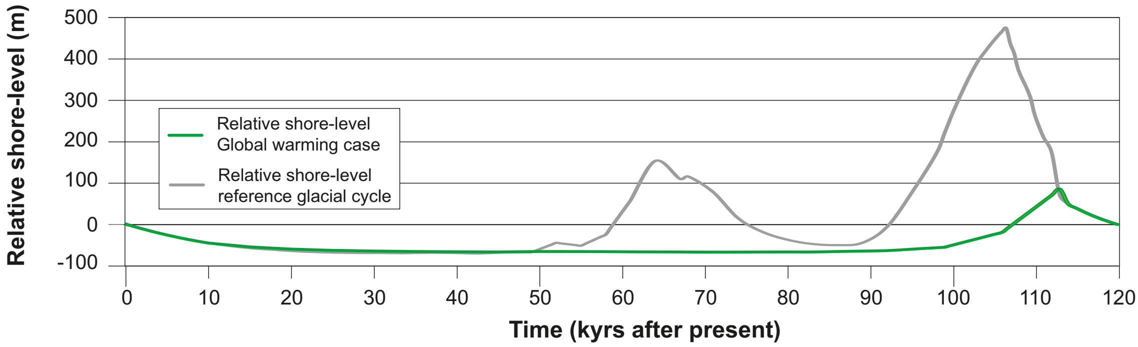

Figure 6-7. *Shore-level evolution at Forsmark for the reference glacial cycle (grey) and the global warming climate case (green). Negative numbers indicate that the area is situated above the present sea level. Figure from* ***Climate report****.*

In the modelling, counterbalancing gravitational effects associated with the removal of the mass of the Greenland ice sheet, combined with the local isostatic rebound that follows removal of the Fennoscandian ice sheet, mean that isostatic changes compensates for the eustatic change at Forsmark (Figure 6-7), resulting in a continuation of the present shore-level displacement (**Climate report** /Milne et al. 1999, Whitehouse 2009/). However, because of the large uncertainties related to the amount of global sea level rise in a warming climate, Forsmark may experience, contrary to what is shown in Figure 6-7, a transgression and associated submerged conditions during the initial few thousands of years, after which the isostatic component again dominates and results in regression. Accordingly, also in the global warming climate case Forsmark will in the long run be situated above sea level until the occurrence of a future Fennoscandian ice sheet (**Climate report**).

6.4.1 Ecosystems in a climate characterised by global warming

/Kjellström et al. 2009/ modelled the development of terrestrial vegetation during conditions of global warming and suggested that Forsmark will be dominated by broadleaved trees with larger biomasses, but with net primary production similar to today. /Craft et al. 2008/ showed that carbon sequestration is negatively correlated to the mean annual air temperature for temperate freshwater peatlands in the USA. A similar pattern has also been described from the former Soviet Union, where accumulation of peat was found to increase during periods of colder conditions /Gorham 1991/. Peat production in peatlands is also a function of precipitation, and a higher temperature combined with increased precipitation may result in periods of unchanged peat accumulation under warmer conditions. An increased temperature, with increased evapotranspiration, will likely lower the groundwater table and increase the heterotrophic respiration. /Strack et al. 2008/ suggested that dry peatland areas such as bog hummocks and ridges will act as smaller sinks or sources of atmospheric carbon, whereas wet zones will likely become greater sinks.

The effects of global warming on aquatic ecosystems are complex and difficult to predict. Many changes in ecosystem properties may vary in both positive and negative directions, depending on a complex set of feedbacks. Although several factors may lead to increased primary production, there are also several factors that may lead to increased respiration, and a possible outcome of warmer conditions is that net ecosystem production will remain almost the same or at least be included within the range of variation in present-day temperate conditions /Andersson 2010, Aquilonius 2010/.

7 Landscape model for radionuclide assessment

Temporal development of discharge areas of deep groundwater is analysed by hydrological models in SR-Site. This approach has been possible by utilisation of extensive site data and systematisation documented processes. The concept builds upon a landscape model exploring dynamics of the environments during non-glacial conditions and screens out potential objects which can be affected by deep groundwater discharge, potentially with radionuclides from the repository. The landscape development is based on a scientific coherent, temporal and spatial understanding of the landscape which is essential to provide robust estimates for the radionuclide model.

The *landscape model* delivers location, delimitation and development of biosphere objects, as well as spatial interactions between neighbouring objects. This chapter summarises the methodology used to link the geosphere models to the surface system and the results derived from the landscape model. Specifically, the following sections present a summary of how the biosphere objects are identified by using the groundwater modelling, together with a discussion on how object development in time is described, using data from the *landscape development model*.

The discharge of deep groundwater in future landscapes is illustrated in Section 7.1, where also the analysis of groundwater flow simulations used to identify biosphere objects is described. Section 7.2 summarises the modelling of near-surface hydrology and transport that was performed in order to support the landscape model. In Section 7.3, the biosphere objects are put together in the evolving landscape. This gives an illustration on how the objects are linked to each other and how the object configuration develops during non-glacial conditions. The input from the landscape development model used to populate the biosphere objects is also described in Section 7.3, and the data used in the *radionuclide model* obtained from the landscape model are explained. The chapter concludes with a short description on application of the landscape model in different climate scenarios.

7.1 Discharge points

7.1.1 Modelling of deep groundwater discharge

The identification of deep groundwater discharge areas in the future Forsmark area is based on the modelling of flow paths from the repository to the ground surface /Section 4.2 in Joyce et al. 2010/. To locate potential discharge areas, the end positions of flow paths emerging at the surface in the particle tracking simulations, so-called discharge points, were related to present and future features of the Forsmark landscape, such as lakes and shallow parts of the sea floor. According to /Joyce et al. 2010/, the discharge pattern is determined mainly by the local topography and the deterministic deformation zones. The pattern does not vary significantly between model realizations. With few exceptions, the discharge points form clusters in limited numbers. For the identification of discharge areas, it was assumed that the locations of these groups indicate areas likely to be affected by discharge of deep groundwater that could potentially be contaminated.

The location of discharge points in the Forsmark landscape shows that: 1) deep groundwater from the repository is primarily attracted to low points in the landscape, e.g. shallow parts of the sea, along the shoreline, and in lakes, streams and wetlands, 2) discharge areas covered by the sea tend to be relatively large, whereas discharge areas above sea level are narrower and primarily located to lake basins (which may be infilled), 3) discharge areas are located in a limited number of basins /Lindborg 2010/. Uncertainties in forecasted location of discharge points are discussed in /Joyce et al. 2010/. Transport in the near-surface and surface system is also compared with results from the more detailed MIKE SHE modelling (Section 7.2.2).

A number of discharge points are concentrated along the north-eastern boundary of the model domain according to the modelling of flow paths /Joyce et al. 2010/. This may indicate that the modelled area should be extended further north-east to consider correctly the transport of particles with the longest transport times. However, even if the modelled area was extended and this resulted in the identification of some additional discharge areas outside the present boundary, it is argued on the basis of the modelled discharge pattern that the same types of discharge areas would be affected (i.e. lakes, streams, wetlands and shallow parts of the sea, see Section 7.2.2). Therefore, the risk calculations based on the currently identified discharge areas are considered to fulfil needs of the assessment.

Shoreline regression affects the size and position of potential discharge areas in two important ways. First, the size of a discharge area that receives groundwater from the repository over extended periods of time (e.g. areas situated above the repository) decreases substantially when the area emerges from the sea. Secondly, changes in the hydrological driving forces due to a regressing shoreline will directly affect the discharge of deep groundwater; the discharge in terrestrial areas will cease with time, whereas new discharge areas will appear in the newly emerged parts of the landscape and in shallow parts of the sea.

7.1.2 Description of delivered discharge points

The hydrogeological modelling, briefly described above, traced the transport of "water parcels" or particles from each canister position through the bedrock and regolith up to the ground surface. The positions where the traces reached the surface are called "discharge points". The present analysis is based on discharge points delivered in September 2009; the data are stored in the SKB SR-Site data storage[1].

There are three data sets with discharge points, two covering the whole model area (regional models) and one for the area close to the repository (local model). The two regional models are based on different hydrogeological models. The differences in traces between the models are small; only nine traces have different exit positions.

Version 1 of the regional models have been used for the selection of basins included in the landscape model. The data set holds 89,908 records. Many of the traces never reach the surface, or may reach the surface when the Forsmark area experiences a glacial climate domain (> 57,000 AD). These records were deleted from the data set; the number of records left after deletion was 20,802. The spatial distribution of the discharge points from the regional model is shown in Figure 7-1. This distribution is not taking the temporal distribution into account and is not to be used to delimit discharge areas. The temporal distribution is discussed in Section 7.3.1 together with the identification of biosphere objects.

Discharge points for the whole simulation period are shown in Figure 7-1. The discharge points are displayed on a background map showing the present shoreline; note that many of the discharge points shown in the figure were calculated using other (future) shoreline positions. The major part of the discharge points are found close to the repository during submerged periods, and a minor part are displaced late in the simulated interglacial in the upper north-eastern area, mainly due to shoreline displacement. The most distant points are displaced approximately 10 km (Figure 7-2).

The distribution of travel distances (calculated as the straight distance between canister and discharge positions) is bimodal with local maxima at c. 750 and 9,250 m, whereas travel distances between 5,000 and 8,000 m are few. Note that more than 500 traces are less than 500 m in travel distance, although the vertical distances alone are almost 500 m; these particles travel straight up through the bedrock. Approximately 42% of the discharge points are within what is referred to as the northern branch and 58% in the southern branch (all canister positions are situated in the southern branch). The distribution of discharge points by basin is shown in Table 7-1.

Five of the basins contain 94% of the discharge points (Table 7-1). The two basins 118 and 124 (Figure 7-8) show high values after normalisation by area. As many as 14 basins have no discharge points and 8 basins have less than 100 discharge points, see Figure 7-8 for a map of basins. The discharge points are mostly situated in low-points in the landscape (groundwater discharge areas) and more than 70% of the points are in consequence situated in present and future lakes.

[1] SKB doc 1263189 (http://svn.skb.se/trac/SR-SiteDataStorage/browser/SERCO/Pathlines/090911) access might be given on request.

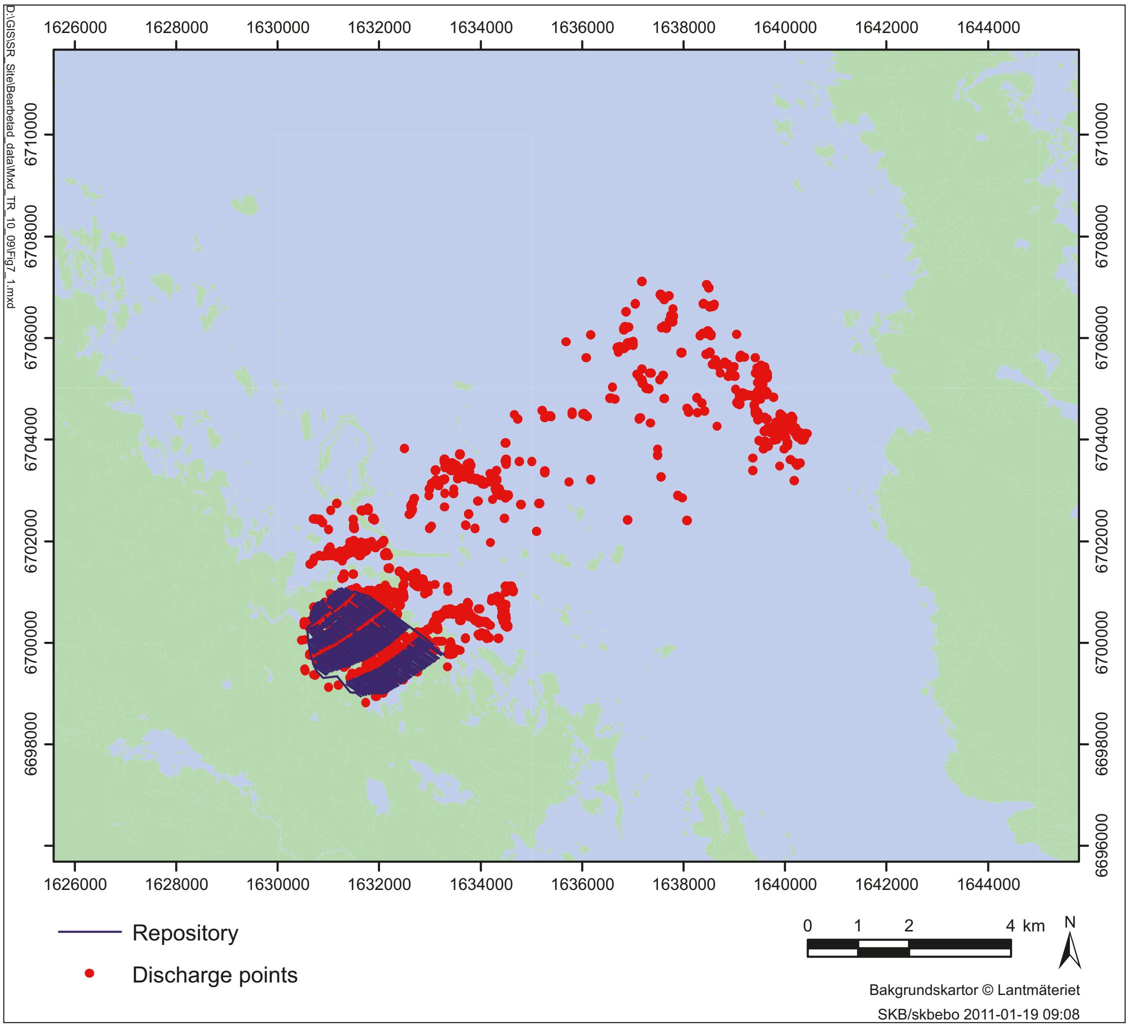

Figure 7-1. *Distribution of future discharge areas resulting from hydrogeological modelling. Note that extension of the sea (light blue) mirrors the current situation. Extension of the sea at the time of future discharge will be reduced as a result of isostatic rebound. The site for the proposed repository is marked with blue frames.*

7.2 Near-surface flow and transport

7.2.1 Flow model results for different climate conditions

The hydrological development of the landscape in a hydrological perspective was studied by analysing the effects of shoreline displacement, development of the regolith layers and the vegetation cover in different climates /Bosson et al. 2010/. Numerical models providing output on present and future conditions were developed using the MIKE SHE tool and applied in order to answer questions about the future hydrology in Forsmark. In particular, the modelling focused on the development of water balances, recharge-discharge conditions and on solute transport in the uppermost part of the bedrock and in the regolith.

Present conditions regarding meteorology, surface water levels and discharges, groundwater levels in regolith and bedrock, and locations of recharge and discharge areas were investigated during the site investigations. Detailed modelling of the present hydrology at the site was performed and presented as a part of the site descriptive modelling /Bosson et al. 2008/. The data and models from the site investigations and the site descriptive modelling provided the basis for the models describing possible futures in Forsmark. Simulations were performed for present conditions, wet temperate climates and for a periglacial climate.

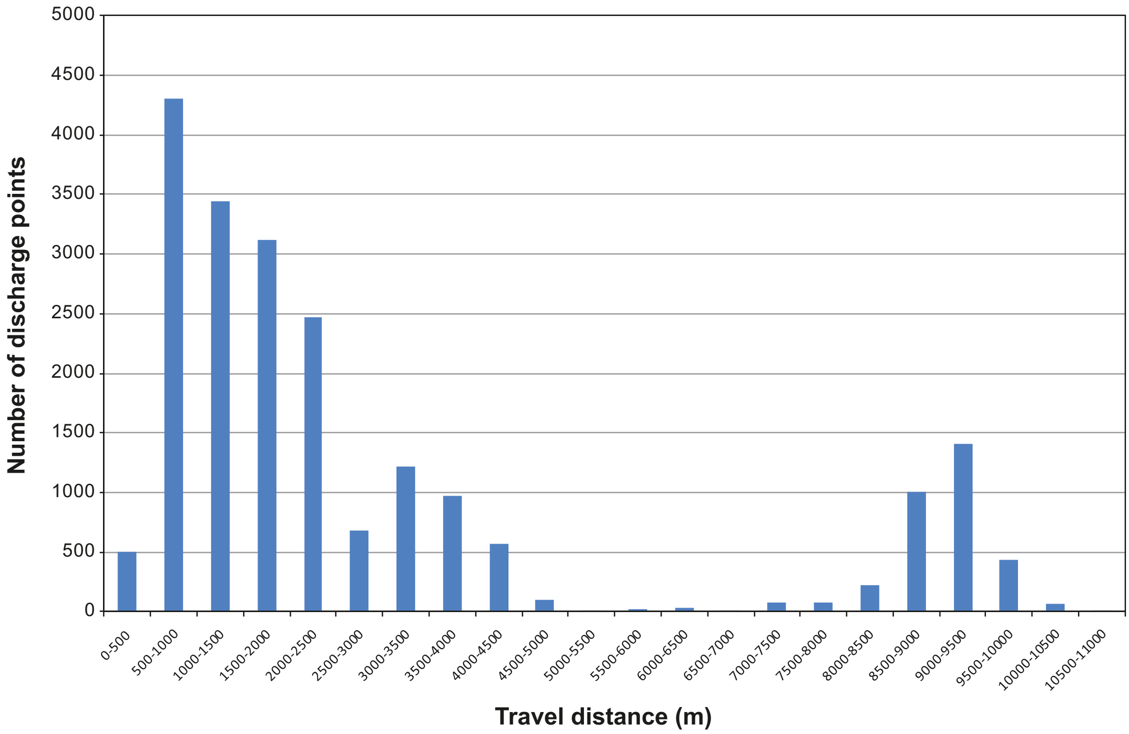

Figure 7-2. *Distribution of particle travel distances between canister positions in the repository and discharge positions on the surface for the whole simulation period. Figure from /Lindborg 2010/.*

Table 7-1. Number of discharge points and density of points per basin /Lindborg 2010/. Locations of individual basins listed below are shown in Figure 7-8.

Basin	Points	Points/km²
101	0	0
105	369	13
107	0	0
108	0	0
109	85	56
110	19	3
112	28	40
113	29	18
114	2,842	150
115	12	3
116	2,940	208
117	14	1
118	5,892	2,939
119	0	0
120	4,511	865
121	3,279	644
122	0	0
123	0	0
124	290	1,189
125	157	449
126	0	0
127	1	3
128	13	182
129	0	0
131	0	0
132	0	0
133	0	0
136	321	143
141	0	0
146	0	0
147	0	0

The SR-Site MIKE SHE modelling were performed as a regional model, primarily used for flow calculations, and two local models that were used mainly for transport modelling (Figure 7-3). The transport analyses included both particle tracking, where calculated flow paths and discharge points were used to assess the discharge points delivered from the modelling of the deeper groundwater system, as described above, and modelling with the MIKE SHE advection-dispersion module, which was used to investigate solute dispersal.

The water balances calculated by numerical modelling with future shorelines do not differ significantly from the measured or calculated water balances for present conditions. Thus, when studying only the effects of the shoreline displacement on the overall water balance, no major changes from present conditions were found. The flows between different model compartments differ less than 10% in all the studied cases. The internal distribution of the precipitation water is approximately 70% evapotranspiration and 30% runoff independently of the shoreline position and hence of the land area considered (present or future land areas).

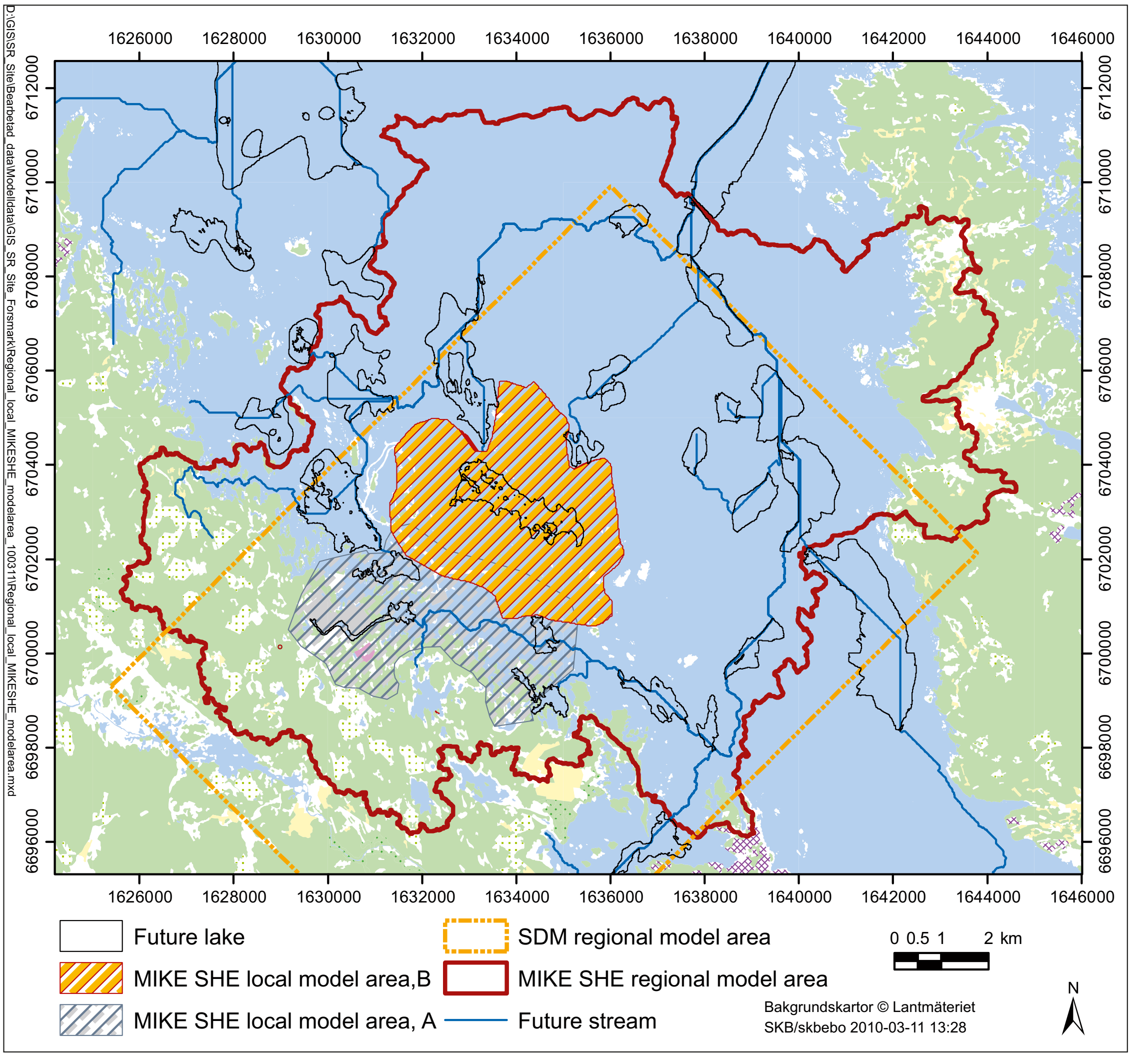

Figure 7-3. *The regional and local MIKE SHE model areas. In the figure, the site descriptive modelling (SDM) regional model area and the future lakes and streams are also marked. Figure from /Bosson et al. 2010/.*

The considered case of a wet temperate climate implies a three-fold increase of the precipitation compared to the current mean annual precipitation. In this case, the runoff is approximately 20% of the applied precipitation and the evapotranspiration is 80%. Due to the higher evapotranspiration caused by the higher temperature and the longer vegetation period, the proportion of the precipitation water leaving the model volume as runoff under wet temperate climate conditions is lower than for normal temperate climate conditions. However, there is an absolute increase in the calculated annual runoff from c. 180 mm to c. 360 mm. The increased runoff under wet temperate climate conditions affects the residence times of water in lakes and streams, which influence the transport of matter within and between the different ecosystems in the landscape.

The largest change in the overall water balance is observed when modelling periglacial climate conditions. The internal distribution of the precipitated water is 50% runoff and 50% evapotranspiration. The water demand from the vegetation is very low, due to a more sparse vegetation cover with less total leaf area, but also because the unfrozen period is short. Even during the active period, the temperature is quite low; thus, there is no driving force for effective evapotranspiration. The precipitation applied when modelling cold conditions is c. 20% lower than for temperate weather conditions. However, because the evapotranspiration is very low, the runoff leaving the system via the surface water streams is larger for the cold climate than under temperate climate conditions, even though the applied precipitation is lower.

The shallow groundwater table at present will prevail also under future conditions. However, a lowering of the water table within the area above the planned repository can be noticed when taking shoreline displacement and the development of the regolith into consideration. At present, the main part of the area has a groundwater table within one metre below ground surface. Under future conditions with a more distant shoreline, the depth to the groundwater will increase somewhat. Specifically, the model results indicate that the part of the model area having depths between 1 and 3 m below ground surface will increase. With a lower groundwater table, the amount of water transported in the upper part of the profile, which has a high transport capacity, will decrease.

The overall pattern of recharge and discharge areas is the same for the different time periods studied. A scattered pattern governed by the local topography is found in the regolith independently of the shoreline position, the vegetation or the applied coupled regolith-lake development model (RLDM) /Brydsten and Strömgren 2010/. In the bedrock, discharges are concentrated to areas under the lakes and stream valleys. Changing the RLDM from the one representing the present conditions to the ones reflecting the regolith development up to 5000 AD or 10,000 AD does not have a strong influence on the pattern of recharge and discharge areas. There are some exceptions, but, in general, the overall recharge-discharge pattern seems to be governed by the topography, and not so much by the stratigraphy, thickness or type of regolith.

7.2.2 Near-surface flow paths

Water flow paths from the deep bedrock do not change with different output from the RLDM or vegetation covers. The areas receiving particles at present are also discharge areas in the future models as long as a temperate climate is applied. As described above, most of the lakes act as discharge areas and the transport under the lakes is dominated by the vertical component as long as the transport takes place in the bedrock. The transport in the regolith under and around the lakes is dominated by the horizontal component. The low conductivity lake sediments reduce the vertical flow through lake bottoms and the main discharge of groundwater is seen along the shorelines of the lakes and wetlands.

Figure 7-4 compares discharge points calculated by particle tracking in the MIKE SHE and ConnectFlow models, where ConnectFlow is the modelling tool used in the bedrock hydrogeology modelling /Joyce et al. 2010/. The starting positions of the particles in the MIKE SHE simulation were given by the ConnectFlow particle positions at 40 m.b.s.l. which means that observed differences in discharge locations are caused by differences between the two models in the representation of properties and processes in the upper 40 m of the system. For the particles going to surface streams, the differences between results from the two models are small. However, some differences can be observed in the lake areas. The particles leaving the MIKE SHE model tend to be more concentrated along the shorelines of the lakes, whereas the particles from the ConnectFlow model mainly appear in the central parts of the lakes.

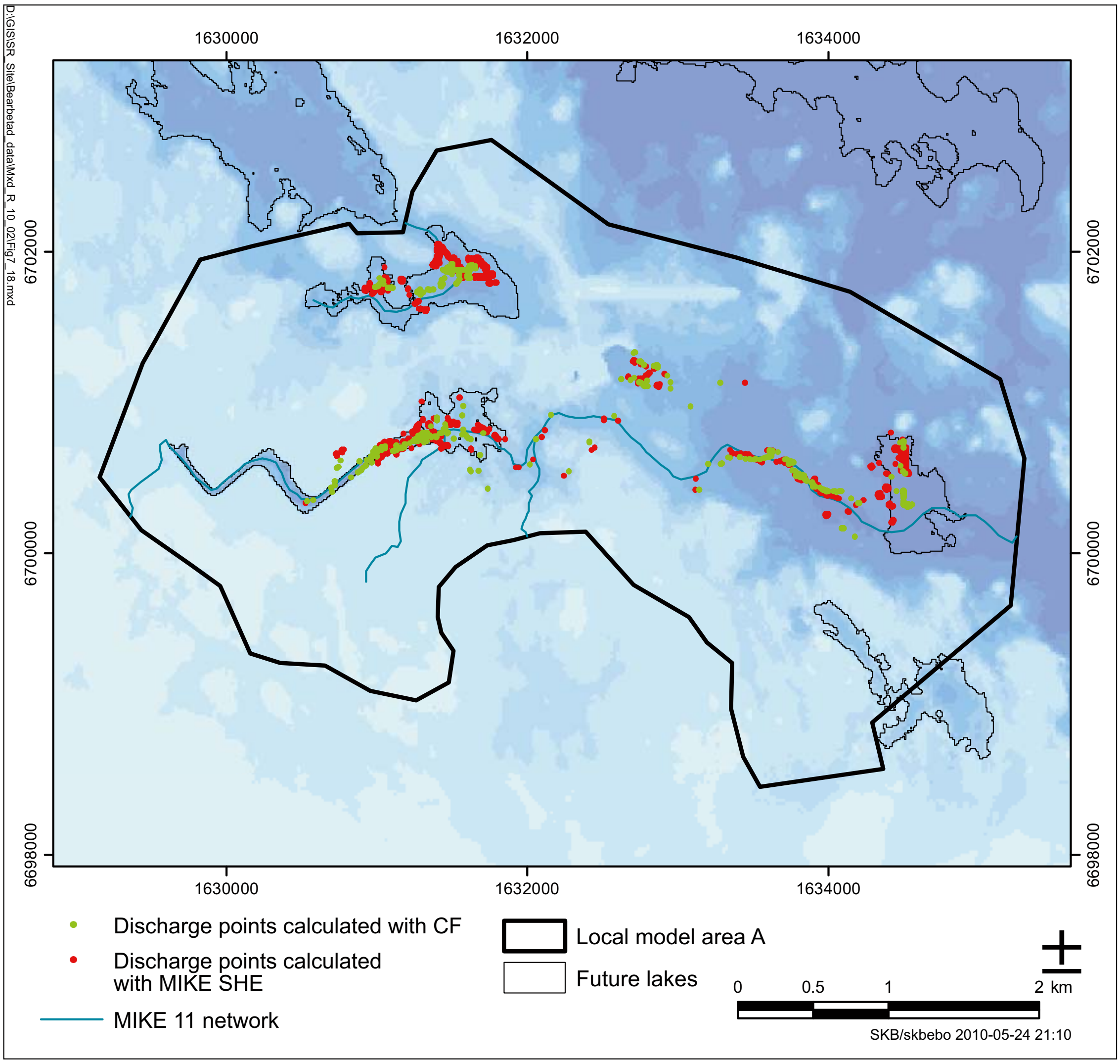

__Figure 7-4.__ Comparison of discharge points in local model A, calculated with MIKE SHE (red dots) and ConnectFlow (CF, green dots). The modelled future surface streams are indicated by blue lines "MIKE 11 network". Figure from /Bosson et al. 2010/.

One reason for the differences between the results from the ConnectFlow model and the MIKE SHE model may be that the extents and thicknesses of the lake sediments are described in more detail in the MIKE SHE model. Another reason is that the MIKE SHE model includes more surface processes than the ConnectFlow model. In relation to the lakes, the evapotranspiration along the lake shorelines decreases the groundwater head in the upper soil layers, creating an upward hydraulic gradient from the deeper layers /Bosson et al. 2008/. However, more important to note is that particles appear to discharge in the same objects in the two models, which means that the simplified representation of the surface system in the ConnectFlow model has no major effects on the identification of biosphere objects in the landscape model (cf. below).

The same pattern as described above is found when a wet temperate climate is applied to the model. Under cold conditions with continuous permafrost, the pattern of recharge and discharge areas changes dramatically. During the present temperate period, the local topography has a strong influence on the location of recharge and discharge areas, whereas the recharge and discharge areas are concentrated to through taliks under permafrost conditions. Through taliks provide the only available pathways for the water, and consequently also for matter transported by water, to be transported up or down through the permafrost. Figure 7-5 shows results of particle tracking between through taliks in a model domain with a 100 m thick permafrost layer (except in taliks).

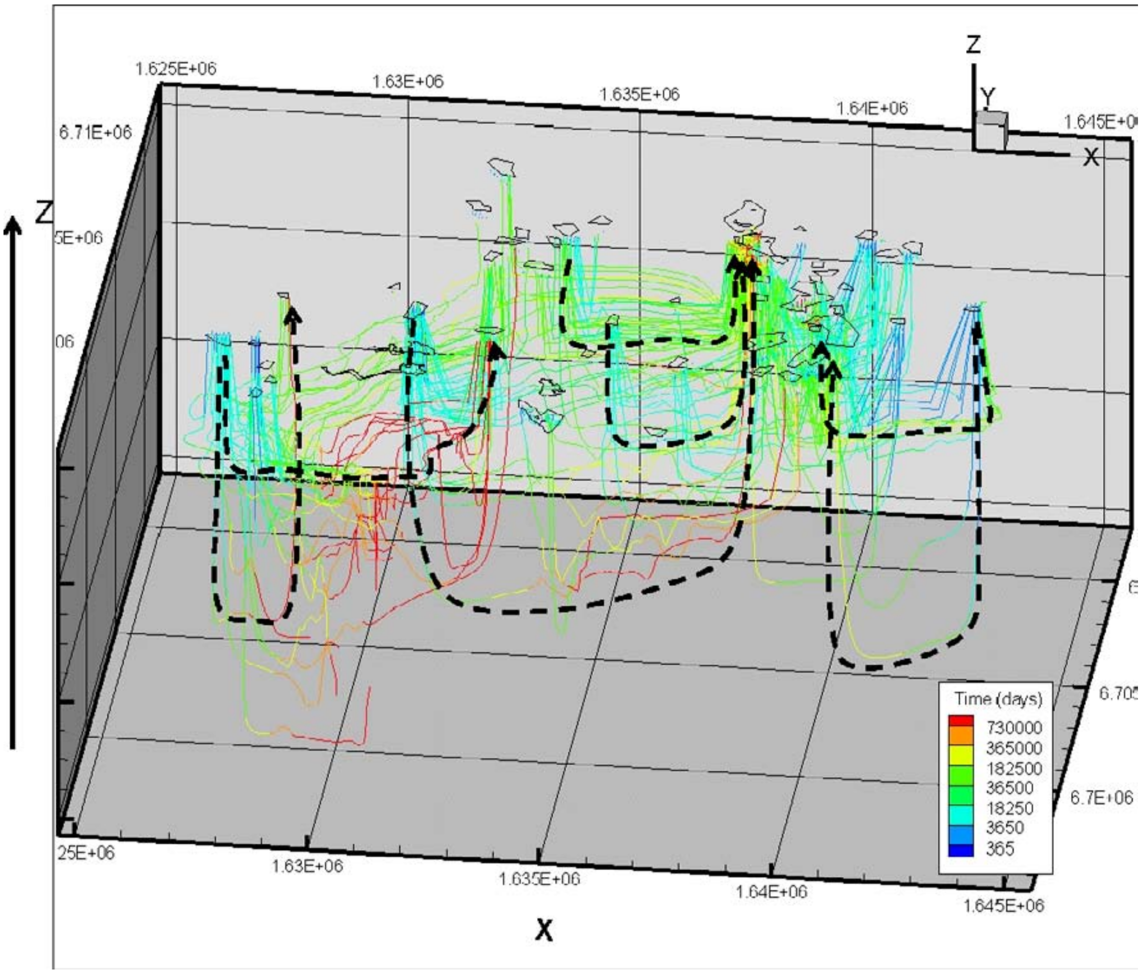

Figure 7-5. Flow paths between through taliks in a model with 100 m thick permafrost (except in unfrozen taliks). Particles were released in the uppermost regolith layer during the thawed season, i.e. the period when this layer is not frozen. The colour along each flow path shows the accumulated particle travel time in days. Figure from /Bosson et al. 2010/.

7.2.3 Transport by advection and dispersion

Of particular interest are the advection-dispersion simulations of transport from sources defined by individual canister positions. These transports are characterised by relatively larger groundwater flow velocities and short transport times to the surface. Figure 7-6 shows results from one of these simulations, which can be regarded as typical. As shown in the figure, transport is in the vertical direction up to the near-surface layers where horizontal spreading takes place. A detailed presentation of this modelling and the results obtained is given in /Bosson et al. 2010/.

7.2.4 Radionuclide retention and reactive transport

In addition to the advective and advective-dispersive simulations discussed above, reactive transport modelling has been performed. The reactive transport modelling takes into account that dissolved substances may be affected by processes such as sorption and precipitation, which act to retain the transported substances in the regolith. This contrasts to the advective and dispersive simulations, which describe how water-borne particles are transported without interactions with solid phases.

Both conceptual modelling of radionuclide retention processes and numerical modelling of coupled advective-dispersive and reactive transport modelling have been performed. This modelling work is reported in /Piqué et al. 2010/, from which the contents of this section were taken; an extended summary is provided in /Lindborg 2010/. The objective of the modelling performed was to evaluate

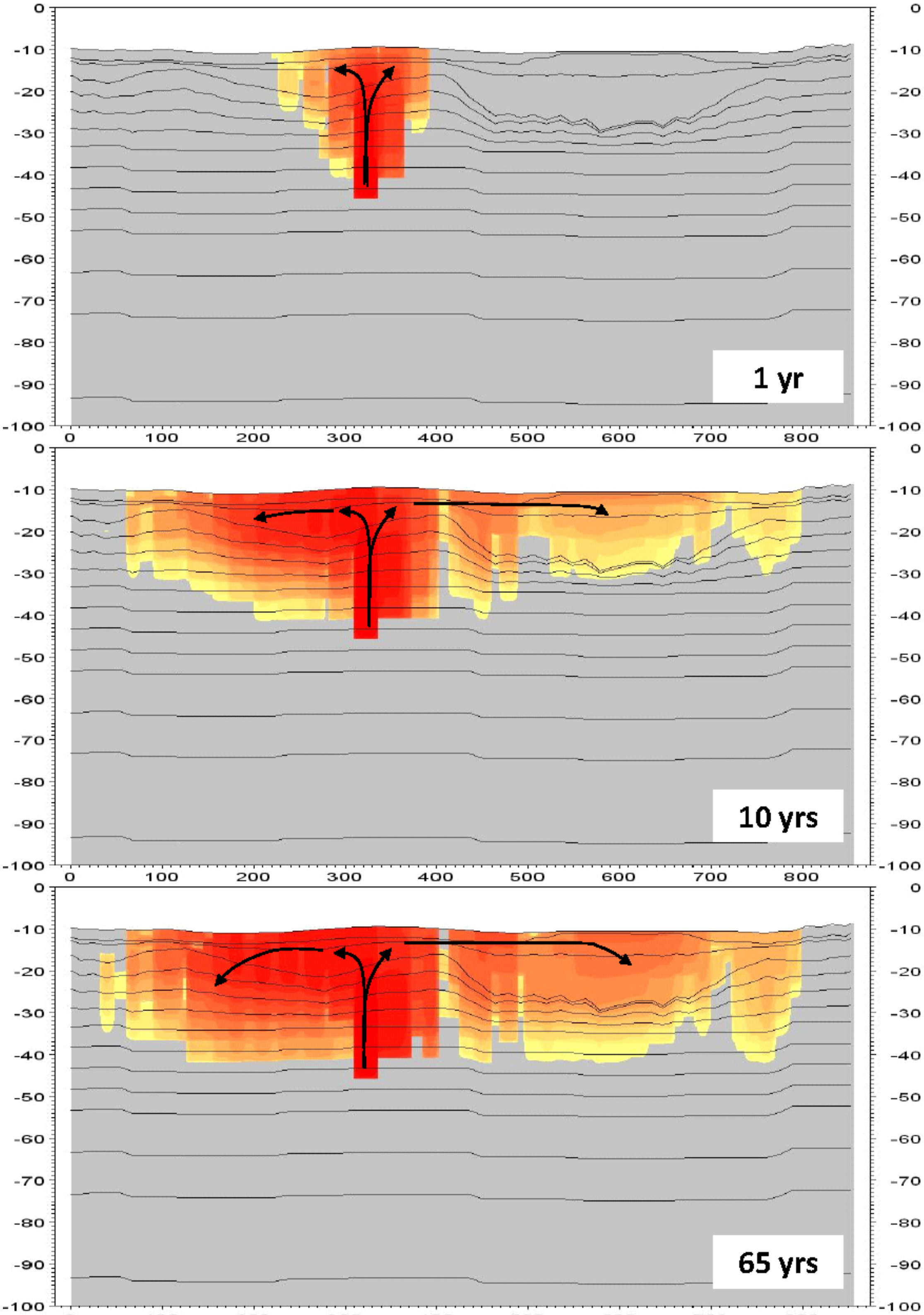

Figure 7-6. *Concentrations after 1, 10 and 65 years of advection-dispersion simulation of transport from a single canister position. The source in MIKE SHE is at –40 m.a.s.l. along a flow path identified by particle tracking in the ConnectFlow model. Red colour indicates high and yellow low concentration. Figure from /Bosson et al. 2010/.*

the retention capacity of the near-surface systems, which in the numerical modelling part of the work were represented by one till system and one clay system. The study was focused on long-lived radioactive isotopes of C, I, Cl, Nb, Ni, Mo, Se, Tc, Th, Sr, Ra, Cs and U.

Conceptual description and numerical simulations of radionuclide reactive transport show that cation exchange and surface complexation on illite are active processes for the retention of several radionuclides (U, Th, Ni, Cs, Sr and Ra). Surface complexation on iron hydroxide is an active process in the till system, able to effectively retain U and Ni. Another retention process of importance is the incorporation of the radionuclides into mineral phases, either by the precipitation of pure phases or solid solutions. Quantitative modelling has been useful to illustrate the incorporation of C and Sr in the carbonate solid solution, as well as the precipitation of uraninite in the clay and the precipitation of native selenium and radiobarite in the till.

Other mineral phases that potentially could retain U, Se, Nb and Tc do not precipitate in the numerical simulations. This is either due to the considered pH-Eh conditions and/or because the dissolved concentrations of the studied elements are not high enough under the considered simulation conditions. It is important to keep in mind that changes in these parameters and in the boundary conditions could modify the predicted behaviour of these elements.

The elements Th, Ni and Cs are most significantly retarded, mainly through sorption onto illite. Therefore, if the amount of illite (i.e. the amount of available sorption sites) decreases, the retardation of these elements will also decrease accordingly, as illustrated by the sensitivity analyses performed. The strong retardation predicted for these elements is in good agreement with reported K_d values for Forsmark till and lake sediments /Sheppard et al. 2009/. According to the models, Cs, Th and Ni are strongly retained, whereas C, U, Sr and Ra are more mobile. The simulations also show that Nb and Tc behave conservatively in both domains, as expected due to their anionic character under these conditions, and Se only in the clay domain.

Although not directly comparable to the calculated effective K_d, it can be stated that the reported K_d values of Forsmark soils and sediments /Sheppard et al. 2009/ show a similar general trend (i.e. the most strongly retained elements are Th, Cs and Ni, followed by U and Sr). Se and Nb are the two exceptions, for which the computed behaviour does not agree with reported K_d values. Not all the possible retention processes considered in the conceptual model were included in the simulation, either due to lack of reliable knowledge on the processes and/or scarcity of thermodynamic data required for the numerical modelling.

Besides the retention mechanisms, other processes that act to reduce radionuclide concentrations in the studied systems are dilution of the radionuclide-bearing deep groundwater, which applies to all elements, and radioactive decay. Decay is not included in the performed modelling, but it can be noted that the radionuclides being most strongly affected by this process are the relatively short-lived Ra-226 and Sr-90.

7.3 Biosphere objects and landscape modelling

The temporal and spatial extension of the biosphere is analysed in a landscape model. This unique approach allows a good resolution of how potential discharges from a future repository can be redistributed in the surface ecosystem considering constraints in the ecosystem, hydrology and land use in a coherent and systematic way. The biosphere at Forsmark is represented by a set of interconnected biosphere objects. A biosphere object is defined as an area of the landscape that can receive radionuclides released, either through discharge of deep groundwater or in contaminated surface water, at any time during a glacial cycle. The identification of biosphere objects, their positions in the landscape, and their development in time, are described below and in more detail in /Chapter 6 in Lindborg 2010/.

7.3.1 Identification of biosphere objects

Clusters of discharge points have been used to identify the locations of biosphere objects in the Forsmark area. By applying discharge points on the landscape development model in time steps of 1,000 years, the spatial and temporal pattern of discharge areas were identified and assigned to specific objects. Three different patterns in time were observed: i) discharge areas that were active under submerged conditions only, ii) areas that received discharge during all succession stages, and iii) discharge that followed the shoreline displacement towards north-east. The outer boundary of each biosphere object was determined from the hypsography of the sea basin during the submerged phase, whereas the shoreline of the lake at time of isolation from the sea delineates the biosphere object during the lake and terrestrial phases. The identification of biosphere objects is illustrated in Figure 7-7 as an example of how discharge points are applied on a specific time step map (11,000 AD) of the future Forsmark landscape.

Key geometrical characteristics of the objects have been determined from the local (i.e. sea or lake basin) topography, whereas the regional geometry defined landscape characteristics, like hydrological links between biosphere objects and sizes of catchment areas. In total ten biosphere objects have been identified, containing a discharge area during any period of the present interglacial. Five additional biosphere objects located downstream of the discharge areas have also been identified. Finally, to represent discharge directly into a stream or a wetland without an initial lake stage, the basin of one of the original biosphere objects has been partitioned into three separate biosphere objects.

7.3.2 Geometric features in the landscape

The landscape model is, apart from the biosphere objects, based on three different geometric features: basins, watersheds and sub-catchments. These partly overlap each other and are used for different tasks to define and populate the final Landscape model. The "basin" is the main feature and most of the parameters are based on data from each basin area. The watershed is the total upstream area for a basin, and the sub-catchment is the drainage area for a biosphere object minus the drainage area for the surface water inlet into the biosphere object. These features are described in more detail below.

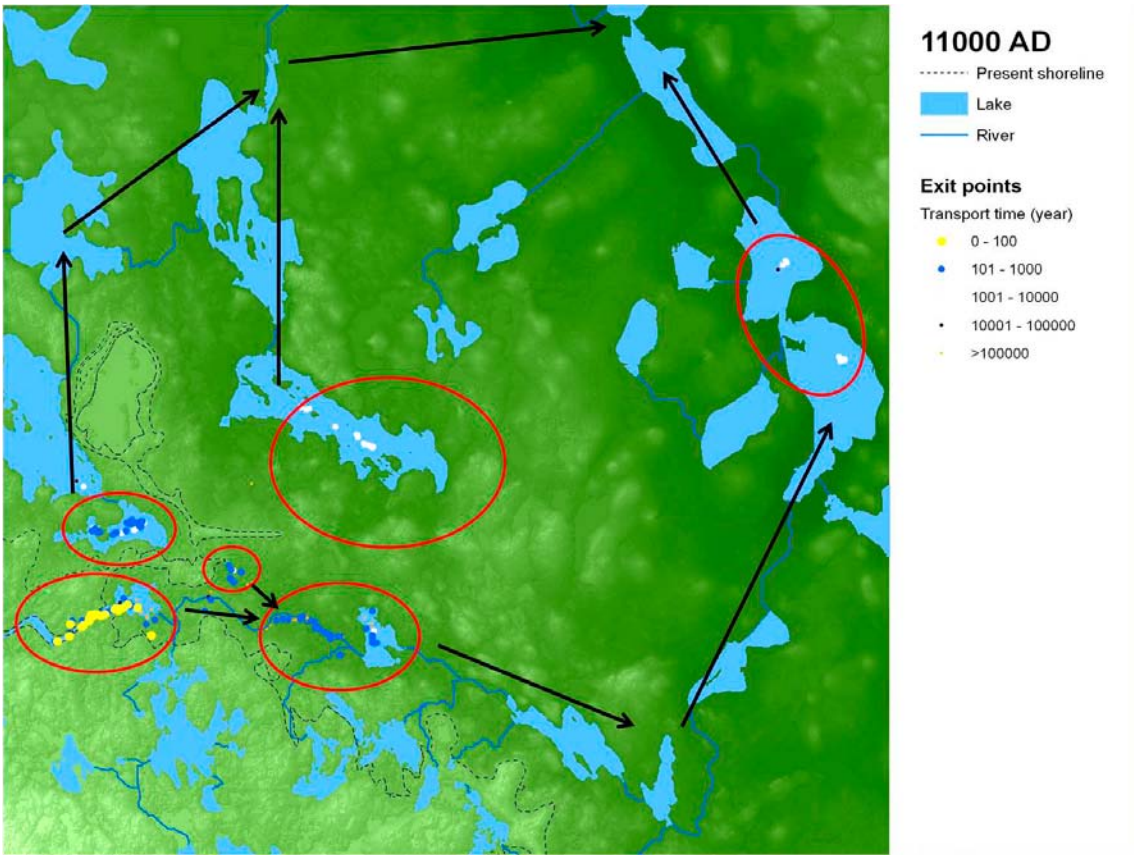

Figure 7-7. *Illustration of the work to identify biosphere objects. The discharge points are displayed on the landscape development model (here shown without sediment dynamics, lake infilling and vegetation type/land use) for a specific time step (11,000 AD). The discharge clusters are encircled in red where the biosphere objects were identified and the black arrows indicate the surface water flow paths. Figure from /Lindborg 2010/.*

Basin

A basin is defined as the catchment for an outlet from a lake all the way to the outlet of next upstream lake. If a basin has two or more major streams (streams discharging lakes treated in the landscape model), the basin is defined as the actual lake catchment minus all upstream lake catchments. The basin area is constant over time and smaller than or equal to the maximum watershed area.

The landscape is divided into basins (Figure 7-8). Each basin holds one single lake (existing or future). The extents of the basins were established by mapping the water divides for the total model area by using digital elevation models and field measurements /Brunberg et al. 2004, Brydsten 2006/. Only basins that are of significance for the radionuclide model are used in the final landscape model. To identify areas of significance, the hydrogeological models were used as described above in this chapter.

Watershed

The watershed is always the largest of the three geometric features used. It is defined as the catchment to an outlet from a lake. The watershed area is used for calculation of discharge ($m^3\ s^{-1}$) with known specific runoff ($m^3\ s^{-1}\ m^{-2}$). The discharge is then used for calculation of the theoretical water turnover time of the lake. It is also used for calculation of the fresh water dilution of the sea water in a basin and also the theoretical residence time of the sea water. In Figure 7-9, the watershed is illustrated for a fictitious lake. All rain that falls within the watershed is drained through the lake

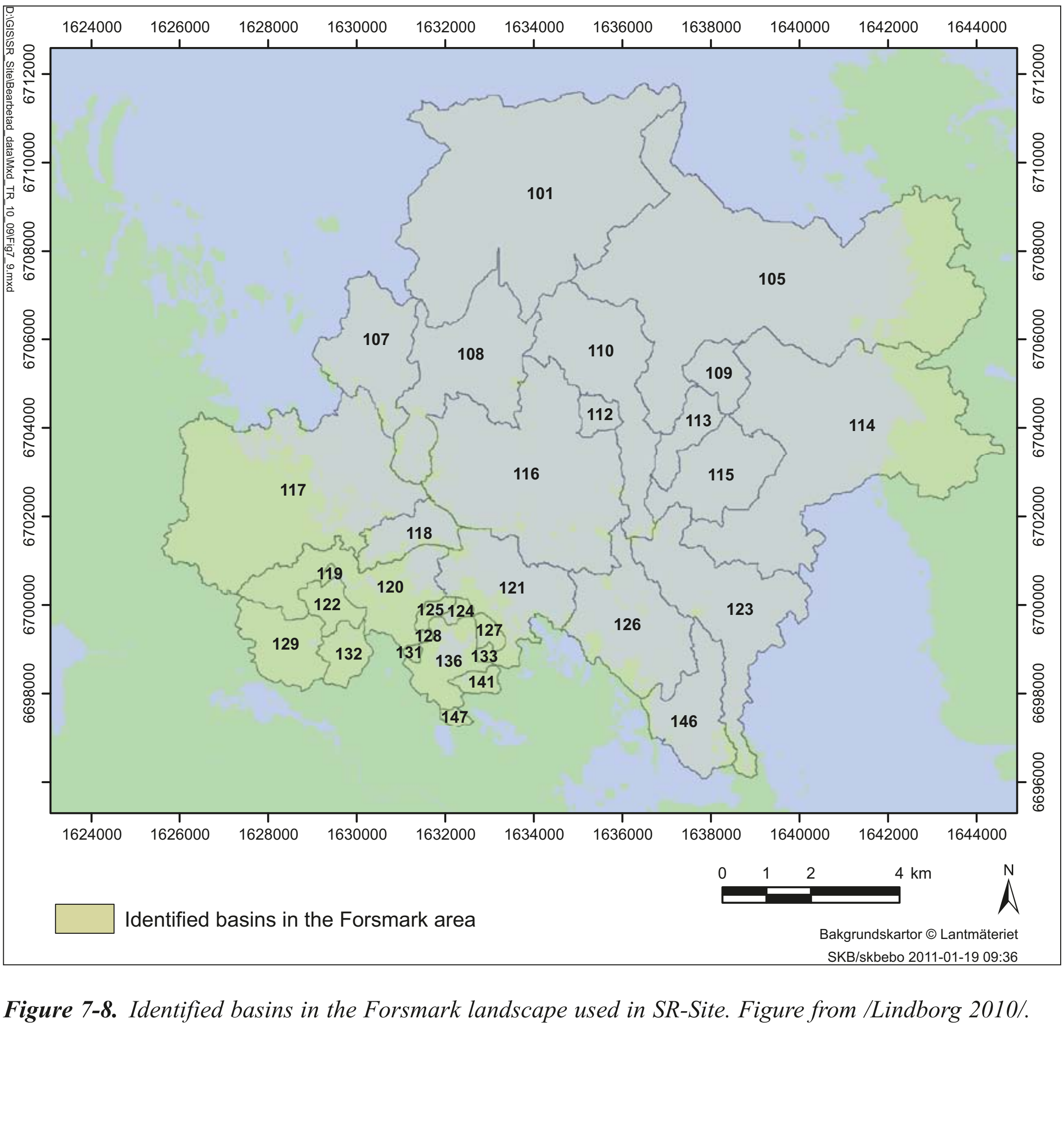

Figure 7-8. Identified basins in the Forsmark landscape used in SR-Site. Figure from /Lindborg 2010/.

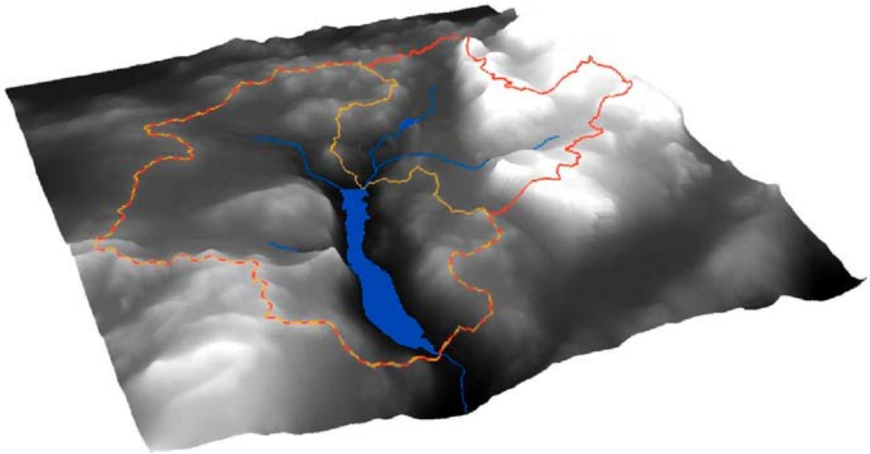

Figure 7-9. Illustration of watershed and sub-catchment for a hypothetical lake. The watershed and the sub-catchment are outlined in red and yellow, respectively. The sub-catchment is defined as the catchment for the lake minus the catchment for the lake inlet (see text for details). Figure from /Lindborg 2010/.

outlet. The watershed area is in Forsmark successively increasing over time due to regression following isostatic rebound during an interglacial. Note that island areas are included in the watershed area and thus the discharge in the stream will not be correctly calculated for time steps with archipelago configuration.

Sub-catchment

The geometric feature sub-catchment is defined as the catchment of the outlet of a lake minus the catchment of the inlet of the same lake. The sub-catchment is used in the radionuclide model for calculation of diffuse discharge of water into the lake, i.e. inflow of water not included in the major stream discharge. The sub-catchment area is a constant and always equal to or smaller than the basin area. The sub-catchment of the hypothetical lake is shown in Figure 7-9. The sub-catchment area is identical to the corresponding basin area for basins situated highest in the river systems. Only small differences in area occur where two linked lakes are in juxtaposed positions.

7.3.3 Temporal development of biosphere objects

The core features of the landscape relief in the Forsmark area are determined mainly by the bedrock topography /Lindborg 2010/. The small-scale undulations of the bedrock surface are smoothed by glacial and post-glacial deposits, which, to a limited extent, are redistributed by wave erosion when the shoreline regresses over the area. Since the bedrock topography is expected to be only marginally affected by weathering, and since the shoreline displacement is expected to be repeated during future glacial cycles, it is argued that the development of the landscape during the present interglacial will give an acceptable representation also of the landscape development during repeated glacial cycles.

Since each biosphere object is associated with the local topography of a sea or lake basin, the physical boundaries of the object reflect the geometry of the bedrock and the overlying till and glacial sediments, which changes marginally during an interglacial. In contrast, the properties of the biosphere objects change continuously, e.g. due to shoreline displacement, wave erosion and sedimentation, lake infilling and ecosystem succession. When the glacial ice sheet has disappeared, all biosphere objects will typically go through a similar succession, from being part of the open sea, over a sea bay phase, to a lake, which eventually will transform into a wetland. The associated work flow for describing the development of a biosphere object is illustrated in Figure 7-10.

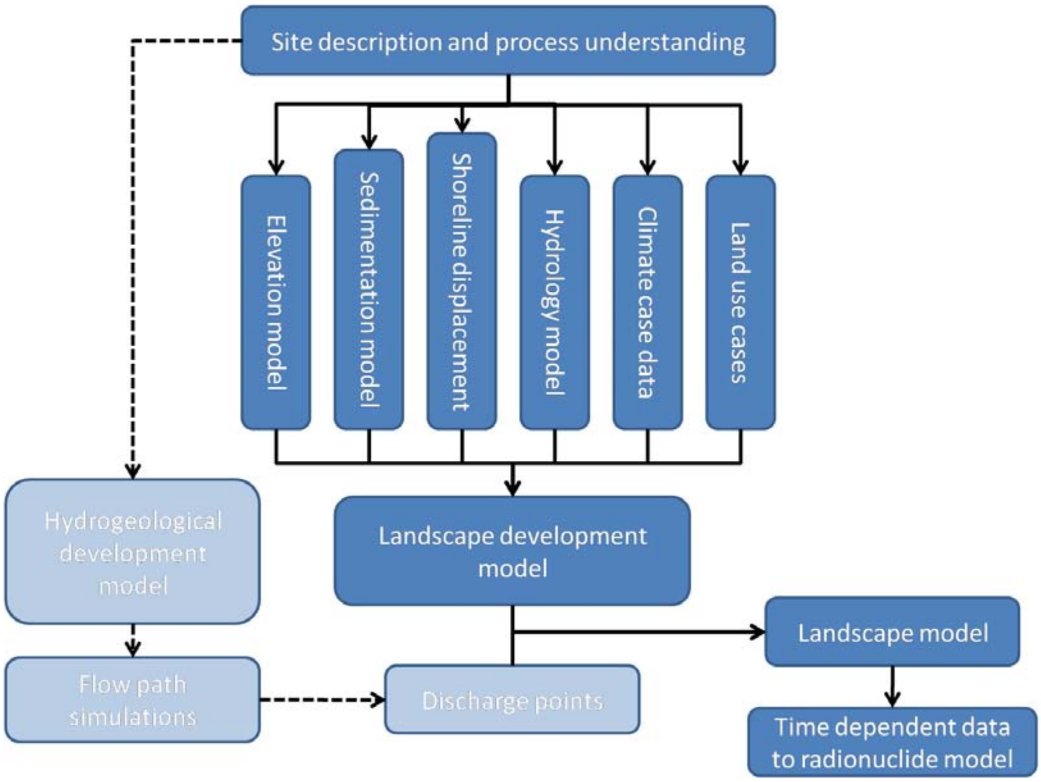

Figure 7-10. *Flow chart of activities and inputs to obtain the biosphere object characteristics. The starting point is the description of present-day and historical conditions of the site. Data from the site description together with process understanding provide the starting point for producing models describing the site development for a number of disciplines. All the combined models are then merged together into a landscape development model. By using the discharge information from the hydrogeological modelling, the biosphere objects are identified. The landscape model is constructed by extracting information from the areas identified as biosphere objects from the landscape development model. Light blue colours indicate activities not performed within the biosphere modelling in SR-Site. Figure from /Lindborg 2010/.*

The temporal development of each object is described by the modelled succession from the landscape development model. Most biosphere objects are predicted to go through a general succession during a temperate interglacial, which is characterized by the following four main stages.

- Sea stage – the biosphere object is a sea basin. As landscape emerges from the sea, it continuously decreases in size. During this period, the object has only an aquatic part and all fluxes from the deep regolith layers are directed to aquatic sediments.
- Transitional stage – the sea bay is isolated and transforms into a lake or a stream (aquatic object) surrounded by wetland (terrestrial), or directly into a wetland. The isolation of a lake in the Forsmark area takes approximately 500 years, and, during this phase, saltwater flooding will occur periodically. During the transitional stage, the values of the aquatic model parameters change continuously from sea to lake characteristics.
- Lake stage – the surrounding wetland expands into the lake, and aquatic sediments are gradually covered by a layer of peat. This process is represented in the radionuclide model by a flux of radionuclides from the aquatic sediments to the terrestrial regolith. The lake stage ends when the lake has been fully transformed into a wetland.
- Terrestrial stage – the biosphere object has reached a mature state and no further natural succession occurs. For the majority of discharge areas, the end stage is a wetland that is drained by a small stream. However, in some small objects located upstream, no stream develops, e.g. object 121_3, and in a few downstream objects a substantial river flows through the object, e.g. object 114.

7.3.4 Biosphere objects in the landscape

Each biosphere object has a defined location in the landscape. The object may change in type of ecosystem or size as described in sections above. This is due to natural succession within objects, or the long-term development of landscape features. Depending on succession stage, the objects that define the landscape model therefore will have a specific set of ecosystems.

At the start of an interglacial, all are objects submerged by approximately 180 metres of water. This landscape is described as a submerged landscape, and all objects interact with their neighbour objects. As the shoreline displacement proceeds, the objects gradually emerge above the sea and become lakes and wetlands. At this stage, the dominating interactions start to go one way, slowly turning into a terrestrial surface flow system where the chain of objects is linked in a one way direction from the most upstream object and down to the final outlet to the Baltic Sea. Figure 7-11 shows the landscape model displayed on the landscape development model at three different times during the modelled time period.

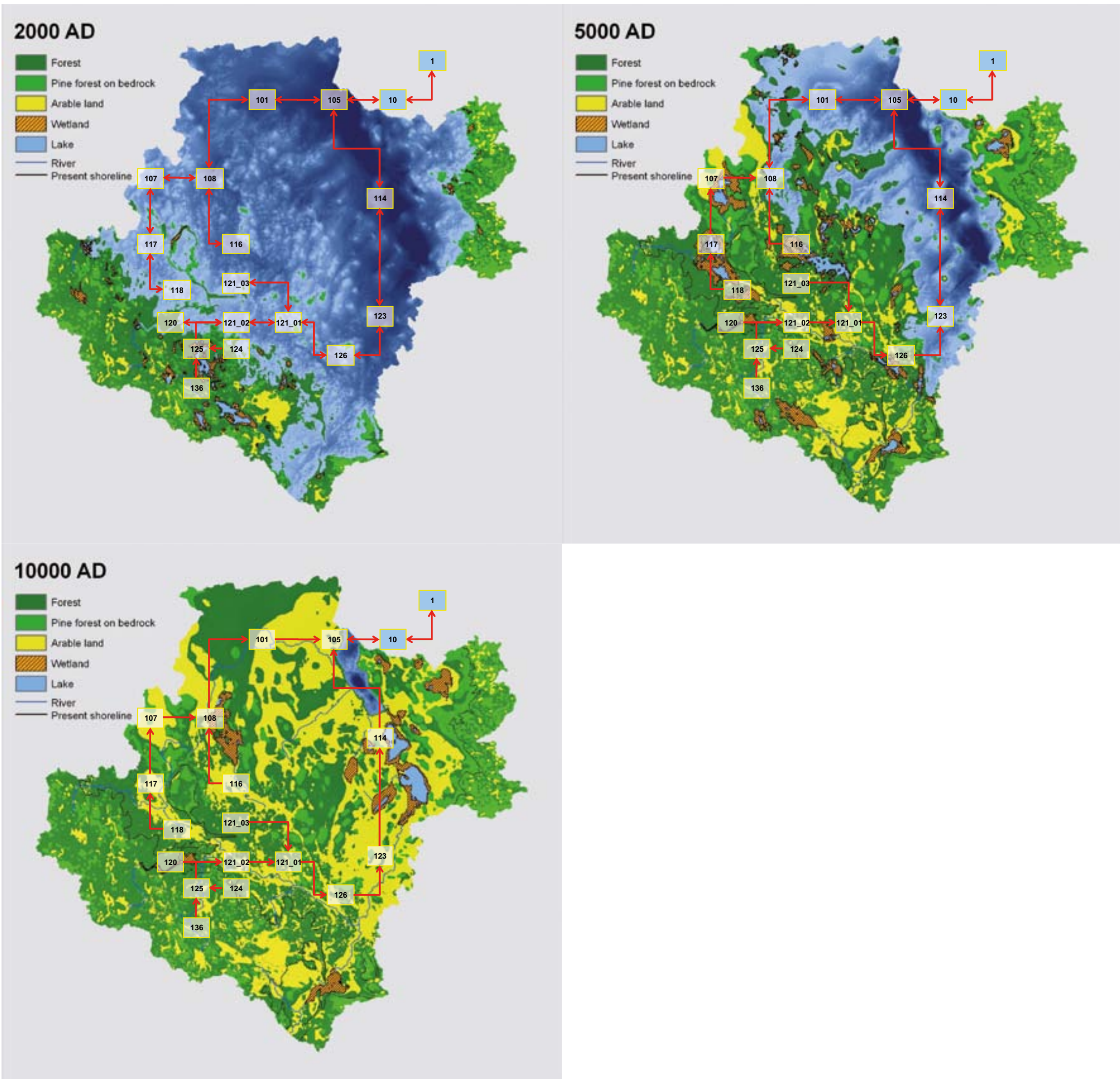

__Figure 7-11.__ The landscape model displayed on the landscape development model at three different time steps (2000, 5000 and 10,000 AD). The boxes shows biosphere objects (with id numbers) at their approximate locations in the landscape and red arrows indicate the surface water flow paths connecting the objects. The blue boxes represent the combined objects of Öregrundsgrepen (object 10), see text, and the model area outlet, the Baltic Sea (object 1).

To represent the total area of the sea covering all submerged basins, a general object is included in the model (object id 10). This object is used to merge all sea objects into one object representing Öregrundsgrepen. Moreover, the landscape constellation of biosphere objects used in the radionuclide model may be changed when performing simulations for different purposes. For example, all objects can be used when analysing transport in the whole surface water network, whereas a simulation calculating concentrations and doses for a single object may be restricted to the object of interest and the affected downstream objects (Chapter 8).

7.3.5 Parameterisation of biosphere objects

The landscape development model is used to parameterise the biosphere objects during landscape development. This model contains all information needed to describe the time-dependent properties for each biosphere object in the landscape over time. By following the succession for each biosphere object on the landscape development model, the data is extracted into tables (Table 7-2). The bedrock topography and the regolith depth has been mapped at the site /Lindborg 2008/. These descriptions have been used to model the landscape development together with the effects of shoreline displacement and lake infilling.

The information from the landscape development model has been integrated and averaged over the object area to describe the development of the biosphere objects in terms of a number of characteristics that change continuously over time. Properties that are used to describe the individual biosphere objects over time include e.g. area and depth of regolith layers, water depth and volume of sea basins and lakes, areas of sea and lake bottoms that can support primary production, sedimentation and resuspension rates, wetland areas and upper regolith depths (soils and sediment).

Table 7-2. The output data from the landscape development model for the biosphere objects (dw stands for dry weight).

Name	Description	Units
Aqu_area_obj	Water area	m^2
area_subcatch	The area of the subcatchment	m^2
area_wshed	Watershed area	m^2
depth_aver	Average water depth	m
depth_max	Maximum water depth	m
growth_rego	Average sedimentation rate calculated for lake and marine bottoms	m/year
res_rate	Resuspension rate	kg dw/(m^2year)
sed_rate	Sedimentation rate	kg dw/(m^2 year)
Ter_area_obj	Organic sediment area in lakes	m^2
threshold_start	The year a threshold starts isolating a bay that will become a lake	year
threshold_stop	The year a threshold has isolated a bay that from that year is a lake	year
threshold_end	Time when ingrowth of wetland stops (in most cases a stream remains)	year
threshold_agriculture	Point in time when wetland is 2 m above sea level	year
Aqu_z_rego_pg	Depth of organic and inorganic postglacial deposits (gyttja, clay gyttja, sand and gravel) under sea, lake or stream	m
Ter_growth_rego	Growth of relative wetland area	m^2/(m^2 year)
Ter_z_regoMid_pg	The depth of the post glacial deposits in the wetland (these are covered by peat)	m
Ter_z_regoUp	The depth of the terrestrial upper regolith layer (peat)	m

7.3.6 The landscape model during the reference glacial cycle

As described in Chapter 6 the landscape will change dramatically during the period of a glacial cycle. This does not necessary mean that the configuration of biosphere objects will alter. We describe how the biosphere objects will undergo a succession from sea stage, via lake/wetland to a terrestrial stage during non-glacial conditions. This is a development that may take between 8,000 and 20,000 years depending on where in the landscape the object is located. The landscape model comprises mainly terrestrial ecosystems when the first period of periglacial domain starts at Forsmark (Figure 7-12). Only one or two objects are still in the lake phase and no objects represent the sea.

The submerged landscape is used to describe the glacial climate domain (Figure 7-12). This is due to the possibility of having a situation where a human population is using the marine landscape for food gathering when the ice edge is close to the site. This situation will only be possible in submerged conditions during ice cap retreat. There is no other relevant landscape configuration under glacial conditions due to absence of inhabitants.

This chapter summarises the methods and results described in /Lindborg 2010/ and provide a few examples of modelling results and supporting analyses. The use of output from the landscape development model and the hydrogeological models to identify discharge areas (biosphere objects) are demonstrated. Further, it is shown how these areas are described in terms of properties and processes needed to model radiological effects of radionuclide releases to man and biota, and how time-dependant changes of biosphere objects are handled. These changes include the whole process from deglaciation, via a temperate climate domain during an interglacial to the periglacial domain, and finally the reappearance of a glacial domain. By applying the described methodology, the landscape data needed to populate the radionuclide model for all biosphere objects are obtained in space and time.

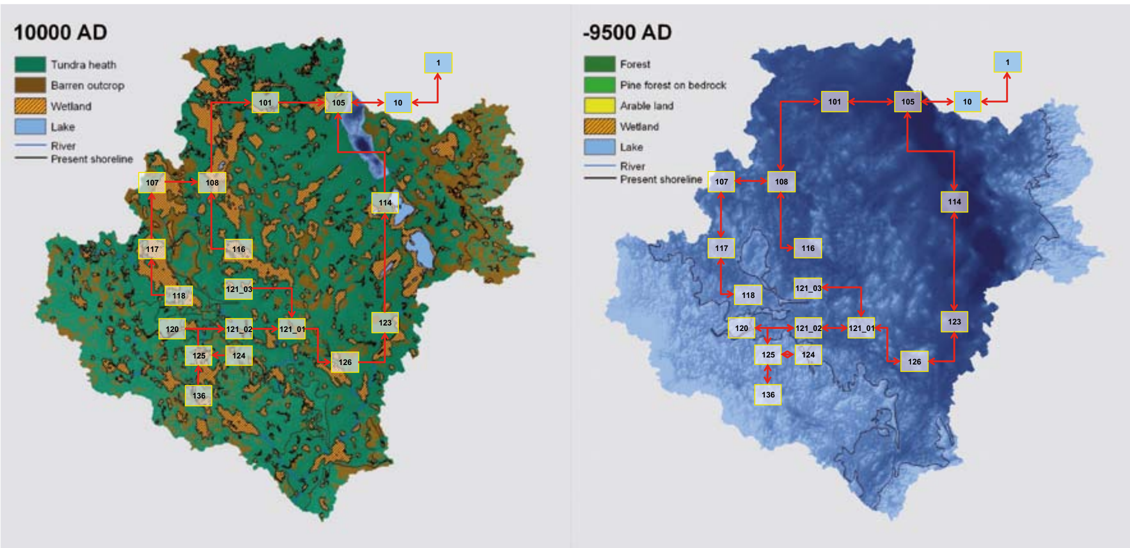

Figure 7-12. *Figure illustrating the landscape model under periglacial and submerged conditions. The boxes show biosphere objects (with id numbers) at their approximate locations in the landscape, and red arrows indicate the surface water flow paths connecting the objects. The blue boxes represent Öregrundsgrepen (object 10) and the model area outlet, the Baltic Sea (object 1).*

8 The radionuclide model for the biosphere

In SR-Site, assessment of doses to humans resulting from releases to the biosphere in different scenarios have been calculated by multiplying release rates, or pulse releases, of different radionuclides with a landscape dose conversion factor (LDF). The LDFs are assessment endpoints for the biosphere analysis and represent the mean annual effective dose to a representative individual from the most exposed group, resulting from a unit constant release rate, or alternatively per unit released in a single pulse to the biosphere, of a specific radionuclide.

In SR-Site the methodology for calculating transport and accumulation in the biosphere has been improved in several ways as compared to previous safety assessments. For example the terrestrial and aquatic ecosystems are combined in one model, and the transition from sea basin to lake and wetland is handled continuously. Plant uptake is included in the mass balance and is modelled as a function of primary production.

This chapter describes the methods used to assess the safety of humans inhabiting potential discharge areas (i.e. to calculate LDFs), and to calculate activity concentrations in environmental media that are used in the assessment of protection of the environment (Chapter 11). The chapter starts by presenting the assumptions made about radionuclide releases from the repository (source terms). It then describes the types of future ecosystems that are considered in the safety assessments and the habits and characteristics of future inhabitants. Next follows sections that describe the conceptual and mathematical model used to simulate transport and accumulation of radionuclides in the biosphere, and the methods used to calculate activity concentrations in environmental media, and to assess human exposure through relevant pathways. The definitions of the LDFs for a continuous release rate and for a pulse release are given, and the procedure to calculate LDFs for different climate conditions is described. The last sections describe the Pandora software used in the calculations and the procedure used to assure quality and traceability from site data to LDF values.

A detailed description of the methods that are presented in this chapter, including the mathematical equations applied in the model, is provided in /Avila et al. 2010/ and /Andersson 2010/.

8.1 Source terms

In the corrosion and the shear load scenarios, radionuclides from the repository are unlikely to reach the biosphere within the first 100,000 years. However after this period contaminated groundwater from the repository may reach the biosphere resulting in a continuous release of radionuclides during more than 1,000,000 years. When a release from the repository reaches the biosphere 100,000 years after closure, the peak release rates for most dose dominating nuclides will remain on a near-constant level for periods of 10,000 years or more (see **SR-Site main report** for details).

In both of the significant release scenarios, radionuclides that reach the biosphere are most likely originating from one single canister. In the corrosion scenario, the failing canister has been deposited in a position with a high groundwater flow rate, which is associated with low geosphere transport resistance. In the shear load scenario, the shearing fracture is assumed to be among the larger in the rock fracture network, and therefore radionuclide retention in the geosphere is pessimistically disregarded in the safety assessment, (see further the **SR-Site main report**). For releases which are associated with low or negligible geosphere transport retention, the shoreline position is expected to have limited effect on the geographical location of the discharge area, and discharge of contaminated groundwater may thus be restricted to one biosphere object /Lindborg 2010/.

For the calculation of LDFs, it has consequently been assumed that the release to the biosphere from the fuel matrix and corroded metals will be approximately constant on the time scale of the biosphere assessment (~20,000 years). It is cautiously assumed that the whole release of radionuclides will reach the discharge area where it will cause maximum exposure (the most exposed group), i.e. the release will not be subdivided over several biosphere objects. Similarly, for the calculations of the modified LDF for pulse releases, it is cautiously assumed that the total instantaneously accessible fraction of radionuclides from fuel dissolution will reach the discharge area where it will cause maximum exposure.

The effect of indirect release to a biosphere object, originating from a contaminated object located upstream, has not been included in LDF calculations. This simplification is appropriate for derivation of LDF values that represent the maximum doses across all biosphere objects in the Forsmark area during the whole simulation period (see Section 12.3.1).

In addition to the radionuclides released into deeper parts of the regolith of a biosphere object, it has been assumed that the released radionuclides also reach a well drilled in the bedrock, as soon as a biosphere object has emerged from the sea.

8.2 Future ecosystems

The radionuclide model for the biosphere simulates transport and accumulation of radionuclides in discharge areas of Forsmark. It is assumed that the landscape development during repeated glacial cycles will follow a path similar to the present glacial cycle. Thus, also after a future deglaciation, discharge areas will go through a succession from being part of the open sea, over a sea bay phase, to a lake, which eventually will transform into a wetland (Section 6.2.7).

Future sea and lake ecosystems are assumed to have similar characteristics as the current aquatic ecosystems in Forsmark. The wetlands that will develop from future lakes are assumed to be similar to the rich fens that are presently found in the area. If drained, these wetlands will provide an organic soil rich in nutrients that will be suitable for cultivation for a limited period of time.

8.3 The most exposed group

In SR-Site, the most exposed group is defined as the group of individuals exposed to the biosphere object with the potentially highest contamination, considering a glacial cycle from a submerged landscape to fully terrestrial conditions. A representative individual from the most exposed group is assumed to spend all time in this object, and get his/her entire supply of food and water from the object.

8.3.1 Production and consumption of food and size of the most exposed group

The production capacity for human food in a biosphere object is directly determined by the size of the object, (i.e. the size of the sea basin or the size of the wetland and the surface water body), and the sustainable yield of natural foods and agricultural products, which in turn may vary with climatic conditions. Assuming that food production is the limiting factor for humans living in a biosphere object, the number of individuals that can be sustained in a biosphere object is thus proportional to the area of the object. However, the size of the population that can be sustained also depends on land use, since the productivity per unit area of crop is two to three orders of magnitude larger than the productivity of natural foods in a wetland.

For SR-Site, it has been assumed that all available food sources from both aquatic and terrestrial parts of a biosphere object are utilised by human inhabitants. Additionally, it is assumed that wetlands will, at least partly, be converted to agricultural land as soon as that is possible (Section 8.3.3). No assumptions are made regarding food preferences of future individuals. Instead, the human diet reflects the production of different types of food in the object.

Thus, the human diet consists of sea food when the biosphere object is submerged by sea water. When the object has been isolated from the sea, the diet consists of natural food from lakes, streams and wetlands. When agriculture is possible, the diet will be a combination of natural food and agricultural produce. The contribution of each food type to the human diet is assumed to be proportional to the production of that food type in the object. When agriculture is possible, it is deemed equally likely that the drained wetland is used for food production such as cereals, root crops, vegetables or fodder for meat and dairy production.

Biosphere objects with a large proportion of wetland that can be drained and cultivated can typically feed a population in the range of 170–1,300 persons. Biosphere objects that cannot be cultivated can only support a limited number of individuals, aorund10 individuals during submerged or coastal conditions and typically one or a few individuals when inhabitants are limited to utilization of lakes and wetlands for food.

8.3.2 Land use on artificially drained wetlands

When the wetland in a biosphere object has emerged to a sufficiently high elevation above sea level to avoid periodic seawater intrusions, it can be drained and used for agricultural purposes. It is assumed that human inhabitants can drain and subsequently use wetlands situated more than 2 metres above the sea level for production of food crops and livestock at any point in time. For the biosphere assessment it is further assumed that a wetland will be converted to agricultural land at the point in time when utilization results in the largest annual dose.

Sustainable use of organic soils that originate from drained wetlands in the Forsmark area is expected to be productive for agriculture only during a limited time. This is because peat subsides when the groundwater is lowered, and the organic layers of the peat and the former lake sediments will typically be oxidised within 50 – 100 years. Regolith underlying surficial organic layers mainly consist of glacial till rich in stones and boulders and is therefore not suitable for cultivation /Lindborg 2010/.

There are areas in Öresundsgrepen that are covered by thick layers of clay and sand. Future shallow wetlands in these areas can probably be drained relatively easily, and the underlying minerogenic deposits can be sustainably cultivated for thousands of years. Thus, the consequences of long-term cultivation have been assessed for areas with deep deposits of glacial and post-glacial clay only (Section 12.2.2).

8.3.3 Water use

The need for drinking water of future human inhabitants living in a biosphere object is assumed to be equally likely to be covered by a well drilled into the rock and by the surface water in the lake or stream passing through the object. Drinking water from a well excavated in till is assumed to have similar composition as contaminated surface water and has not been treated as separate source of drinking water.

Exposure from contaminated drinking water is considered from the point in time when a biosphere object has emerged from the sea. Livestock is assumed to consume water from the same sources as human inhabitants, i.e. consumption of surface water and a water from well drilled through bedrock is considered equally likely.

Exposure from irrigation with contaminated surface water has been considered in the production of vegetables. Surface water for irrigation of agricultural soils will be readily available in all biosphere objects, and irrigation with water from a drilled well has consequently not been included as it is considered unlikely to occur /Löfgren 2010/.

8.4 Modelling transport and accumulation of radionuclides in biosphere objects

The radionuclide model for the biosphere is a compartment model. A graphical representation of the conceptual model is shown in Figure 8-1, where each box corresponds to a model compartment. Definitions of the compartments are presented in Table 8-1. A main assumption in the model is that radionuclides entering a compartment become homogeneously mixed in the compartment within the relevant time scale of the model. The model supports the description of the lower regolith with any number of compartments. In simulations for estimating LDF values only one compartment has been used (Section 10.1). However, the effect of finer discretisation of the lower regolith has been investigated in a separate analysis (Section 12.3.1).

8.4.1 Radionuclide fluxes

The arrows in Figure 8-1 represent radionuclide fluxes between compartments and fluxes into and out of the system. Radionuclide fluxes are linked to the main fluxes of matter in the biosphere, i.e. water fluxes (2 in Figure 8-1), gas fluxes (3) and particle fluxes (4). Radionuclide transfers mediated by biota, like uptake by primary producers, have also been included in the model (6). The arrow reaching the lower regolith compartment (1) represents radionuclide releases from the geosphere into the biosphere object. These releases are directed to the deeper parts of the regolith, which at the site normally consists of glacial till deposited on the bedrock.

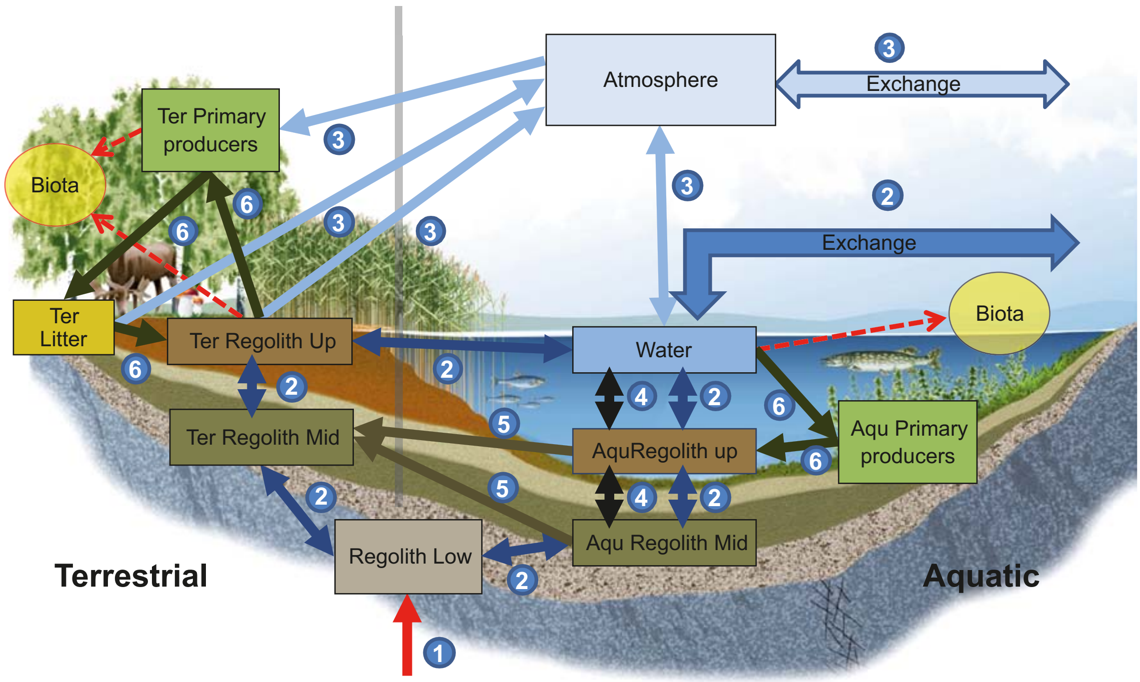

Figure 8-1. *Conceptual illustration of the radionuclide model for the biosphere. Boxes represent compartments, thick arrow fluxes, and dotted arrows concentration computations for biota (not included in the mass balance). The model represents one biosphere object which contains an aquatic (right) and a terrestrial part (left) with a common lower regolith and atmosphere. The source flux (1 Bq/y) is represented by a red arrow (1). The radionuclide transport is mediated by different major processes, indicated with dark blue arrows for water (2), light blue for gas (3), black for sedimentation/resuspension (4), dark brown for terrestrialisation (5), and green for biological uptake/decomposition (6). Import from and export to surrounding objects in the landscape is represented by arrows marked "exchange". A detailed explanation can be found in /Andersson 2010/ and descriptions of the compartments are given in Table 8-1. Figure from /Andersson 2010, Avilia et al. 2010/.*

Table 8-1. Compartments included in the radionuclide model for the biosphere.

Model name	Description
Regolith Low	The lower part of the regolith overlying the bedrock, primarily composed of till. It is common to the terrestrial and aquatic parts of biosphere objects and originates from the glaciation.
Aqu Regolith Mid	The middle part of the regolith in the aquatic part, usually consisting of glacial and postglacial clays, gyttja and finer sediments which mainly originate from the period after the retreat of the glacial ice sheet, or from later resuspended matter mixed with organic sediments.
Aqu Regolith Up	The part of the aquatic regolith with highest biological activity, comprising 5-10 cm of the upper aquatic sediments where resuspension and bioturbation can maintain an oxidizing environment.
Ter Regolith Mid	The middle part of the terrestrial regolith, containing glacial and postglacial fine material, i.e. former sediments from the seabed / lake bottoms.
Ter Regolith Up	The upper part of the terrestrial regolith which has the highest biological activity, primarily composed of wetland peat.
Litter	Dead plant material overlaying the regolith.
Water	The surface water (stream, lake, or sea water).
Aqu Primary Producers	The biotic community in aquatic habitats, comprising both primary producers and consumers.
Ter Primary Producers	Terrestrial primary producers.
Atmosphere	The lower part of the atmosphere where released radionuclides are fully mixed.

Radionuclides released to the lower regolith compartment are distributed to the upper layers of the ecosystems by advection and diffusion. The representation of the waterborne transport of radionuclides between compartments is based on detailed hydrological modelling with MIKE-SHE /Bosson et al. 2010/. These studies have shown that the vertical hydrological fluxes in the deep regolith layer of sea basins and bays are limited. Discharge areas above sea level may, on the other hand, have substantial vertical fluxes with preferential flow paths through areas of higher permeability within a biosphere object, as in wetlands surrounding lakes and streams.

The effect of radionuclide sorption on the advective and diffusive transport of radionuclides is taken into account by assuming equilibrium between the pore water and the solid phase of the compartments. The model also considers the transport of radionuclides absorbed to suspended particles driven by surface water fluxes, sedimentation and resuspension processes.

The radionuclide transport mediated by biota is described in the model through fluxes driven by primary production, in both terrestrial and aquatic ecosystems. It is assumed that equilibrium is established between the concentration of radionuclides in the newly produced biomass and the corresponding environmental media (regolith for terrestrial primary producers and water for aquatic primary producers). This is an improvement from traditional models as plant uptake is a function of growth and the uptake is including in the mass balances /Avila 2006, Andersson 2010/. Losses from the regolith and surface waters via degassing processes are conservatively neglected for all radionuclides, except for C-14. For the terrestrial biota, fixation of carbon from air by primary producers is the main entry point of C-14 into the food chain. Therefore, gas-exchange processes between regolith and the atmosphere, and between surface waters and the atmosphere, have been represented in the model for this radionuclide /Avila et al. 2010/.

8.4.2 The temporal development of biosphere objects

To be able to handle the continuous development of the landscape, the aquatic and terrestrial ecosystem were simulated simultaneously in one model. Consequently, the radionuclide model has two parts, one aquatic (right side in Figure 8-1) and one terrestrial (left side). The temporal development of an object is handled by varying the sizes and properties of these two parts in accordance with the simulated natural development of the specific biosphere object, resulting from shoreline displacement, sedimentation, and lake infilling (see Section 7.3.5 for details on the development of biosphere objects).

Throughout the succession from open sea to a wetland, the model representation of a biosphere object changes as follows. During the sea stage there are no terrestrial compartments, and all fluxes from the deep regolith layers are directed to aquatic sediments. During a transitional stage (~500 years), the sea bay is isolated and transforms into a lake, and a wetland starts to develop. The flux of radionuclides from the deep regolith will gradually shift from aquatic sediments to sediments under the wetland. During this phase, saltwater intrusions will occur with a reduced intensity, and consequently the values of the aquatic model parameters change continuously over the transition, from sea to lake values. After isolation is completed, the surrounding wetland will continue to expand into the lake. Thus, during the lake stage, aquatic sediments are gradually covered by a layer of peat. In the model this processes is represented by a flux of radionuclides from the aquatic sediments to the terrestrial regolith (arrows 5 in Figure 8-1). The natural end state of the biosphere objects is a wetland.

8.4.3 Model represention of arable land

When the wetland in a biosphere object has emerged to a sufficiently high elevation above sea level, it is assumed that human inhabitants can drain and subsequently use wetlands for crop and livestock production /Löfgren 2010/. The organic layers (peat and gyttja) on drained and cultivated wetlands will rapidly become oxidised and compacted (Section 6.1.8), resulting in an agricultural soil which is a mixture of contaminated organic matter and deeper mineral layers (glacial and postglacial deposits), where radionuclides may have accumulated since the early sea stage.

Once the wetlands have been drained, further contamination through groundwater is assumed not to be of quantitative importance. Instead, radionuclides are leached from the soil through runoff. Accordingly, the highest concentrations of radionuclides in agricultural soil are expected in the period directly after drainage, and thus the 50 years immediately following drainage are cautiously used to assess the average exposure during a life time from the use of contaminated agricultural soil.

It is assumed that radionuclides will continuously accumulate in the wetland during the whole simulation period, and for assessing the doses it is further assumed that the wetland will be converted to agricultural soil at the point in time that results in the maximum doses.

8.4.4 Modelling radionuclide flux between biosphere objects

Biosphere objects can receive radionuclide releases to the deep regolith or from contaminated surface water originating from another adjacent biosphere object. The radionuclide model has been implemented for each identified biosphere object and the individual models have been connected with each other according to the flux of surface water in the developing landscape (Figure 7-11).

Thus, the flow of radionuclides between biosphere objects has been modelled as a function of surface water and suspended particle fluxes. In the sea stage, each sea object interacts with the entire Öregrundsgrepen (object 10 in Figure 7-11) via water exchange in both directions. From Öregrundsgrepen radionuclides are then discharged to the rest of the Baltic Sea, which is treated as a sink in the model /Andersson 2010/. In the transition, lake and terrestrial stages, the radionuclide fluxes from a biosphere object (arrows marked with "exchange" that are directed from the object in Figure 8-1) are directed to the connected downstream objects. Hence, all downstream objects will receive inputs from one or several upstream objects.

8.4.5 Model represention of a well drilled through bedrock

In addition to the radionuclides released into deeper parts of the regolith of a biosphere object, a unit release rate has also been applied to a hypothetical well drilled through bedrock. The activity concentration in well water (Bq/m^3) is calculated by dividing the release rate (Bq/y) by the well capacity (m^3/y). The capacity of the well has been selected to represent a drilled well in the central site investigation area /Gentzschein et al. 2007/ where it would have the possibility to receive 100% of the released radionuclides from the repository /Andersson 2010/.

8.4.6 The mathematical representation

The mathematical model for each biosphere object consists of a system of ordinary differential equations (ODEs). Each ODE represents the rate of change for a radionuclide inventory (Bq) in a model compartment, as a function the radionuclide fluxes (Bq/y) into and out from the compartment, and radioactive decay.

The model assumes that the radionuclide fluxes are proportional to the radionuclide inventory in the source compartment (Bq), multiplied by a transfer rate coefficient (1/y). Radionuclide-specific behaviour is taken into account by using element-specific values for some of the model parameters that describe e.g. retention (distribution coefficients or Kd) and biological uptake (concentration ratios or CR).

The radionuclide fluxes have been modelled in the same way for all radionuclides, except for C-14. In the case of C-14, the uptake by biota is modelled using a specific activity approach /Avila and Pröhl 2008/, and gas exchange between the peat and surface water on the one hand and the atmosphere on the other hand has been represented /Andersson 2010/.

The radionuclide model has the same mathematical formulation for all biosphere objects. The differences between biosphere objects have been captured by using object-specific values for parameters describing the geometry of the biosphere objects, the depths of regolith layers, and the rate and timing of transitions between sea, lake and terrestrial stages.

8.5 Estimating activity concentrations

The radionuclide model simulates the radionuclide inventory (Bq) dynamically in ten compartments of the biosphere object (Figure 8-1). From these, the activity concentrations in the upper regolith (peat, agricultural soil, aquatic sediments), in the atmosphere and in the surface water are calculated. Environmental concentrations are used to assess the impact on non-human biota (Chapter 11) and to calculate human exposure (see the following sections).

Environmental activity concentrations in regolith and surface water (Bq/kg dw or Bq/m3) are calculated by dividing the inventory of the compartment with the mass (for regolith) or the volume (water and atmosphere) of the compartment. The activity concentrations in atmospheric air (Bq/m^3), due to dust are calculated by multiplying the activity concentrations in terrestrial regolith (Bq/kg dw) by the dust concentrations (kg dw/m^3) in air /Andersson 2010/.

The initial inventory in agricultural soil (Bq) is calculated by summing the radionuclide inventories in the upper terrestrial regolith compartment and in 25 cm of the middle terrestrial compartment (representing depth of ploughing). The average inventory in the agricultural soil during a period of 50 years is then calculated assuming leaching due to runoff. For vegetables, additional input via contaminated irrigation with surface water is taken into account. The activity concentration (Bq/kg dw) in soil is obtained by dividing the average radionuclide inventory by the soil mass (kg dw), which is the product of agricultural soil density (kg dw/m^3) and ploughing depth (m) /Andersson 2010/.

The activity concentrations in human foods (Bq/kg C) are calculated from concentrations in environmental media (upper regolith and surface water), assuming equilibrium between the concentrations in food and in the corresponding environmental media. For aquatic food (e.g fish, crayfish and mussels), the activity concentrations are calculated by multiplying the activity concentration in water with the concentration ratio (Bq/kg C per Bq/m^3) for each food item, respectively. For terrestrial food, activity concentrations are calculated by multiplying the activity concentration in upper regolith (peat or agricultural soil) with the corresponding concentration ratios (Bq/kg C per Bq/kg dw) /Nordén et al. 2010/.

To determine the activity concentration in meat from game and cattle and in dairy products, the concentrations in the animal diet (wetland vegetation or green fodder) are first calculated by multiplying activity concentrations in upper regolith with the corresponding concentration ratios (Bq/kg C per Bq/kg dw). Activity concentrations in meat and milk are then calculated from the concentrations in animal diet and animal consumption rates, using equilibrium models. Radionuclide intake from contaminated water and ingestion of soil are also included in these calculations /Nordén et al. 2010/.

8.6 Assessment of human exposure

The activity concentrations in environmental media are used to assess human exposure. For these assessments, it is assumed that a representative individual of the most exposed group spends all time in the contaminated biosphere object, and gets his or her full demand of food and water from that biosphere object (Section 8.3).

In the SR-Site biosphere analysis, the average exposure over the lifetime of individuals that will live in the Forsmark area in the far future is assessed. For this assessment, adults were considered to provide a sufficiently good approximation of the average exposure during a lifetime. This is in line with the ICRP recommendations /ICRP 2000, ICRP 2006/.

To estimate annual exposure during the lifetime of an individual, predicted doses have been averaged over a period of 50 years, which is the integration period used by ICRP in the derivation of dose coefficients for adults. Exposures have been calculated following the methods outlined in /Avila and Bergström 2006/, summing the contributions from all relevant pathways. Below is a brief description of the assumptions made in the calculations of human exposure from inhalation, external irradiation, and consumption of contaminated food and water. A detailed description can be found in /Avila et al. 2010/.

8.6.1 Exposures via inhalation and external irradiation

To calculate exposure from inhalation and external irradiation, it was assumed that the human inhabitants are subjected to a constant exposure. Shielding by buildings is assumed to be negligible. Annual doses by inhalation (Sv) are calculated by multiplying the activity concentrations in air (Bq/m^3) with the inhalation rate (m^3/h), the exposure time (h/y) and the dose coefficient for inhalation (Sv/Bq). Annual doses from external irradiation (Sv) are calculated by multiplying volumetric concentrations in peat and agricultural soil (Bq/m^3) by the exposure time (h/y) and the dose coefficient for external exposure (Sv/h per Bq/m^3).

8.6.2 Exposures from consumption of contaminated water

To calculate exposure via ingestion of contaminated water it was assumed that future human inhabitants are equally likely to satisfy their need for drinking water from a well drilled into the rock and from the surface water. Doses via water ingestion (Sv/y) are calculated by multiplying the activity concentration in drinking water (Bq/m^3) by the water ingestion rate (m^3/y) and the dose coefficient for ingestion (Sv/Bq).

8.6.3 Exposure from food consumption

To calculate exposure via ingestion of contaminated food it was assumed that human inhabitants are self-sustaining and utilise all available food sources in proportion to their productivity (Section 8.3). Doses via food ingestion (Sv/y) are calculated by multiplying the activity concentration in food (Bq/kg C) with the food ingestion rate (kg C/y), and the Dose Conversion Coefficient for ingestion (Sv/Bq).

8.7 Landscape dose conversion factors

In SR-Site, doses to humans are assessed by multiplying release rates or instant releases to the biosphere by *landscape dose conversion factors* (LDFs). Two different LDFs were derived: i) LDFs that are applicable to continuous long-term releases at a constant rate, and ii) modified LDFs for pulse releases that are applicable for releases of radionuclides that reach the biosphere as a pulse with a duration of years or hundreds of years. The definition of these LDFs is provided below and details on how they have been derived are given in /Avila et al. 2010/.

8.7.1 LDF and modified LDF for pulse release

Initial simulations demonstrated that LDF values which represent the maximum doses across all biosphere objects did not depend on surface water transfer between objects (Section 13.3.1 and /Avila et al. 2010/). Thus to simplify calculations the LDF and the modified LDF for pulse release were calculated by running the radionuclide model for each biosphere object separately. The LDF for each potentially released radionuclide is defined as the mean annual dose to a representative individual from the most exposed group resulting from a constant unit release rate of this radionuclide. The exposure is averaged over the lifetime of an individual, and the units of the LDFs are Sv/y per Bq/y.

The modified LDF for pulse releases for each potentially released radionuclide is defined as the mean annual dose to a representative individual from the most exposed group, resulting from a unit pulse release of this radionuclide. The exposure is averaged over the lifetime of an individual, and the units of the modified LDF for a pulse are Sv/y per Bq.

8.7.2 LDF values for different climatic conditions

LDF values were calculated for three different periods of the reference glacial cycle; a period of submerged conditions following the deglaciation, the whole interglacial period, and a prolonged period of periglacial conditions /Avila et al. 2010/. Additionally, LDFs were calculated for the global warming climate case. The modified LDF values for a pulse release were calculated for the interglacial period only.

The calculation period starts at the time for the deglaciation around 9000 BC, when the landscape experiences submerged conditions. The length of the submerged period differs between biosphere objects since it takes about 12,000 years from the emergence of the first biosphere object until the last marine embayment is turned into a lake (Section 6.2.5). During submerge conditions consumption of contaminated sea-food is the only considered exposure pathway.

The initial period of temperate climate domain, i.e. the period from deglaciation to the onset of periglacial domain (Section 6.2.1), is represented by climate conditions similar to those of today and is, in accordance with the reference glacial cycle, assumed to prevail for 18,400 years (i.e. from –9000 to 9400 AD). As land has emerged sufficiently from the sea, wetlands are assumed to be converted to arable land. Drinking water for humans and livestock during the terrestrial stage of this period is supplied in equal parts from surface water and from a contaminated well drilled into the bedrock (Section 8.3.4).

The initial period of temperate climate conditions is followed by a period of periglacial conditions in the reference glacial cycle. For the LDF calculation, periglacial conditions are assumed to prevail until the onset of the next glaciation around 60,000 AD. During this period, it is assumed that agriculture is not possible, and drinking water from a contaminated deep drilled well is not accessible /Avila et al. 2010/.

Permafrost will prevent discharge of deep groundwater to most lakes and wetlands in the area during periods of a periglacial domain, and an expected decrease in runoff will reduce surface water fluxes in lakes where discharge occurs /Bosson et al. 2010/. This will result in lower or no radionuclide releases to most biosphere objects. Permafrost conditions will also result in changes in the terrestrial vegetation community and in primary production. The effects of permafrost conditions on LDF values were studied by alternative simulations, which are described in /Avila et al. 2010/ and further discussed in Section 9.3.1.

Releases to the biosphere under glacial conditions, when the site is covered by an ice sheet, are unlikely to give exposure to humans. Humans might be exposed to radionuclides through ingestion of sea food when the ice margin is situated close to the repository. As a cautious estimate of the exposure from releases during glacial conditions, the LDFs from the time when isolation of the sea basin starts are used in the assessment.

In the SR-Site global warming climate case, it is assumed that the temperate climate domain is extended with approximately 50,000 years as compared with the reference glacial cycle (i.e. the temperate climate domain prevails until 60,000 AD (Section 5.1 in **Climate report**). Human utilisation of natural resources under this extended period of non-glacial conditions is assumed to be similar to that of the inter-glacial period, i.e. wetlands are converted to arable land when possible, and drinking water for humans and livestock is supplied by surface water and water from a contaminated well drilled through bedrock.

8.8 Software implementation

The radionuclide model was implemented in the software package Pandora /Åstrand et al. 2005, Ekström 2011/. Pandora is an extension of the codes Matlab and Simulink /http://www.mathworks.com/. The tool is described in detail in /Ekström 2011/. Below is a brief description of the development, functionality and features of the Pandora tool.

Pandora was developed by Facilia AB togheter with SKB for the specific needs of the biosphere modelling, and it has been used by SKB and Posiva OY for their safety assessments of high level waste repositories. Pandora supports solution of systems of ODEs using numerical methods that are appropriate for solving stiff and non-stiff problems, and has all required functionalities for such biosphere assessments, including handling of large sets of parameters, handling of time-evolving parameters, representation of discrete transitions between states, handling of large numbers of radionuclides and decay chains, and performance of probabilistic simulations.

Pandora also simplifies the development of compartment models consisting of large systems of ordinary differential equations and the handling of radionuclide decay chains. The tool comprises a library of Simulink blocks that facilitates the creation of compartment models, a Manager that aids the model building, and a standalone assessment tool called Pandas.

Pandora extends the Simulink graphical user interface to allow the user to easily inspect and modify the conceptual and mathematical models implemented. Since Pandora is integrated with the assessment tool Pandas, it facilitates performance of sensitivity and uncertainty analyses of the implemented models.

Pandora has been benchmarked, tested and compared with other similar tools /Åstrand et al. 2005/ and /Ekström 2011/. The solutions with the predecessor of Pandora (Tensit) were compared with analytical results, as well as with numerical results obtained with other simulation tools /Jones et al. 2004, Jones et al. 2005/. These comparisons have shown that Pandora provides reliable solutions.

8.9 Quality assurance

Controlled handling of data and workflow is crucial to guarantee the quality of data and model results. Consequently, SR-Site Biosphere follows the quality assurance plan that has been developed for the SR-Site project (see Section 2.9 in **SR-Site Main Report**). In addition, tools and routines to maintain a high quality in the daily workflow were developed within the biosphere project. These routines include the use of version and tracking systems, controlled handling and delivery of data, and reasonability assessment of model results.

8.9.1 Version handling and tracking systems

To secure full traceability in the daily work, with data, modelling, and production of reports, and in the handling of issues in the project, a sophisticated version handling system was integrated (*SubVersion*, /http://svnbook.red-bean.com/) with an errand tracking system (*Trac*, /http://trac.edgewall.org/) in SR-Site Biosphere project.

Thus storage and updates of parameters, models, results, and reports were handled with *SubVersion*, keeping a full record from data sources (e.g. SDM data, scientific results, new calculations, and GIS manipulations) to delivery in SKB doc (e.g. final report text) or the GIS database (GIS projects). *SubVersion* was also used as a secure backup system, keeping a complete track of the time and user responsible for updating a file. Moreover, with this system the calculation environment that produced a specific result can always be reconstructed, disregarding later changes in codes or input data.

Trac is an issue tracking system, which was used to track delivery and control of data and simulation results, and to file related issues. The system was also used to document issues from reviews of earlier safety assessments (SR-Can, SAR08) and how they were handled in SR-Site.

8.9.2 Handling of primary and generic data

All primary data collected in the field are stored in the SKB databases Sicada and SKB-GIS. The delivery of data to the databases are specified in the SKB QA document SDK-508 and involves several steps with review of data to ensure quality and to eliminate mistakes introduced by data transfer. In SR-Site, approved (signed) tables from the Sicada and SKB GIS databases were the only sources for primary data collected at the site. All orders and data deliveries were registered, and followed SKBs quality assurance system.

The quality of information from sources other than the previous SKB site investigation phase was also assessed. The generic data were treated in standard scientific manner and traceability secured by references to the literature from where the information was gathered. In the large literature datasets collected from the database EMRAS, a quality check was performed to guarantee that data were correctly transferred to the parameter files used in the radionuclide model /Nordén et al. 2010/.

8.9.3 Handling of parameters to the radionuclide model

To allow simulations with a minimum of interference with the source data, correct and consistent parameter files were delivered to a pre-specified location in SubVersion. The format and content of the parameter-files were assessed by the deliverer, an independent reviewer and by the modeler. A ticket in the tracking system Trac accompanied the delivery of each file, and modifications made to the parameter files were documented on the ticket and in the logbook in Subversion.

In short, format according to existing specifications, and completeness and correctness of data, were checked by the deliverer. A reviewer panel checked the reasonablility of data with respect to the magnitude of values, parameter correlations and parameter time dependencies. Finally, the modeller confirmed that the file contained sufficient data for successful simulations.When mistakes or inconsistencies were detectected, the file was reassigned to the deliverer and the original file was updated and the procedure started over again.

8.9.4 Handling of results

To verify results from the Pandora simulations, the radionuclide model was also implemented in Ecolego. The simulation results obtained with the two packages were practically identical /Avila et al. 2010/.

The reasonability of model results with respect to transport and accumulation of radionuclides was assessed by subject-matter experts. For example, the changes of radionuclide inventories and concentrations over time were evaluated in relation to parameters describing the development of the landscape (e.g. geometric and regolith parameters), stage transitions (sea to lake transition) and the development of aquatic and terrestrial ecosystems (e.g. biomass, production and decomposition). The consistency in behaviour of nuclides and elements with similar properties were also assessed.

9 Data for assessment

SR-Site has a unique position to include site data in the biosphere assessment. Site data describes both important ecological and hydrological processes as well providing concentrations of elements in site specific organisms, regolith and waters, together with a high resolution DEM and a detailed stratigraphy of the regolith /SKB 2008/. This dataset is probably the most detailed collection of synchronised surface data ever produced in Sweden. Moreover, site investigations of the two candidate sites Forsmark and Laxemar-Simpevarp were coordinated, which gives valuable possibilities to validate data and build confidence. The radionuclide model for the biosphere has, as far as possible, utilised the site specific data both for describing parameters and populating parameter values.

The radionuclide model for the biosphere presented in Chapter 8 relies on nearly 140 input parameters, of which one third represent radionuclide- or element-specific properties. For each parameter, a best estimate was derived from site and/or literature data, and the parameter uncertainty was described by a probability density function (PDF). The best estimate was used for deterministic calculations of human exposure (Chapter 10) and to assess potential radiological impacts on the environment (Chapter 11).

To identify model parameters with a large influence on exposure estimates, and to assess the precision of these estimates, probabilistic simulations with the radionuclide model were also performed. For these calculations, parameter values were randomly varied according to their PDFs. In order to summarise the number and types of parameters that are used to model transport and accumulation of radionuclides in the biosphere and the potential exposure to organisms, the parameters have been divided into a number of categories (Table 9-1).

The parameters used in the radionuclide model reflect important processes relating to transport, accumulation and exposure to radionuclides at the site over time, thus including the effects of site development. This chapter starts with a description of the principles and methods used to select parameter values that represent the site and to determine PDFs that represent the natural variation and the uncertainties associated with the selected parameter values (Section 9.1). The bulk of the chapter is devoted to describing the parameters in the context of the categories (Section 9.2), and in the last section (Section 9.3) parameterisations for different climatic conditions are discussed.

9.1 Methods for selecting parameter values and probability density functions

The extensive site investigations performed by SKB at Forsmark have resulted in a detailed description of the site and its development (Chapters 5 and 6). Data from this description have been the primary source for parameter values of the radionuclide model. Below is a brief description of the principles used to derive typical values of input parameters, and to describe the natural variation and measurement uncertainties in model parameter values. When the available site data were insufficient for reliable parameter estimation, site data were combined with data from the open literature. The procedures used to combine site and literature data when calculating concentration ratios is described in a separate section (Section 9.1.2).

9.1.1 Principles and uncertainties in parameterisation

For each parameter describing a property or process in biosphere objects, a best estimate has been derived from site and/or literature data, and the parameter variation has been described by a probability density function (PDF). Objects develop in time, but for the purpose of the assessment the properties within an object are assessed to be homogenous and to represent a yearly average. Thus, the parameter values that are used in the simulations of transport, accumulation and exposure, should give representative descriptions (typical) of compartments or flows between compartments within a biosphere object, disregarding spatial variation *within* the compartments, and *temporal* variations within a year. This means that when the distributions of parameters values are given (e.g. standard deviation, max, min),

Table 9-1. Parameters used in the radionuclide model. [a] each parameter estimated for 48 radionuclides, [b] each parameter estimated for 31 stable elements, [c] time-dependent parameters for which a separate parameter value is given for each time step and object (8 landscape geometry parameters, 4 regolith parameters, 8 aquatic ecosystem parameters and 1 surface hydrology and water exchange parameter). Total number of parameters listed in parenthesis. The references are given in the footnote below the table.

Type of parameter	N	Section	Example	Source	Reference
Nuclide specific[a]	1	9.2.1	Radionuclide half life	Literature	TR-10-07
Landscape geometries[c]	13	9.2.2	Size of biosphere objects and catchment areas, sedimentation and resuspension rates	Site investigation, site modelling	TR-10-05
Regolith properties[c]	27	9.2.3	Depth, density and porosity of sediments and soil	Site investigation, site modelling	TR-10-01, TR-10-02, TR-10-03, TR-10-05
Aquatic ecosystem properties[c]	17	9.2.4	Biomass, productivity, gas exchange	Site investigation, site modelling	TR-10-02, TR-10-03
Terrestrial ecosytem properties	34	9.2.4	Biomass, productivity, gas exchange	Site investigation, site modelling	TR-10-01,TR-10-07
Surface hydrology and water exchange[c]	9	9.2.5	Runoff, vertical and horizontal advective fluxes, marine water exchange	Site investigation, site modelling	TR-10-01, TR-10-02, TR-10-03
Distribution coefficients and diffusivity[b]	10	9.2.6	Element-specific solid/liquid distribution coefficients (Kd) for regolith and particulate matter	Site investigation, literature	TR-10-07
Concentration ratios, retention and release[b]	19	9.2.7	Element-specific ratios between environmental media and organisms (CR)	Site investigation, literature	TR-10-07
Human characteristics	5	9.2.8	Life span, energy and water consumption	Literature	TR-10-07
Dose coefficients[a]	4	9.2.8	Radionuclide-specific factors for radiation exposure through external exposure, inhalation and ingestion	Literature	TR-10-07

References:
TR-10-01: /Löfgren 2010/
TR-10-02: /Andersson 2010/
TR-10-03: /Aquilonius 2010/
TR-10-05: /Lindborg 2010/
TR-10-07: /Nordén et al. 2010/

these should reflect the random variation of the typical value between years, or, if such data are not available, the random variation between compartments in similar landscape objects within the study area. Only the natural variation existing within a climate domain is used to characterize the probability distribution of a parameter.

The term "parameter uncertainty" is used in the context of assessing the precision of estimated LDFs. The parameter uncertainty refers to the sum of natural variation, comprising variation due to real and identifiable heterogeneity in nature and measurement uncertainties (i.e. errors in measurement or limitations in the assessment).

Each parameter has been described by a best estimate and a probability density function (PDF), which includes both natural variation and measurement uncertainties. The shape of the PDF for each parameter was judged to be either log-normal or normal. For a lognormal distribution, the geometric mean and standard deviation were used to describe the best estimate and the variation around the mean whereas the arithmetic mean and standard deviation were used for parameters with a normal distribution. For each parameter, maximum and minimum values were also identified to set limits on the possible range of the parameter value. The possible range includes expected natural variation that is not observed at the site presently, but may historically have existed at the site or is expected in the future under similar climate conditions (e.g. presence/characteristics of species/communities that are likely to develop on the site, but are not presently observed).

When data were insufficient to estimate a parameter distribution (e.g. for properties of future site conditions estimated from literature data) the parameter was represented with a uniform distribution. For most of these parameters, the best estimate corresponded to the arithmetic mean of the min and max values.

9.1.2 Estimating concentration ratios from site and literature data

In the radionuclide model, distribution coefficients (Kd) and concentration ratios (CR) are used to describe radionuclide retention and biological uptake. In previous safety assessment /**SR-Can main report**/ literature data were used to derive the parameter values. In the SR-Site safety assessment, sufficient site-specific data for calculations of many distribution coefficients and concentration ratios were available in varying degrees for most elements of interest. The method to derive element ratios varied with the availability of site and literature data.

When site-specific data were available, but representative literature data could not be found, best estimates and PDFs were derived from the site data only, assuming a log-normal distribution. When both site-specific and literature data were available, Bayesian inference methods were used to derive best-estimate values and PDFs by combining the site and literature data /Nordén et al. 2010/. Literature data were primarily retrieved through the EMRAS and ERICA databases /IAEA 2010, Beresford et al. 2007/. Where data were missing in these databases, parameter values compiled for previous SKB safety assessments were used /Karlsson and Bergström 2002/.

For a few elements, appropriate data were not available from the site or from the open literature. In these cases, data for other biota types or analogue elements were used to derive best estimates and PDFs for model parameters. Concentration ratios for herbivores were derived from a kinetic-allometric model /Nordén et al. 2010/. A detailed description of the methods used to derive best estimates and PDFs for element ratios is presented in /Nordén et al. 2010/.

9.2 Description of model parameters

Parameters used in the radionuclide model have been divided into 10 categories that are described below. In addition, all parameters are listed in Appendix 2 where there are references to reports in which the parameter calculations are described and in which files they have been delivered to the radionuclide modelling.

9.2.1 Nuclide specific parameters

This parameter category contains parameters connected to radioactive decay. Forty radionuclides were considered in the biosphere assessment of SR-Site. The half-life, dominant radiation type from decay and the decay chains considered in the assessment are presented below (Table 9-2). The data were taken from (Firestone and Ekström 1999. www table of radioactive isotopes, version 2.1 [Online]. Available at http://ie.lbl.gov/toi/).

9.2.2 Landscape geometries

The continuous temporal development of the landscape results in time-specific volumes and areas of objects and surrounding catchments, and determines the type of ecosystem at different time steps in the model (i.e. terrestrial or aquatic). The geometric parameters describe geometric extensions (i.e. areas and depths) and sediment parameters as well as transition times for different ecosystem stages, e.g. the time of transition between marine and limnic stages.

Table 9-2. Radionuclides considered in SR-Site safety assessment. Half-life and the decay chains considered in the safety assessment are listed.

Nuclide	Half-life (y)	Decay chain	Nuclide	Half-life (y)	Decay chain
Ac-227	$2.18 \cdot 10$		Pa-231	$3.28 \cdot 10^{4}$	
Ag-108m	$4.18 \cdot 10^{2}$		Pb-210	$2.23 \cdot 10^{4}$	
Am-241	$4.32 \cdot 10^{2}$				
Am-242m	$1.41 \cdot 10^{2}$		Pd-107	$6.50 \cdot 10^{6}$	
			Po-210	$4.00 \cdot 10^{-1}$	Pb-210–>Po-210
Am-243	$7.37 \cdot 10^{3}$	Am-243–>Pu-239–>U-235–>Pa-231	Pu-238	$1.90 \cdot 10^{-17}$	
C-14	$5.73 \cdot 10^{3}$		Pu-239	$2.41 \cdot 10^{4}$	
Ca-41	$1.03 \cdot 10^{5}$		Pu-240	$6.56 \cdot 10^{3}$	
Cd-113m	$1.41 \cdot 10$		Pu-242	$3.73 \cdot 10^{5}$	
Cl-36	$3.01 \cdot 10^{5}$		Ra-226	$1.60 \cdot 10^{3}$	Ra-226–>Pb-210–>Po-210
Cm-244	$1.81 \cdot 10$		Se-79	$1.13 \cdot 10^{6}$	
Cm-245	$8.50 \cdot 10^{3}$		Sm-151	$9.00 \cdot 10$	
Cm-246	$4.73 \cdot 10^{3}$		Sn-121m	$5.50 \cdot 10$	
Cs-135	$2.30 \cdot 10^{6}$		Sn-126	$1.00 \cdot 10^{5}$	
Cs-137	$3.01 \cdot 10$		Sr-90	$2.88 \cdot 10$	
Eu-152	$1.35 \cdot 10$		Tc-99	$2.11 \cdot 10^{5}$	
H-3	$1.23 \cdot 10$		Th-229	$7.34 \cdot 10^{3}$	
Ho-166m	$1.20 \cdot 10^{3}$		Th-230	$7.54 \cdot 10^{4}$	Th-230–>Ra-226–>Pb-210–>Po-210
I-129	$1.57 \cdot 10^{7}$		Th-232	$1.41 \cdot 10^{10}$	
Mo-93	$4.00 \cdot 10^{3}$		U-233	$1.59 \cdot 10^{5}$	U-233->Th-229
Nb-93m	$1.61 \cdot 10$		U-234	$2.46 \cdot 10^{5}$	U-234–>Th-230–>Ra-226–>Pb-210–>Po-210
Nb-94	$2.03 \cdot 10^{4}$		U-235	$7.04 \cdot 10^{8}$	U-235–>Pa-231
Ni-59	$7.60 \cdot 10^{4}$		U-236	$2.34 \cdot 10^{7}$	
Ni-63	$1.00 \cdot 10^{2}$		U-238	$4.47 \cdot 10^{9}$	U-238–>U-234–>Th-230–>Ra-226–>Pb-210–>Po-210
Np-237	$2.14 \cdot 10^{6}$		Zr-93	$1.53 \cdot 10^{6}$	

Geometric extensions

The geometric extensions of the biosphere objects were calculated in a *coupled regolith-lake development model* (RLDM) for Forsmark /Brydsten and Strömgren 2010/. The outputs from the model were areas of the biosphere objects (Aqu_area_obj and Ter_area_obj), average and maximum depths of the aquatic object (depth_aver and depth_max) and areas of watersheds and sub-catchments (area_wshed and area_subcatch). These parameters changes over time due to shoreline displacement and ecosystem succession (Chapter 6).

The outer boundary for each biosphere object during submerged conditions was determined from the bathymetry of the sea basin, whereas the shoreline of the lake at the time of isolation from the sea delineates the biosphere object during the lake and terrestrial stages. For the majority of the objects, the wetland in the terrestrial stage is drained by a small stream. The morphometry of the stream flowing through the wetland is calculated based on stream length and stream width/depth/cross-section geometry /Lindborg 2010/.

Sediment parameters

Parameters representing sedimentation processes in aquatic ecosystems were calculated by the RLDM. Sedimentation (sed_rate) represents the amount of particulate matter that is deposited on lake and sea bottoms in a year. Some of this material will accumulate permanently (growth_rego) and some will be resuspended and return to the water column (res_rate). In streams, resuspension is set to the same value as modelled sedimentation, and accumulated material is set to zero, i.e. all sedimented material is assumed to be transported further downstream /Andersson 2010/.

Transition times

Due to shore line displacement, sea bays are isolated and transformed into lakes or streams surrounded by wetlands, or directly into a wetland. The isolation of a lake from a sea bay in the Forsmark area takes approximately 500 years /Lindborg 2010/, and during the transitional stage the values of the aquatic model parameters change linear in time from sea to lake values. The isolation starts (threshold_start) when the basin is isolated from the adjacent marine areas for at least part of the year and isolation ends (threshold_stop) when there are no saltwater intrusions to the lake basin even at high sea water levels.

As soon as a lake is formed, it starts to get infilled and is gradually transformed into a wetland. The time (threshold_end) when the entire lake is infilled (in most cases a stream remains) was modelled for each object. In the radionuclide model, it is assumed that when a mire object is located 2 m above sea level, it can be drained and used for agriculture /Lindborg 2010/.

9.2.3 Regolith

The regolith parameters describe properties of different generalized geological units found in the biosphere objects. The regolith in each biosphere object is described according to the conceptual model of the spatial distribution of regolith at Forsmark (Figure 9-1) based on the surface map of regolith, the regolith depth model (RDM) /Hedenström et al. 2008/, the soil type map /Lundin et al. 2004/ and the RLDM /Brydsten and Strömgren 2010/.

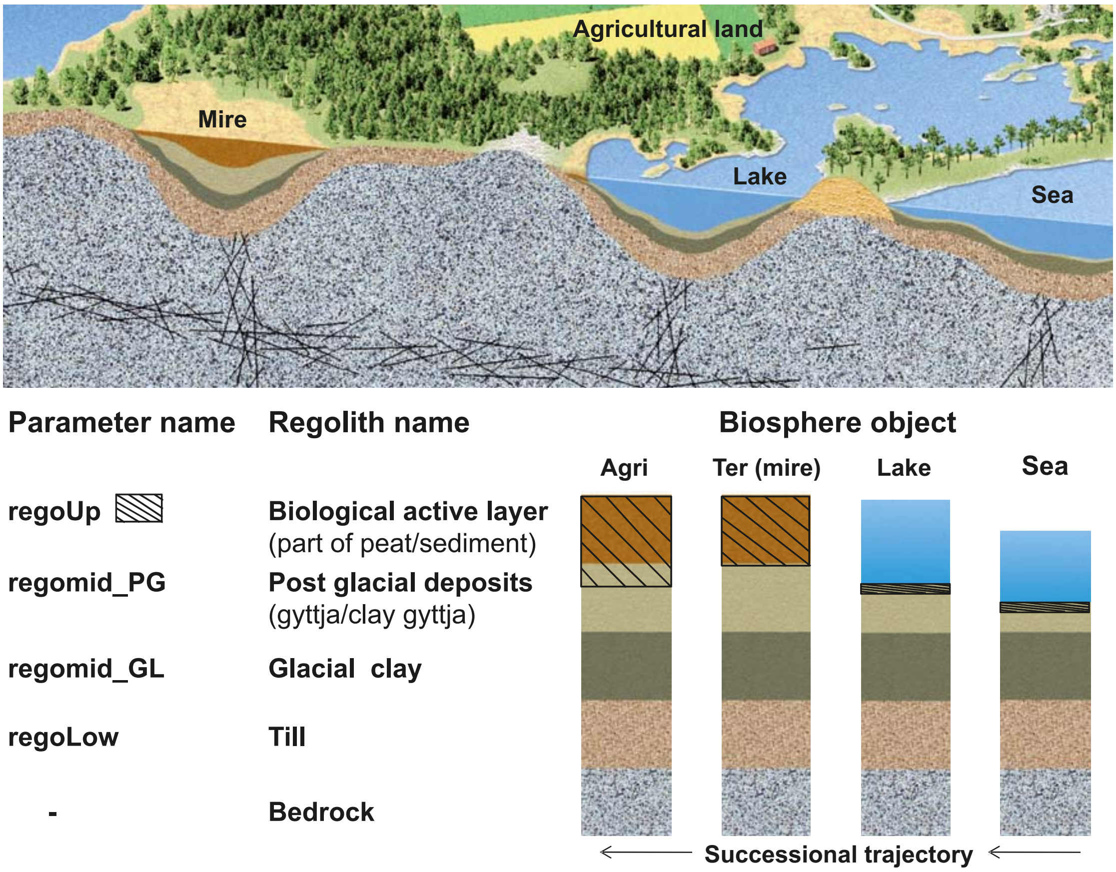

Figure 9-1. Conceptual model of generalized distribution of regolith for different types of biosphere objects at Forsmark. The different depths of the various regolith layers in profiles are also seen in the landscape pictures, which represent a generalized succession trajectory from sea to wetland that is later converted to agricultural land by draining. In the radionuclide model, the postglacial and glacial clay deposits are combined in regard to the radionuclide inventory.

The regolith is divided into four layers: regoUp, regoMid_PG, regoMid_GL and regoLow. In the radionuclide model, RegoMid_PG (i.e. gyttja and clay gyttja) and regoMid_Gl (glacial clay) are combined into one layer, regoMid (Figure 9-1).

Depths of the regolith layers

The upper regolith is defined as the bioactive layer and the thickness of this layer differs between ecosystem types. In aquatic ecosystems, the upper regolith is defined as the oxygenated upper sediments where bioturbation occurs. The marine parameter value (Sea_z_regoUp) is taken from literature and is a mean for the Baltic Sea /Aquilonius 2010/ whereas the limnic parameter value is calculated from site measurements in Forsmark /Andersson 2010/.The upper regolith in wetlands (Ter_z_regoUp) represents the peat layer and the peat ingrowth is modelled using the RLDM /Brydsten and Strömgren 2010/ (Chapter 6). In agricultural land, the bioactive layer represents the thickness of the cultivated soil layer that is regularly ploughed (taken from literature) /Löfgren 2010/.

Depths of organic and inorganic postglacial deposits (Aqu_z_rego_pg and Ter_z_regoMid_pg) change over time and are modeled in the RLDM for each time step and object used in the radionuclide model. The depth and distribution of the glacial clay (z_regoMid_gl_basin and Aqu_z_regoMid_gl_lake), and till (Sea_z_regoLow, Lake_z_regoLow), on the other hand, are regarded as constant over time. However, the depth of the glacial clay and till layers varies in the landscape and is specific for each object, based on the RDM /Hedenström et al. 2008/.

Density and porosity

The density and porosity of the upper regolith, differs between ecosystems. The density and porosity of the upper regolith in aquatic ecosystems (Aqu_dens_regoUp and Aqu_poro_regoUp) are based on measurements of the water content and organic carbon content of sediments from both limnic and coastal surface samples at Forsmark. The dry bulk density and porosity of wetlands (Ter_dens_regoUp and Ter_poro_regoUp) are taken from site measurements from several depths in one mire in the Forsmark area /Löfgren 2010/. Density and porosity of drained wetlands, which are assumed to be used for cultivation (Agri_dens_regoUp and Agri_poro_regoUp) are based on literature data for organic soils.

In the middle and lower regolith layers, the same density and porosity parameter values are used for aquatic and terrestrial ecosystems. The dry bulk density and porosity of postglacial deposits and glacial clay in aquatic and terrestrial regolith (Aqu_dens_regoMid_pg, Ter_dens_regoMid_pg, Aqu_dens_regoMid_gl, Ter_dens_regoMid_gl, Aqu_poro_regoMid_pg, Ter_poro_regoMid_pg, Aqu_poro_regoMid_gl, Ter_poro_regoMid_gl) are based on site measurements in lakes and marine basins at Forsmark. The parameter values of dry bulk density and porosity of the lower regolith (dens_rego_low, poro_regoLow) are based on site-specific measurements, at varying depths in the till at four terrestrial localities.

9.2.4 Ecosystem properties

The ecosystem parameters describe relevant properties of aquatic and terrestrial ecosystems in the Forsmark area today and in the future. It is not possible to predict species composition in a fully dynamic future ecosystem in detail, and instead data from the site and nearby ecosystems are used as natural analogues for the future ecosystems. This is based on the assumption that all relevant interactions among species and between organisms and the abiotic environment are contained in these analogue ecosystems.

Aquatic ecosystems

Aquatic ecosystems include marine, lake and stream stages of the aquatic objects. Lakes and marine basins are parameterised with site data, i.e. with data from brackish marine basins and oligotrophic hard-water lakes at Forsmark today. The maximum and minimum parameter values were selected to cover changes that may be induced due to altered salinity in the marine basins, and altered nutrient conditions in the oligotrophic lakes. Ecosystem properties include chemical and biological parameters, as well as parameters connected to human utilisation of the ecosystem. The ecosystem properties parameters for limnic and marine ecosystems are fully described in /Andersson 2010, Aquilonius 2010/.

Biological parameters

Biomass and production of biota in the aquatic ecosystems are calculated for three categories, 1) the pelagic community (Aqu_biom_pp_plank, Aqu_prod_pp_plank), 2) the benthic macro community (Aqu_biom_pp_macro, Aqu_prod_pp_macro), and 3) the benthic micro community (Aqu_biom_pp_ubent, Aqu_prod_pp_ubent). Biomasses include both primary producers and consumers. Production is the net ecosystem productivity (NEP) and is calculated as the difference between primary production and respiration. Biota incorporate radionuclides during primary production and the production excess (i.e. the NEP) settles on the lake floor as sediment or is transported to downstream objects. Biomass and net ecosystem production are based on site investigations together with modelling of the future depth distribution of the aquatic objects. The major factors affecting biomass and production of the biotic community in aquatic ecosystems are water depth and light penetration, and thus biomass and production parameters change over time due to landscape development.

Chemical parameters

Chemical parameters include concentrations of particulate matter and inorganic carbon as well as fluxes of carbon dioxide gas across the air-water interface. Parameter values of concentrations of particulate matter (conc_PM) and dissolved inorganic carbon (conc_DIC) are annual averages calculated from site-specific measurements in lakes and in the sea.

There is equilibrium of CO_2 between air and surface waters resulting in a flux of carbon dioxide upon primary production (consuming CO_2) or respiration (releasing CO_2) in water bodies. Thereby, primary production and respiration in aquatic ecosystems result in a flux of C-14, across the air-water interface. For other radionuclides and their analogues, this flux is considered to be small or insignificant. The CO_2- flux is related to primary production and gas influx (gasUptake_C) and is calculated for the aquatic objects as a proportion of net primary production. The data for NPP are based on site-specific measurements and modelling of future objects. Gas outflow from the aquatic objects (Aqu_degass_C) were calculated by assuming a mass balance for the ecosystem, i.e. the amount of carbon entering the system must be the same as the amount of carbon leaving the system.

Parameters related to human utilization of the ecosystem

The production in aquatic ecosystems that can be sustainably harvested is parameterised in order to evaluate the potential utilisation of ecosystems. It is assumed that fish, mussels, and crayfish are organisms normally consumed from the aquatic ecosystems by humans. Fish production that can be sustainably harvested (prod_edib_fish_Sea and prod_edib_fish_Lake) was estimated based on site data on fish sizes and conversion factors from literature. Parameter values for crayfish in future lakes were estimated based on literature, but crayfish are assumed not to occur in the future marine basins. Fish and crayfish are sensitive to shallow water depths (and effects of this, such as poor oxygen conditions and habitat type) and constraints were introduced that only allow fish and crayfish in lakes with certain minimum depth (z_min_prod_edib_fish_Lake, and z_min_prod_edib_crayfish_Lake). Based on literature and knowledge from the site, filter feeders are assumed not to be part of the diet from aquatic ecosystems in Forsmark.

Terrestrial ecosystems

Terrestrial ecosystems include both agricultural land and wetlands. Wetlands are parameterised with data from forested wetlands at Forsmark and Laxemar-Simpevarp. Ecosystem properties include production and decomposition, fluxes between the terrestrial area and the atmosphere and fluxes out of the system, as well as parameters connected with human utilisation of the ecosystem. Unless otherwise stated in the text below, these parameters are fully described in /Löfgren 2010/.

Biomass, production and decomposition

Biomass and production of primary producers in wetlands (Ter_biom_pp and Ter_prodBiom_pp) include, vascular plants (including trees) and mosses and are calculated based on site data for three localities, two of which are wetlands and one is a moist drained peatland with planted forest.

The decomposition rate in wetlands (Ter_decomp), i.e. the amount of litter that is respired each year, is estimated based on long-term (1,600 years) mean accumulation from the bog Rönningarna in Forsmark /Sternbeck et al. 2006/ by subtracting the mean accumulation in peat from the net primary production of the median wetland. It was thereby assumed that the long-term accumulation in the vegetation was close to zero.

Fluxes of carbon between terrestrial area and the atmosphere

Fluxes of carbon between atmosphere and the terrestrial part of the ecosystem include release to the atmosphere from peat (upper regolith in wetlands), release to the atmosphere from decomposing biota and uptake from the atmosphere by plants. The release from wetlands to the atmosphere is calculated based on the concentration of carbon in the regolith (Ter_conc_C_regoUp) and the release of carbon as CO_2 (Ter_degass_C). The release of CO_2 is dependent on dissolved inorganic carbon and pH, and this flux is based on literature conditioned by pH values of wetlands in Forsmark.

Decomposition of litter based on site data (see above) results in fluxes to the atmosphere and to dissolved inorganic and organic carbon in the soil. The fraction of decomposed carbon that is released to the atmosphere (frac_C_atmos) was based on literature. Uptake of carbon from the atmosphere by plants is calculated based on biomass and production of primary producers (see above), carbon concentration in the air (conc_C_atmos) and the height of the atmospheric layer from which CO_2 is taken up by primary producers (Ter_z_mixlay).

C-14 is exported from the atmosphere above the terrestrial areas by wind exchange. The export was calculated based on wind velocity (vel_wind), the height of the atmospheric layer where CO_2 is taken up by vegetation (Ter_z_mixlay) and the zero displacement height of the wetland/agricultural field (Ter_z_roughness, i.e. where the wind speed becomes zero when the wind profile above the canopy is extrapolated down through vegetation). Wind velocities are site specific, whereas the other parameters influencing the export are taken from literature /Nordén et al. 2010/.

Parameters related to human utilization of the ecosystem

The production in terrestrial ecosystems that can be sustainably harvested is parameterised in the radionuclide model. In addition, humans are exposed to radionuclides by inhalation. Humans may also influence exposure by activities such as irrigation.

From wetlands, the production of berries, mushrooms and game meat (prod_edib_berry, prod_edib_mush, prod_edib_game) are taken to be consumed by humans. In addition to production of game meat, the fraction of mushrooms in the diet of terrestrial herbivores (frac_mush_Herbiv) has been considered in the model. These parameters are based on both site data and literature.

From agricultural land, the production of domestic animals (prod_edib_meat and prod_edib_milk), cereals (prod_edib_cereal), tubers (prod_edib_tuber) and vegetables (prod_edib_vegetab) are utilised by humans. The production of domestic animals is dependent on fodder production (prod_fodder) which is also considered. These parameters are calculated based on literature and knowledge of common crops and husbandry representative of the Forsmark region today.

Some characteristics of agricultural products are important for the exposure estimates in the radionuclide model, i.e. carbon concentrations in milk and meat (conc_C_milk and conc_C_meat) and density of milk (densMilk). Leaf area index (leaf_areaIndex), based on literature values of the ratio of the total upper leaf surface of vegetation divided by the surface area of the plot and CR (see Section 9.2.7) are used to calculate the concentrations of radionuclides in vegetables. Characteristics of products are further described in /Nordén et al. 2010/.

Based on literature data, parameter values for ingestion rates of food, water and soil by dairy cattle and beef cattle (ingRate_food_milk, ingRate_water_milk, ingRate_soil_Cow, ingRate_food_meat, ingRate_water_meat) are included in the radionuclide model, described in /Nordén et al. 2010/.

In order to estimate the human exposure to radionuclides due to inhalation of dust, the concentration of dust in the air above agricultural land (Agri_conc_Dust) and wetlands (Ter_conc_Dust) were included in the radionuclide model. These parameters are based on literature /Nordén et al. 2010/. The time spent in the agricultural and wetland areas is also important and is treated in Section 9.2.8.

In the base case of SR-Site, irrigation of vegetables with surface water occurs during the time period when agricultural practises are considered possible. The parameters used to describe irrigation are the total amount of water used per year (vol_irrig), the number of irrigation events per year (numb_irrig), the leaf water storage capacity of the vegetation (leaf_StoreCapac) and an element-specific parameter describing the retention on the vegetation surfaces (coefRetent, Section 9.2.7). All irrigation parameters are fully described in /Nordén et al. 2010/.

9.2.5 Surface hydrology and water exchange

It is assumed that waterborne transport of radionuclides in the biosphere is proportional to the transport of water. Surface water fluxes in marine, terrestrial and limnic ecosystems have been modelled and the capacity of a well above the repository has been estimated.

Water fluxes in the sea

The hydraulic residence time for the marine stages of objects (wat_ret), i.e. the average time a water parcel spends within a given volume was calculated with a hydrodynamic model using external forcing factors from the atmosphere, the surrounding sea and land runoff /Karlsson et al. 2010/. The estimates of these factors are based on site data from Forsmark. The major time-dependent forcing factor influencing retention time in the models is the bathymetry (depth and shoreline), which was determined from the DEM /Brydsten 2006/.

In the sea, it is assumed that there is a net upward flux through the regolith layers (Sea_adv_low_mid), equal to the flux from the geosphere to the lowest regolith layer. This flux is assumed constant through the regolith layers because there is no influence of lateral surface fluxes like in lakes and terrestrial objects /Bosson et al. 2010/. In the radionuclide model, it is assumed that there is no influence of lateral advective fluxes in the marine biosphere object as in lakes, and therefore there is no water flux between the regolith and surface water (i.e. sea_adv_mid_up is set to 0). However, there is a transport from sediments to water also in the marine basins caused by resuspension (Section 9.2.2) and diffusion (Section 9.2.6).

Water fluxes in lakes and terrestrial areas

The representation of the waterborne transport of radionuclides between compartments in the limnic and terrestrial ecosystems is based on detailed hydrological modelling with MIKE SHE /Bosson et al. 2010/. Water balances for today's conditions have been analysed for different landscape objects and by simulating different time periods, i.e. different shoreline positions, regolith distribution, and climate cases, the dynamics (i.e. the fluxes) of the groundwater and surface water in the future have been described /Bosson et al. 2010/. MIKE SHE and the radionuclide model divide the ecosystem components somewhat differently and the outputs from water balances in MIKE SHE had to be transformed in order to fit the set-up in the radionuclide model (Figure 9-2). This is extensively described in /Andersson 2010/.

In the model simulations, the radionuclide releases from the geosphere are directed to the lower regolith. Thereafter a vertical flux from the lower regolith to the middle regolith (lake_ adv_low_mid) and distribution of this flux between terrestrial area (i.e. wetland) and lake is calculated (fract_mire). In the wetland, a flux from the middle regolith (i.e. post-glacial and glacial deposits) to the upper regolith (i.e. peat) is calculated. The vertical fluxes between the lake water and sediment are assumed to be equal in both directions. The same fluxes are used to represent the water exchange between the top sediment (i.e. upper regolith) and the rest of the sediment (i.e. middle regolith layer). Thus, in the radionuclide model, the there is a flux from the middle regolith layer to surface water (Lake_Aqu_adv_mid_up_norm).

The lateral fluxes between wetland and lake are calculated as functions of the sub-catchment areas of the object (area_subcatch) and the runoff (runoff) and by introducing a flooding coefficient (Flooding_coef). The runoff and flooding coefficient were estimated based on water balances in the MIKE SHE SDM-Site model /Bosson et al. 2008/.

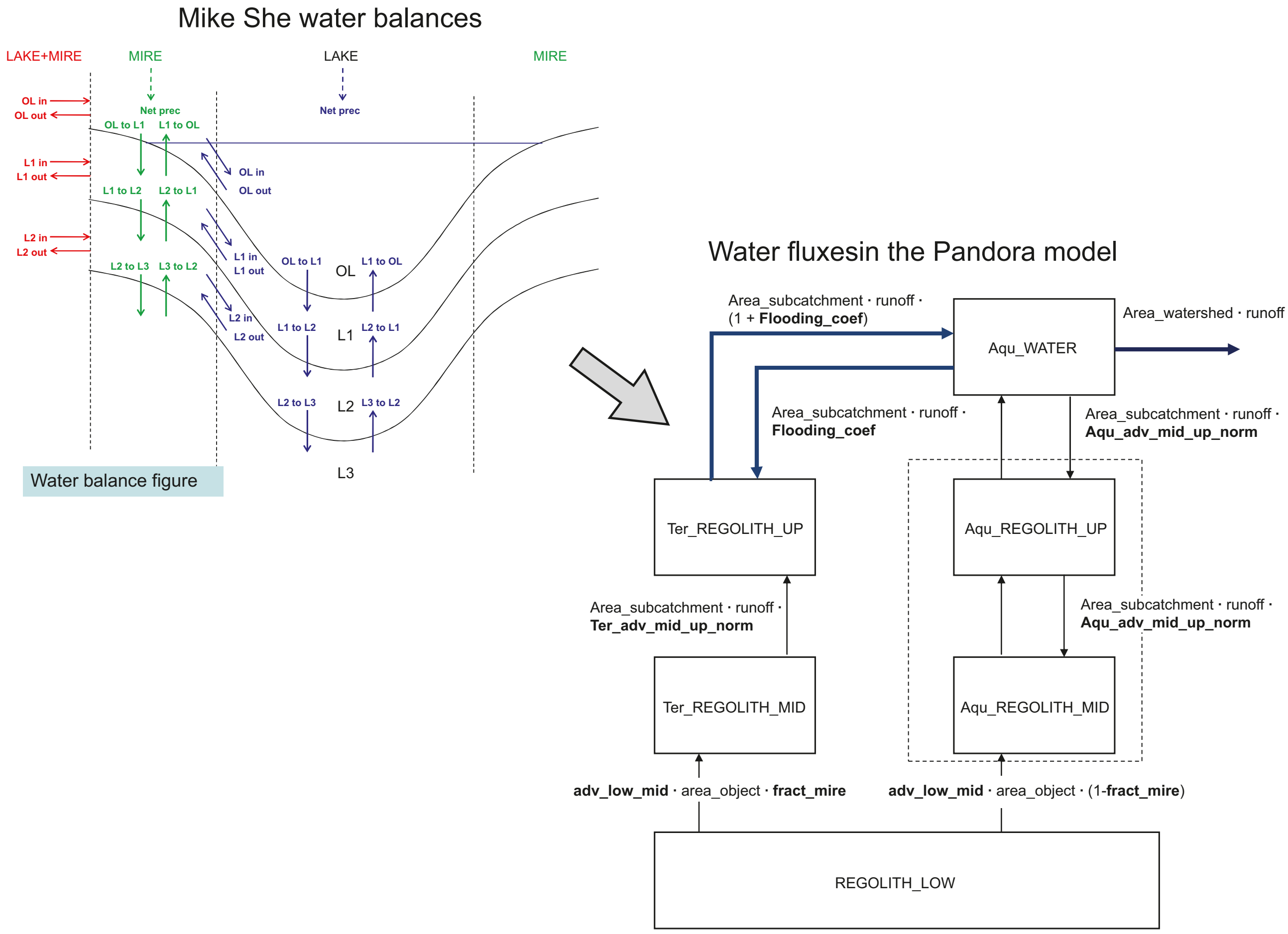

Figure 9-2. *Detailed hydrological models are used to parameterise water fluxes between compartments in the radionuclide model. Parameter names in bold are water fluxes described in Section 9.2.5.*

Well capacity

The well capacity in the Forsmark area (wellCapac) is estimated based on site data from 22 percussion boreholes /Gentzschein et al. 2007/.

9.2.6 Distribution coefficients and diffusivity

In the radionuclide model, distribution coefficients (hereafter named Kd) and diffusivity are element-specific parameters that are used in simulating the radionuclide transport in the deposits. The diffusivity (diffcoef) was used for calculation of the diffusion fluxes between different regolith compartments, whereas Kd values are used to describe retention within the deposits. The Kd concept assumes a reversible, linear relationship between sorbed and dissolved species of an element in the soil, sediments and particulate matter /Tröjbom and Nordén 2010/. To include variations in Kd values between sites with different local environments, in situ measurements from both Laxemar and Forsmark, as well as literature data, have been used to assign the PDFs. The use of empirical in-situ measurements also ensures that the effect of competing stable elements is included in the Kd values.

Kd values have been assigned for inorganic deposits (kD_regoLow) and organic deposits in terrestrial and aquatic environments (Ter_kD_regoUp, Ter_kD_regoMid, Lake_kD_regoUp, Lake_kD_regoMid, Sea_kD_regoUp and Sea_kD_regoMid) as well as for particulate matter in limnic and marine environments (Sea_kD_PM, Lake_kD_PM). These parameters are further described in /Nordén et al. 2010/.

When estimating Kd values, available site-specific data have been combined with literature data, as described in Section 9.1.2. The reported parameter value ranges were often several orders of magnitude.

9.2.7 Concentration ratios, retention and release

The modelled uptake of radionuclides in biota is described by concentration ratios (CR) in SR-Site. The concentrations of different radionuclides in terrestrial vegetation (natural as well as crops) and mushrooms (cR_soilToPast, cR_soilToCereal, cR_soilToTuber, cR_soilToVegetab, Ter_cR_pp, cR_soilToBerr, cR_soilToMush) were related to the corresponding concentrations in the soil whereas concentrations in terrestrial herbivores (cR_foodToHerbiv) were related to concentrations in their food. For aquatic biota (Lake_cR_pp_plank, Lake_cR_pp_ubent, Lake_cR_pp_macro, cR_watToFish_Lake, cR_watToCray_Lake, Sea_cR_pp_plank, Sea_cR_pp_ubent, Sea_cR_pp_macro, cR_watToFish_Sea) the radionuclide concentrations were related to the corresponding concentrations of the water in their habitat. These element-specific parameters are described in /Nordén et al. 2010/.

Modelling plant uptake via CR factors reflects a reversible transport mechanism including both influx and efflux depending on the concentrations in plants and soil. The CR calculation approach assumes a linear relationship between plant and soil concentrations /Tröjbom and Nordén 2010/. To include this variation, available site specific data have been combined with literature data when estimating CR (Section 9.1.2). The reported parameter value ranges are often several orders of magnitude.

The retention of radionuclides supplied to vegetation surfaces as a consequence of irrigation by contaminated water is described by an element-dependent retention factor (coefRetent). The values used are those recommended in /Bergström and Barkefors 2004/.

To describe the turnover of elements in terrestrial ecosystems, one parameter describing the behaviour of different elements during decomposition was used (Ter_df_decomp). The parameter gives the fraction of the element retained in the organic part of the litter compared with the amount present in the dry mass. Elements were grouped into carbon-like elements or other elements according to patterns identified in /Brun et al. 2008/.

9.2.8 Human characteristics and dose coefficients

Parameters that describe habits and characteristics of the exposed individual were primarily collected from the literature. In SR-Site, these parameters include the amount of food and water consumed (ingRate_food and ingRate_water), inhalation rate (inhRate) and time spent in the contaminated area (expTime), as well as dose coefficients for external exposure, inhalation, and ingestion of water and food (dosCoef_ext, dosCoef_inhal, dosCoef_ing_water, dosCoef_ing_food).

The dose coefficients used in the dose calculations take into account retention of radionuclides in the human body and exposure from daughter radionuclides, as well as radiation sensitivities of different tissues and organs. Doses calculated using these coefficients are committed effective doses, which are appropriate for calculating the probability of harmful effects of ionizing radiation using the dose to risk factors given in the Swedish regulation /SSM 2008/.

In line with international recommendations /ICRP 2006/, fixed, slightly conservative values were chosen for these parameters. Thus, these parameters were excluded from the probabilistic simulations, leaving the uncertainty distribution in LDFs to primarily reflect the environmental uncertainties.

The food consumption rate was expressed in kg carbon per year, since the total intake of carbon by an individual is related to the food energy intake. The water consumption rate used did not include the water contained in the food, since its contribution to man's water balance is indirectly included in the calculations of the internal dose from food ingestion. The inhalation rate and exposure time used were conservative (high) values.

The dose coefficients for ingestion and inhalation were taken from /EU 1996/, whereas the values for external exposure were taken from /Eckerman and Leggett 1996/. These parameters are further described in /Nordén et al. 2010/. As recommended by the ICRP /ICRP 2000/, only dose coefficients for adults have been used.

9.3 Parameterisation at different climate stages

The biosphere safety assessment has been performed for the reference glacial cycle (including temperate, periglacial, and glacial climate and submerged conditions) and the global warming climate case (**Climate report**). Descriptions of the Forsmark site for the different climate domains are presented in Chapter 6 and how this has been considered in the safety assessment is described in Section 8.7.2.

The parameter description above refers to values for a *temperate* climate domain. For *periglacial* climate domain, the state of the biosphere is expected to be similar to the temperate climate, with the adjustments that the agricultural pathways are omitted and that there are no wells. Other potential implications, such as changed hydrology and altered parameter values, are considered in supporting calculations (see below). In a similar way, the *global warming* climate case is treated as an extended temperate climate and temperate parameterisation was prolonged up to year 60,000 AD in the calculations of LDFs. For warmer conditions (e.g. following global warming), production in terrestrial areas is likely to increase, but no supporting calculations to investigate the effects of this on LDFs have been performed (Chapter 12 and in /Löfgren 2010/). During periods of *glaciation*, it is possible that a small human population could potentially utilise fish from the sea at the ice margin and the temperate parameterisation for the sea stage has been used to encompass this possibility. In summary, the only case for which a different parameterisation has been used for other climate conditions than temperate is for the supporting calculation performed for the periglacial climate domain (for a discussion of the results of this simulation, see Chapter 12).

9.3.1 Periglacial parameterisation for supporting calculation

During a periglacial climate domain, the processes in the biosphere that affect transport, accumulation and exposure are expected to be altered in several ways. For example, permafrost will prevent discharge of deep groundwater to most of the lakes and wetlands in the area /Bosson et al. 2010/. Another effect is that surface water fluxes in lakes where discharge occurs will be reduced, mainly due to lower precipitation. The terrestrial vegetation community will change with climate. Primary production will decrease in a harsher climate, resulting in a reduced rate of in-growth of wetlands into lakes /Brydsten and Strömgren 2010/ and a reduced productivity of natural foods and agricultural crops in the area /Löfgren 2010/.

During permafrost periods, parameters that describe hydrological fluxes (runoff, Lake_aqu_adv_mid_up_norm, Lake_fract_Mire, Lake_adv_low_mid, Ter_adv_mid_up_norm and Flooding_coef) and properties of wetland vegetation (Ter_biom_pp, Ter_prodBiom_pp, Ter_z_roughness, Ter_z_mixlay, Ter_decomp and frac_C_atmos) and crops (prod_edib_cereal, prod_edib_tuber, prod_fodder, prod_vegetab and leaf_areaIndex) were given values representative of permafrost conditions /Bosson et al. 2010, Löfgren 2010, Andersson 2010/ and the wetland ingrowth rate was reduced by 75% /Brydsten and Strömgren 2010/.

Under permafrost conditions, modelled parameters describing hydrological fluxes are generally lower than in temperate conditions, although the runoff is larger /Bosson et al. 2010/. The terrestrial ecosystem parameters are also, in general, lower during permafrost conditions. Values for these parameters were derived from other parts of Sweden, or from other sites, e.g. Greenland /Löfgren 2010/. For most aquatic ecosystem parameters, on the other hand, the same parameter values were used for temperate and periglacial conditions. The exceptions were production of fish and crayfish in lakes (prod_edib_fish_Lake and prod_edib_cray_Lake), which were assumed to be lower in a colder climate.

The permafrost depth and area of open water were used to determine whether the conditions were favourable to permafrost development under lakes /Brydsten and Strömgren 2010/. During conditions with permafrost under lakes, it is assumed that there is no further release of radionuclides to the object. It was also assumed that drilled wells would provide no water during periglacial climate domains.

The transition between temperate conditions and full permafrost conditions in the whole Forsmark area has been estimated to prevail for a time period varying between 2,000 and 5,000 years (**Climate report**). Transition periods, in which parameters affected by permafrost were assumed to change continuously between temperate and permafrost values, were assumed to be 2,000 years for the modelled biosphere object.

10 The landscape dose conversion factors (LDF)

In SR-Site, doses to humans resulting from releases to the biosphere in different scenarios have been calculated by multiplying release rates or pulse releases of radionuclides to the biosphere with a corresponding maximum landscape dose conversion factor (LDF). The maximum LDFs were generated by running the radionuclide model for each separate biosphere object as described in Chapter 8 and using the parameterisation presented in Chapter 9. For each radionuclide, the maximum LDFs were derived by first finding the maximum annual dose over time per unit release rate or unit release to a representative individual of the most exposed group in each biosphere object, and thereafter finding the maximum dose conversion factor across all biosphere objects.

This chapter summarises the results from the radionuclide model. First, the calculated LDFs are presented and compared with results from other assessments. Thereafter, brief descriptions of the resulting patterns of LDFs in space and time are provided, including a discussion of the mechanisms behind the behaviour. Finally, some calculations for additional, near future scenarios and for illustration of barrier functions are presented. The chapter ends with a comparison between measured, present-day activity concentrations and calculated concentrations resulting from a potential release from the repository. A more complete description of the model and results, including examples from the different steps in the calculation of LDFs and of the modified LDFs for a pulse release, are provided by /Avila et al. 2010/.

10.1 Resulting LDFs

Maximum LDFs for a constant unit release rate (1 Bq/year) of different radionuclides were calculated for the three different climate domains within a reference glacial cycle; temperate (represented by the interglacial period), periglacial, and glacial domains, and for the global warming climate case (see Section 8.7.2 for details on calculations). Results for the 19 radionuclides that were expected to contributed the most to human exposure are presented in Figure 10-1. LDFs for all 40 assessed radionuclides are presented in /Avila et al. 2010/ and in the **Data report**.

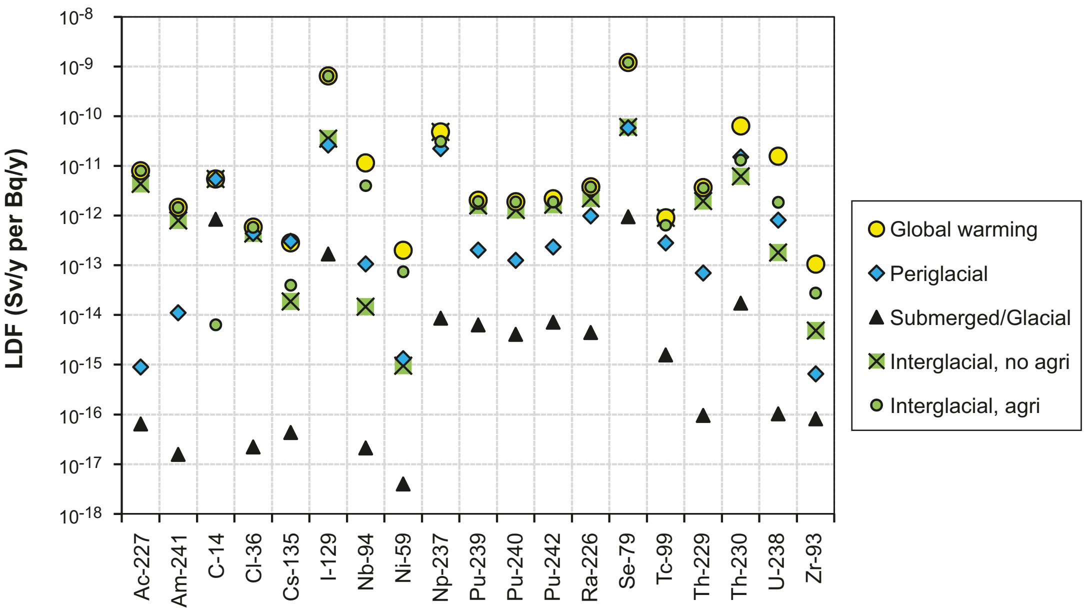

Figure 10-1. *Calculated maximum LDFs (the highest LDF over time among all biosphere objects) for different climate domains/condition. LDFs for the initial submerged period were used to represent glacial conditions in the assessment. The effect on the LDFs of using agricultural products as food is evaluated by contrasting LDFs for the intergalacial period before after agriculture is possible. Figure from /Avila et al. 2010/.*

During the reference glacial cycle, the maximum LDF is consistently higher under the interglacial period than under the other climate domains (Figure 10-1). For instance, LDFs for glacial conditions were below the values for interglacial conditions by two orders of magnitude. The maximum LDFs during periglacial conditions were also lower than during temperate conditions, and these results were confirmed by detailed simulations of periglacial conditions (Section 12.2.1). Hence, the maximum LDFs for the interglacial period are also maximum values during the whole reference glacial cycle, and have therefore been used for cautious dose assessments for long-term release of radionuclieds from the repository.

For most radionuclides, the LDF for temperate conditions differs marginally between the periods with and without agriculture (Figure 10-1). However, for a few radionuclides (i.e. C-14, I-129, Nb-54, Ni-59, U-238), the LDFs differ by more than an order of magnitude between these two situations, and it is only for C-14 that the LDF is higher in the period when agriculture is not possible. The reason for these differences are discussed in /Avila et al. 2010/. Since the maximum value over the whole period is used as maximum LDF, the differences have no effect on the final risk estimates. However the results imply that the most exposed group corresponding to different radionuclides can be in viewed as homogenous with respect to land use.

In the biosphere assessment, the global warming climate case is represented by a 50,000 year extension of temperate conditions. Consequently, radionuclides that do not reach steady state activity concentrations within the initial temperate period (–9000 to 9400 AD) will continue to accumulate during the extended temperate period. However, most radionuclides have approached steady state at 9400 AD, and additional accumulation and associated increase in maximum LDF is marginal for radionuclides expected to contribute to dose. Only for two radionuclides, Cs-135 and U-238, LDFs were larger (approximately an order of magnitude) in the global warming climate case than under the reference glacial cycle, which can be explained by several factors as discussed in /Avila et al. 2010/. However, due to the small contribution of Cs-135 and U-238 to the total risk estimate resulting from a long-term release (see Section 13.5.4 in **SR-Site main report**), a tenfold increase in the LDFs of these nuclides would not affect the final risk estimates significantly.

Table 10-1. Characteristics of radionuclides contributing most to dose in the central corrosion case /Section 13.5.4 in SR-Site main report/. Pathway shows the dominant exposure pathway(s). The contribution to dose from drinking water (Ingestion water) is in % of the LDF. Doses from inhalation and external irradiation are insignificant for all radionuclides presented in the table. The columns Time (AD), N and Biosphere object show the time, number of affected individuals and biosphere object, respectively, for the maximum LDF value. The Biosphere objects are shown in Figure 7-11.

Radionuclide	Maximum LDF (Sv Bq^{-1})	Pathway	Ingestion water (%)	Time (AD)	N	Biosphere object
Ra-226	$3.8 \cdot 10^{-12}$	Vegetables	54	9400	79	121_3
Se-79	$1.2 \cdot 10^{-9}$	Vegetables, cereals	0	4750	79	121_3
I-129	$6.5 \cdot 10^{-10}$	Vegetables, milk	0.1	4050	79	121_3
Np-237	$4.8 \cdot 10^{-11}$	Crayfish, fish	1.0	3200	0.9	118
Cs-135	$1.8 \cdot 10^{-16}$	Vegetables, milk	18	9400	80	124
Cl-36	$3.8 \cdot 10^{-15}$	Vegetables, milk, cereals, roots	1.2	3900	79	121_3

10.1.1 Comparison with results from earlier studies

The method used for calculating landscape dose conversion factors in SR-Site has been updated in several important ways since the last two biosphere assessments of a deep repository: SR-Can (**SR-Can main report**) and SR-97 /SKB 1999/. Data from the site have been used to modify parameter values, increasing their relevance and representativeness of the site. The changes in methodology and parameter values, and their consequences for exposure, are discussed in detail in /Avila et al. 2010/.

The maximum values of the ecosystem specific dose conversion factors (EDF) used in SR-97 /SKB 1999/ were systematically higher than the LDFs calculated in the present assessment, with exception for a few radionuclides (e.g. C-14) (Figure 10-2). These differences are attributable to important methodological differences between the two assessments, including the delineation of the sub-catchment, assumptions on where a release will reach discharge areas and enter the ecosystems, as well as differences in the represention of the well /Avila et al. 2010/. Moreover, in the SR-97 assessment generic parameter values were used in most cases, whereas data from the site investigation programs have been used to a large extent in the SR-Site assessment.

The methodology applied in SR-Site is based on that developed in SR-Can, but has been updated in several important ways. In the SR-Can assessment it was assumed that the releases were distributed over the whole landscape, whereas in SR-Site it is assumed that all releases will reach the discharge area where it will cause maximum exposure (i.e. to the most exposed group). In SR-Site, the representation of ecosystems and of the transition between them has been improved, and radionuclide transport in till (lower layer of the regolith) has been explicitly included in the biosphere model. For radionuclides where the consumption of contaminated food is the dominant pathway for exposure, the LDFs are typically an order of magnitude higher in the SR-Site than in the SR-Can assessment. However, the activity concentration in well water was calculated in a similar way in the two assessments (though the exposure from the well was not combined with other pathways in SR-Can), and consequently LDFs for radionuclides where drinking water is the dominant pathway is similar in the two assessments /Avila et al. 2010/.

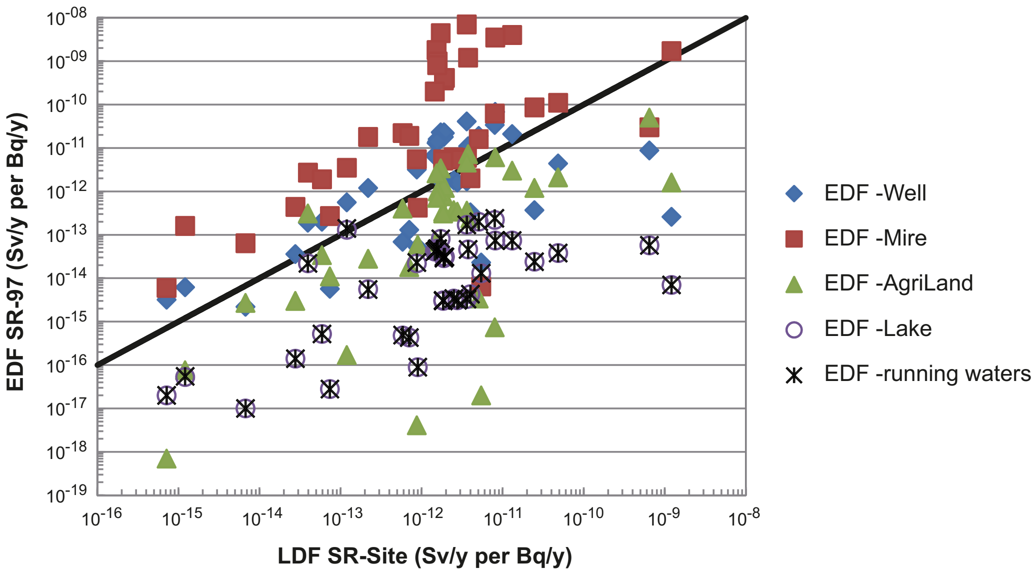

Figure 10-2. *Comparison of the SR-Site LDFs with corresponding dose conversion factors (EDF) reported in SR-97 /SKB 1999/. The solid line represents a 1:1 relationship between SR-Site and the SR-97 dose factors, and each point represents a specific in radionuclide. Figure from /Avila et al. 2010/.*

10.2 Variation of LDFs in time and between biosphere objects

The effects of the shoreline regression and the subsequent succession of biosphere objects on LDFs are similar for many of the radionuclides expected to contribute to dose (Figure 10-3). LDFs increase continuously with time during the sea stage (1 in Figure 10-3), reflecting a gradually increasing activity concentration in sea water. The flux of radionuclides to the water column increases when deep accumulation bottoms are first exposed to wave erosion (1a), but this is a transient phenomenon. The increase in concentrations during the sea stage is primarily driven by a decrease in water exchange as the sea basins gradually become sheltered, and this development becomes most pronounced towards the end of the stage when land starts to emerge out of the sea (1b).

The LDFs increase further in the transition stage (2). In Figure 10-3, the selected biosphere object develops directly into a wetland, and the increase in the LDF during the transition stage is a function of the gradual accumulation of radionuclides in peat. In the terrestrial stage (3) the wetland is fully developed. A steep increase in LDFs early in this stage occurs when it is first possible to transform the wetland into arable land (3a). This is because the agricultural soil is enriched in radionuclides in comparison with wetland peat, as a consequence of draining and mixing with deeper regolith layers by ploughing. From this point, further accumulation of radionuclides in agricultural soil only marginally affects the LDFs. For some radionuclides long-term accumulation results in a slight increase of LDFs (e.g. Cs-135), whereas for others (Se-79, I-129) wetland concentrations are slightly lower under stable conditions.

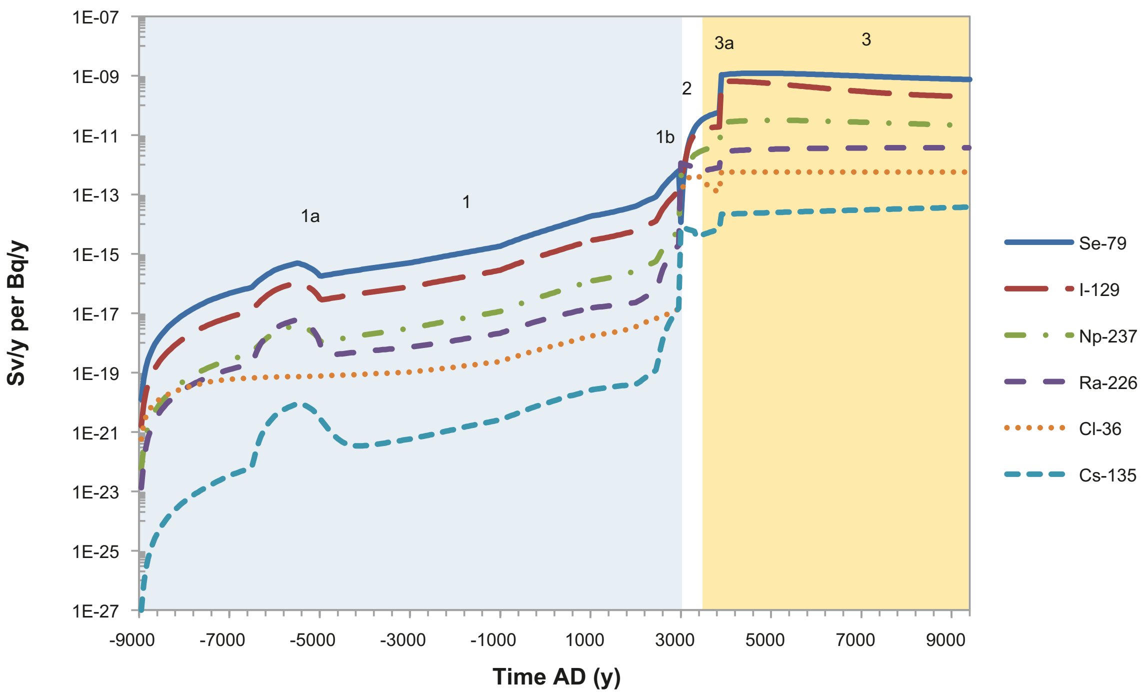

Figure 10-3. *The development of LDFs for a number of dose-contributing radionuclides during an interglacial for Biosphere object 121_3. The nuclides Se-79, I-129, Ra-226 and Cl-36 all had their maximum LDFs from this biosphere object. The objects goes through three development stages: 1) the sea stage (blue), 2) the transitional stage (white) and 3) the terrestrial stage (brown). Index letters refer to events that cause relatively fast changes in the LDFs and are explained in the text. Note that object 121_03 does not go through a lake stage, but the sea bay develops directly into a wetland. Figure from /Avila et al. 2010/.*

The dose factors clearly vary between biosphere objects, but the degree of variation depends on the properties of radionuclides (Figure 10-4). Landscape object 105, which is in the sea stage during the full temperate period, has maximum LDFs that for all radionuclides are consistently lower by three orders of magnitude or more, compared with all other objects. For radionuclides where exposure from food is the dominant exposure pathway (i.e. C-14, Cl-35, I-129, Nb-94, Np-237, Se-79, Sn-126 and Tc-99), LDFs typically vary by two to three orders of magnitude (excluding object 105). However, for radionuclides where drinking water is an important pathway for exposure (e.g. Am-241, Pa-231, Pu-231, Pu-239, Pu-242, Ra-226 and Th-229), the variation in LDFs between objects is typically within a factor of three. Furthermore, the order of objects with respect to LDF values is similar for most radionuclides. For example, the biosphere object 121_3 yields the highest LDF for most of the examined radionuclides /Availa et al. 2010/.

10.3 Calculations for pulse release, near future scenarios and illustrations of barrier functions

The methodology for calculating maximum LDFs for long-term releases has gradually developed from the earlier assessments SR-97 /SKB 1999/ and SR-Can (**SR-Can main report**). During the SR-Site work results have been thoroughly explored and validated, and models and parameter values iteratively updated. For short pulse releases and for releases in the near future, the results have not been iterated and validated in the same thorough way. There is confidence that the numerical model can be applied also to these situations and that derived results do not underestimate the risk. However, the temporal and spatial resolution of the model may not be sufficent to capture the detailed dynamics of transient events. Moreover, some parameter values may have to be adjusted to be representative for short-term equilibriums, and there are also a number of radionuclides appearing in these situations which have received less attention at the site investigation and in the literature.

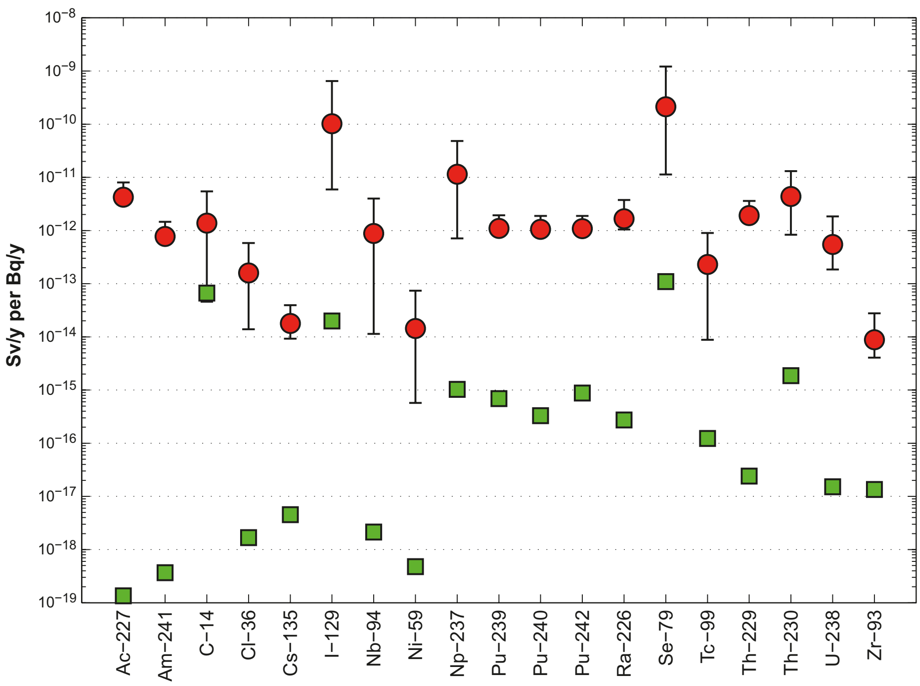

Figure 10-4. *Mean (red circles), minimum and maximum LDF for a selection of radionuclides across biosphere objects (excluding object 105). The LDF values for object 105, which is submerged during the whole interglacial, are shown separately (green squares). Figure from /Avila et al. 2010/.*

10.3.1 Modified LDF for pulse release

The maximum LDF for each potentially released radionuclide is defined as the average annual dose during the lifetime of a representative individual of the most exposed group, resulting from a constant release rate of 1 Bq/y of this radionuclide. By contrast, the modified LDF for pulse releases is defined as the average annual dose during the lifetime of a representative individual of the most exposed group, resulting from a unit pulse release. The modified LDFs are used to evaluate doses from pulse releases of the fraction of the inventory in a canister that is assumed to be instantaneously available for release upon water contact.

Values for the modified LDF for pulse release (derived for radionuclides likely to be present in a pulse releases), are presented in Table 10-2. These values correspond to the maximum value of the annual doses obtained from simulation with pulse releases of 1 year duration, occurring at different time points within an interglacial period.

Table 10-2. Modified Landscape Dose conversion factors derived for pulse releases. LDFs were obtained from simulations where a total of 1 Bq was released to a biosphere object during one year.

Radionuclide	LDF pulse Sv/y per Bq
I-129	$5.6 \cdot 10^{-14}$
Se-79	$9.7 \cdot 10^{-14}$
Cl-36	$4.3 \cdot 10^{-15}$
Tc-99	$2.8 \cdot 10^{-15}$
Sn-126	$2.3 \cdot 10^{-15}$
Ag-108m	$5.1 \cdot 10^{-16}$
Cs-135	$1.8 \cdot 10^{-16}$
Nb-94	$3.2 \cdot 10^{-16}$
Ni-59	$9.7 \cdot 10^{-18}$

10.3.2 Early canister failure due to shear load

Canister failure due to rock shear has a low probability in the reference evolution, and the only identified cause for such failure is a large earthquake close to the repository (Section 13.6 in **SR-Site main report**).

For times up to 1,000 years after closure, the probability that one out of the 6,000 canister has failed at the end of the period is $2.4 \cdot 10^{-5}$ (Section 13.6 in **SR-Site main report**). For such short periods, the LDFs do not give a reasonable representation of consequences of a radionuclide release to the biosphere. That is, the LDFs represent an upper bound of consequences from an approximately constant release during a full interglacial, or from a short pulse released at any time during an interglacial. The release that would result from an earthquake in the near future would on the other hand occur when a large part of the present interglacial period has elapsed (and hence not contribute to accumulation in the biosphere) and the release rate would vary continuously over time.

Thus, to calculate the consequences from a failure due to an earthquake that occurs for times up to 1,000 years after the repository is sealed, the near-field release was used as a time dependent input parameter to the radionuclide model. For these simulations it was assumed that each landscape object received the full release, and dose curves were generated for each biosphere object. By selecting, for each radionuclide individually, the maximum dose over all biosphere objects for each point in time, a dose curve representing the landscape was generated for each nuclide (Figure 10-5). These results are presented and discussed in Section 13.6 in the **SR-Site main report**, as a part of the shear load scenario.

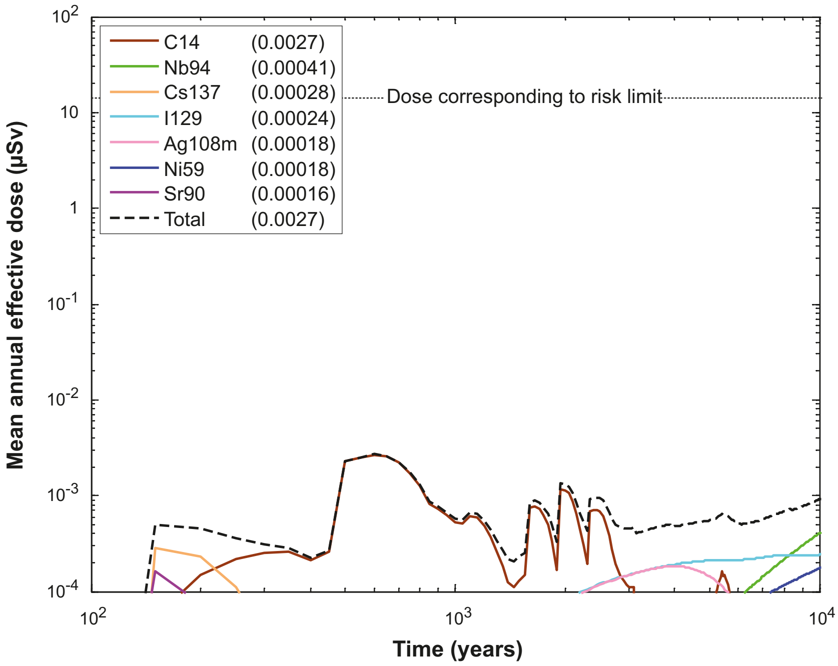

Figure 10-5. *Mean annual effective dose from probabilistically calculated consequences of shear failure occurring randomly during the initial 10,000 years. The peaks correspond to the time of the transition period between the sea and lake stage for different biosphere objects in the Forsmark landscape. Figure from Section 13.6 in* ***SR-Site main report****.*

10.3.3 Residual scenarios to illustrate barrier functions

The radionuclide model has also been applied to illustrate the barrier function of the repository for a number of hypothetical release scenarios, where losses of barrier function are assumed already at deposition (see Section 13.7 in **SR-Site main report** for details). These hypothetical residual scenarios include one failure mode where an initial defect in the canister copper shell of each canister grows into a larger defect, and also calculation cases where there is a large opening in the copper shell of all canisters.

In the above scenarios *all* canisters contribute to the release of radionuclides to the biosphere and the assumption that the entire release will reach one biosphere object (as in the LDF calculations) is clearly not valid. For these scenarios it was instead assumed that the release of radionuclides would be distributed over all identified discharge areas in the landscape, and that each biosphere object would get a release proportional to the fraction of release points in the object, at each point in time.

To assess consequences in the period directly after closing the repository, the release was used as a time dependent input parameter to the radionuclide model (see above). Dose curves were generated for each biosphere object. By selecting the maximum dose over all biosphere objects for each point in time a dose curve representing the landscape was generated for each nuclide.

To assess periods far into the future, when the release is expected to vary little within time spans of 10,000 years, a constant unit release was distributed over the Forsmark landscape. LDFs were then calculated in accordance with the methods described in Chapter 8. That is, the LDF for each radionuclide was defined as the maximum dose over all biosphere objects and time points during a full interglacial.

10.4 Natural concentrations of radionuclides in surface ecosystems

A comparison between the background levels of radionuclides which occur naturally in the environment, and the activity concentrations resulting from a potential release from the repository, may give an indication of the extent to which the exposure of humans and organisms living in the Forsmark area would be affected by a potential release. Below follows an attempt to compare measured activity concentrations of naturally occurring radionuclides in Forsmark, in the previously considered Laxemar site, and in a number of reference sites /Aastrup 1981, Porcelli et al. 2001, UNSCEAR 2010/, with the calculated concentrations resulting from a release according to the central corrosion case.

The naturally occurring radioactive isotopes that contribute the most to the alpha activity in natural waters are U-238, U-234, Ra-226 and its daughter products and Po-210 /Östergren et al. 2003/. Data from the site investigations also confirm that uranium isotopes (U-234, U-235, U-238), and daughter products from the decay of uranium (Ra-226, Th-230), contribute to a significant part of the total background activity concentrations in surface water, sediments and soil in the Forsmark area today /Tröjbom and Grolander 2010/. Deep groundwater, which is enriched in uranium and radium isotopes (as compared to surface water), is a potential source of the activity concentration presently found in the environment in Forsmark, and natural fluxes of U-238, U-234 and Ra-226 to the investigation area has been estimated to be $4.7 \cdot 10^5$ Bq/yr, $1.2 \cdot 10^6$ Bq/yr and $7.6 \cdot 10^6$ Bq/yr, respectively (**Radionuclide transport report**). Thus, isotopes of uranium, thorium and radium were used to compare background levels of radionuclides with those expected to result from a potential release from the repository.

The activity concentrations resulting from a constant release of radionuclides to natural ecosystems in potential discharge areas in Forsmark were calculated with the radionuclide model, assuming the maximum release for each radionuclide given the central corrosion case /Avila et al. 2010/. The maximum activity concentrations in surface water, near surface groundwater and upper regolith across all biosphere objects were extracted, considering a full interglacial period. In addition, calculated peak values for Biosphere object 136 (Lake Bolundsfjärden) were used to contrast calculated activity concentrations resulting from a release into a discharge area which is well represented in site data.

The natural activity concentrations in surface water observed in Forsmark and Laxemar, and in reference sites available in the literature /Porcelli et al. 2001/, were all several orders of magnitude higher than the expected contribution from a potential release from the repository to sea and lake water (Table 10-3). Similarly, the background activity concentrations near surface groundwater at the two investigated sites and in samples collected across Sweden /Aastrup 1981/ were orders of magnitude higher than the expected contribution from a repository release.

A comparison between measured activity concentrations in upper regolith and calculated concentrations resulting from a release yielded similar results. That is, the natural activity concentrations observed at Forsmark and Laxemar were several orders of magnitude higher than those expected to result from a potential release from a repository at Forsmark (Table 10-4). This was also true for the comparison of calculated activity concentrations in peat with that reported for top soils in Northern Europe /UNSCEAR 2010/. Thus, it can be concluded that the natural background radiation from uranium, thorium and radium in potential discharge areas in Forsmark would not be significantly affected by a release of these radionuclides from the repository.

Table 10-3. Calculated activity concentrations in lake and sea water and in near surface groundwater, resulting from a release of radionuclides given the central corrosion case. Activity consentrations are compared with measured concentrations (median values) from Forsmark and Laxemar and from reference sites available in the literature /Porcelli et al. 2001, Aastrup 1981/.

	Calculated concentrations from a release		Measured background concentrations		
Radionuclide (Bq/l)	**Biosphere object 136**	**Max across all biosphere objects**	**Forsmark**[1)]	**Laxemar**[2)]	**Literature**
Lake water					
Ra-226	$4.5 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$	$6.0 \cdot 10^{-3}$		$4.6 \cdot 10^{-4}$ [3)]
Th-230	$1.6 \cdot 10^{-12}$	$1.1 \cdot 10^{-11}$	$4.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-3}$	
Th-232	$1.3 \cdot 10^{-16}$	$1.1 \cdot 10^{-16}$	$2.0 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$8.2 \cdot 10^{-5}$ [3)]
U-234	$1.0 \cdot 10^{-10}$	$4.0 \cdot 10^{-10}$	$1.7 \cdot 10^{-2}$	$7.3 \cdot 10^{-3}$	
U-235	$9.9 \cdot 10^{-12}$	$2.7 \cdot 10^{-11}$	$6.2 \cdot 10^{-4}$	$3.2 \cdot 10^{-4}$	
U-238	$1.1 \cdot 10^{-10}$	$2.9 \cdot 10^{-10}$	$1.5 \cdot 10^{-2}$	$6.3 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$ [3)]
Sea water					
Ra-226	$3.1 \cdot 10^{-9}$	$7.2 \cdot 10^{-9}$	$3.1 \cdot 10^{-3}$		$1.1 \cdot 10^{-3}$ [3)]
Th-230	$5.0 \cdot 10^{-17}$	$4.2 \cdot 10^{-15}$	$3.5 \cdot 10^{-4}$	$8.2 \cdot 10^{-4}$	
Th-232	$2.8 \cdot 10^{-21}$	$2.3 \cdot 10^{-20}$	$1.6 \cdot 10^{-4}$	$5.4 \cdot 10^{-4}$	$3.1 \cdot 10^{-6}$ [3)]
U-234	$9.6 \cdot 10^{-14}$	$3.0 \cdot 10^{-12}$	$1.8 \cdot 10^{-2}$	$8.3 \cdot 10^{-3}$	
U-235	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-13}$	$2.9 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$	
U-238	$9.8 \cdot 10^{-14}$	$2.1 \cdot 10^{-12}$	$1.5 \cdot 10^{-2}$	$6.4 \cdot 10^{-3}$	
Near surface groundwater					
Ra-226	$4.2 \cdot 10^{-5}$	$4.4 \cdot 10^{-4}$	$7.2 \cdot 10^{-2}$	$5.9 \cdot 10^{-2}$	$4.2 \cdot 10^{-3}$ [4)]
Th-230	$1.8 \cdot 10^{-10}$	$1.8 \cdot 10^{-9}$	$1.7 \cdot 10^{-3}$	$4.2 \cdot 10^{-3}$	
Th-232	$1.3 \cdot 10^{-14}$	$1.3 \cdot 10^{-13}$	$9.0 \cdot 10^{-4}$	$2.7 \cdot 10^{-3}$	
U-234	$6.8 \cdot 10^{-9}$	$7.1 \cdot 10^{-8}$	$8.8 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$	
U-235	$6.7 \cdot 10^{-10}$	$6.9 \cdot 10^{-9}$	$2.5 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	
U-238	$7.5 \cdot 10^{-9}$	$7.7 \cdot 10^{-8}$	$7.4 \cdot 10^{-2}$	$2.1 \cdot 10^{-2}$	

[1)] /Tröjbom and Grolander 2010/, [2)] /Roos et al. 2007/, [3)] /Porcelli et al. 2001/, [4)] /Aastrup 1981/

Table 10-4. Calculated activity concentrations in sediments and soil, resulting from a release of radionuclides given the central corrosion case. Activity consentrations are compared with measured concentrations (median values) from Forsmark and Laxemar and from reference sites available in the literature /UNSCEAR 2010/.

	Calculated concentrations from a release		Measured background concentrations		
Radionuclide (Bq/l)	**Biosphere object 136**	**Max across all biosphere objects**	**Forsmark**[1)]	**Laxemar**[2)]	**Literature**
Limnic sediment					
Ra-226	$2.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-2}$	$3.6 \cdot 10$	$7.0 \cdot 10$	
Th-230	$9.4 \cdot 10^{-8}$	$2.9 \cdot 10^{-6}$	$2.9 \cdot 10$	$2.8 \cdot 10$	
Th-232	$7.3 \cdot 10^{-12}$	$3.1 \cdot 10^{-11}$	$2.0 \cdot 10$	$2.4 \cdot 10$	
U-234	$7.4 \cdot 10^{-7}$	$2.3 \cdot 10^{-5}$	$1.3 \cdot 10^{2}$	$1.6 \cdot 10^{2}$	
U-235	$7.2 \cdot 10^{-8}$	$1.5 \cdot 10^{-6}$	5.3	6.2	
U-238	$8.1 \cdot 10^{-7}$	$1.6 \cdot 10^{-5}$	$1.1 \cdot 10^{2}$	$1.3 \cdot 10^{2}$	
Marine sediment					
Ra-226	$3.5 \cdot 10^{-4}$	$6.4 \cdot 10^{-4}$	8.5	8.5	
Th-230	$2.1 \cdot 10^{-9}$	$6.8 \cdot 10^{-8}$	5.6	$2.7 \cdot 10$	
Th-232	$1.2 \cdot 10^{-13}$	$3.8 \cdot 10^{-13}$	5.8	$2.6 \cdot 10$	
U-234	$2.2 \cdot 10^{-8}$	$3.4 \cdot 10^{-7}$	8.5	$9.9 \cdot 10$	
U-235	$2.0 \cdot 10^{-9}$	$2.2 \cdot 10^{-8}$	$3.8 \cdot 10^{-1}$	4.0	
U-238	$2.2 \cdot 10^{-8}$	$2.4 \cdot 10^{-7}$	8.0	$8.1 \cdot 10$	
Top soil					
Ra-226	$2.2 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$	$3.9 \cdot 10$	$1.6 \cdot 10$	2–1000 [3)]
Th-230	$1.8 \cdot 10^{-7}$	$2.4 \cdot 10^{-6}$	$1.7 \cdot 10^{-5}$	5.6	
Th-232	$1.4 \cdot 10^{-11}$	$1.8 \cdot 10^{-11}$	9.6	4.5	0.5–115 [3)]
U-234	$1.3 \cdot 10^{-6}$	$8.6 \cdot 10^{-6}$	$5.1 \cdot 10$	$4.8 \cdot 10$	
U-235	$1.3 \cdot 10^{-7}$	$5.7 \cdot 10^{-7}$	1.8	1.8	
U-238	$1.5 \cdot 10^{-6}$	$6.1 \cdot 10^{-6}$	$4.6 \cdot 10$	$3.4 \cdot 10$	10–1000 [3)]

[1)] /Tröjbom and Grolander 2010/, [2)] /Roos et al. 2007/, [3)] /UNSCEAR 2010/

11 Assessment of impact on non-human biota

The aim of this chapter is to summarise the assessment of the impact on non-human biota of potential radioactive releases from the high-level waste repository planned at Forsmark, in order to ensure adequate protection of the environment /Torudd 2010/. Doses to reference organisms corresponding to species of interest at the site were calculated with the ERICA software tool, assuming release under the central corrosion case (see Secation 3.5.4 in **SR-Site main report**). Results were assessed in the light of regulations and requirements of the Swedish Radiation Safety Authority concerning protection of the environment /SSM 2008a/.

11.1 Background

Attitudes concerning the protection of animals and plants from deleterious effects of ionising radiations have changed considerably over the last 35 years. Up until around 1975, the issue was entirely ignored. As a next stage, the 1977 Recommendations of ICRP /ICRP 1977/ made the assumption that if man is adequately protected, then other living things are also likely to be sufficiently protected, and essentially the same attitude was taken in the 1990 ICRP Recommendations /ICRP 1991/. The 2007 ICRP Recommendations /ICRP 2007/, however, include a systematic approach for radiological assessment of non-human species. This was not driven by any particular concern over environmental radiation hazards. It was meant to fill a conceptual gap in radiological protection, and to develop a protection policy in line with society's general goals for environmental protection.

However, the objectives of such a protection policy for non-human biota are not yet as clear as those of human radiological protection, which aims to prevent deterministic tissue reactions and reduce stochastic effects as much as reasonably achievable. /ICRP 2007/ suggests that the aim should be a negligible effect on the maintenance of biological diversity, the conservation of species, and the health and status of natural habitats, communities, and ecosystems. In line with this, /ICRP 2008/ notes that the biological endpoints of most relevance in individuals after radiation exposure will be those that could lead to changes in population size or structure.

/ICRP 2008/ goes on to say that some form of practical means is required to translate knowledge of the effects of radiation on different types of animals and plants into advice on management decisions and judgements that may be needed. To this end, ICRP proposes the use of a limited set of Reference Animals and Plants to serve as a basis for the understanding and interpretation of the relationships between exposure and dose, and between dose and certain categories of effect, for a few, clearly defined types of animals and plants.

Furthermore, /ICRP 2008/ notes that "dose limits" of the form used in human radiological protection would be inappropriate, but that some form of numerical guidance is required, and sets out proposed bands of "derived consideration reference levels". Within these bands, there is likely to be some chance of deleterious effects of ionising radiation to the pertinent Reference Animal or Plant that could be used to optimise protection efforts (and by inference, below these bands the risks would appear to be negligible).

In parallel and aligned with these developments, a series of major research projects (EPIC, FASSET, ERICA, PROTECT) concerning these issues has been funded under the European Commission Euratom Framework programmes. SKB participated in the FASSET and ERICA project. An overview of the entire series and detailed descriptions of each project, including links to the resulting scientific publications, are available at the *erica-project.org* web site. The project programme generated the ERICA Integrated Assessment approach and the ERICA tool used in the present study and described in Chapter 12. The screening dose rate used in the ERICA tool is, again, not a "dose limit". It is an instrument to assist in the separation of situations of negligible concern from those situations where it is appropriate to pause for reflection to consider whether any concern is warranted. Thus, the ERICA screening dose rate and the ICRP derived consideration level serve much the same purposes.

The current awareness of environmental protection issues has emerged over about a decade, and the policy advice of ICRP and the practical tools provided by the Euratom research framework programmes were generated over that time-scale. However, the present study is one of the very first cases where the policy and the tools are applied to a practical case where the results are intended to form part of the underpinning of a license application for the localisation of a repository for spent nuclear fuel.

11.2 Methodology

The assessment of the environment has been carried out by evaluating the potential effects of a radionuclide release on individual organisms. The rationale for this approach is the assumption that if there are no detrimental effects at the level of individuals, then negative consequences at the population, community or ecosystem levels can also be excluded.

For the assessment, radionuclide release from the geosphere was used as input to the radionuclide model for the biosphere (Chapter 8). Radionuclide activity concentrations in environmental media in discharge areas in the Forsmark landscape were then simulated for an interglacial (Figure 11-1).

The activity concentrations in water and sediments in freshwater and marine ecosystems, and in peat and air in wetland ecosystems were used as input in the ERICA tool /Brown et al. 2008/ to obtain activity concentrations in selected organisms.

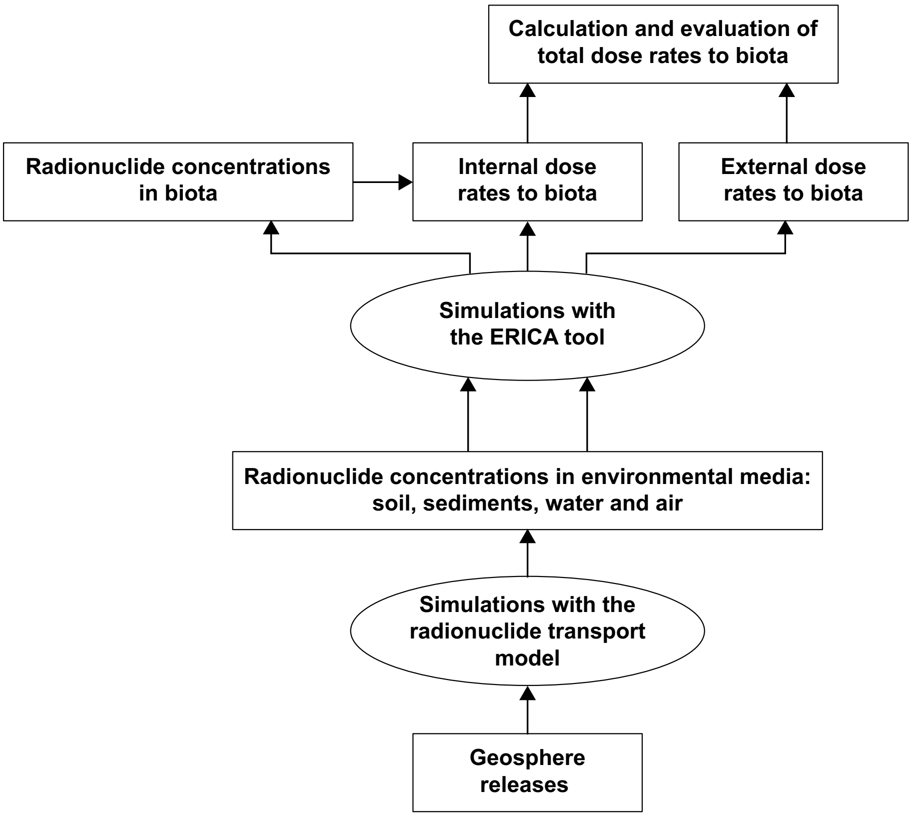

Figure 11-1. *Assessment of the consequences of radionuclide releases for non-human biota. The assessent starts by calculating radionuclide concentrations in environmental medias. These concentrations are then used as input data to the ERICA tool, and the resulting dose rates are compared to a screening dose rate. Each step in the calculation procedure are explained in Sections 11.2.1 to 11.2.8 below, and details are provided in /Torudd 2010/. Figure from /Torudd 2010/.*

The ERICA tool calculates the internal dose rates to biota from modelled activity concentrations in the different organisms, and estimates the external dose rates from the activity concentrations in environmental media. The numerical endpoint of the consequence assessment is the total absorbed dose rate to the selected organism from each radionuclide considered in the assessment. Finally, the sum of the dose rates was evaluated against a screening dose rate, corresponding to the lowest dose rate that potentially may lead to detrimental effects on individual organisms, (i.e. a no-effects dose rate).

11.2.1 Radionuclides considered in the assessments

The list of radionuclides considered in the assessment is presented in Table 11-1. This list covers all nuclides included in the SR-Site safety assessment, with the exceptions of Ac-227, Pa-231and Pd-107. For these three nuclides neither site nor literature data were available with respect to biological uptake (i.e. CR), precluding a meaningful analysis. Most of the 37 radionuclides (of 24 elements) included in the assessment are present by default in the ERICA tool, but some isotopes, shown in italics in Table 11-1, were added to the ERICA database.

11.2.2 Organisms considered in the assessments

In order to prevent or reduce the frequency of deleterious radiation effects in the environment to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities and ecosystems, there is a need to relate exposure to dose, dose to effect, and effect to consequences /ICRP 2008/. To permit such analyses, the ERICA tool uses a small, well-defined set of data for the *reference organisms*. Each reference organism has its own specified geometry and selection of habitat in terrestrial, freshwater or marine ecosystems. The approach is compatible with that used by ICRP, and some of the geometries proposed for the ICRP "Reference Animals and Plants" /ICRP 2008/ are used as defaults in the ERICA tool.

Species that are presently found in the Forsmark area were the primary target for the SR-Site assessment. To ensure that ecosystem functioning is protected, organisms playing a critical role (key-stone species) or being very abundant (foundation species) and representing different functional groups, were identified. In addition, species that have an economic importance to man (e.g. livestock, fish and game) or a conservation value (e.g. endemic and endangered species) were identified.

The assessment was limited to species occurring in marine and freshwater ecosystems and in wetlands, since it was expected that these are the natural ecosystem types that may be most affected by potential releases (Chapter 7). Agricultural ecosystems were not considered in the analysis. This was because future contaminated agricultural land in Forsmark is likely to originate from drained wetland, and these agricultural soils are expected to be productive (and thus provide a stable environment) for 100 years or less (Section 8.3.3). Thus, the species associated with this land would either be introduced by humans (crop or livestock), or invade from adjacent agricultural land and consequently they would be part of large and more stable biological populations.

Table 11-1. Elements and radionuclides considered in the assessments. Entries in italics were added to the default database of the ERICA tool /Torudd 2010/.

Element	Radionuclide	Element	Radionuclide
Ag	Ag-108m	Pb	Pb-210
Am	Am-241, *Am-243*	Po	Po-210
C	C-14	Pu	Pu-239, Pu-240, *Pu-242*
Ca	*Ca-41*	Ra	Ra-226
Cl	Cl-36	Se	Se-79
Cm	Cm-244, *Cm-245*, Cm-246	*Sm*	*Sm-151*
Cs	Cs-135, Cs-137	*Sn*	*Sn-126*
Ho	*Ho-166m*	Sr	Sr-90
I	I-129	Tc	Tc-99
Nb	Nb-94	Th	*Th-229*, Th-230, Th-232
Ni	Ni-59, Ni-63	U	*U-233*, U-234, U-235, *U-236*, U-238
Np	Np-237	Zr	*Zr-93*

For most of the identified species of interest, site and literature data were lacking. Instead, each species was mapped to a reference organism of similar taxonomy within the appropriate ecosystem. The mapping of functional and dominant species and economically important species can be found in Table 11-2 and Table 11-3 respectively. Identified endangered or "red-listed" species (~100 species) and their corresponding reference organisms are listed in /Torudd 2010/.

According to /Beresford et al. 2007/, the selection of reference organisms included in the ERICA tool makes it possible to address all protected species within Europe. Nevertheless, to increase the confidence in the analysis, a number of common species currently found in Forsmark were also included.

For most of the species sampled at the site, concentration ratios for a number of radionuclides (CR, see below) and morphology were available from the site investigation or could be determined. However, most species were represented by a few individuals only (typically three or less). Thus, it was unlikely that the field data would capture the large inherent variability in the equilibrium concentration ratios at the species level /Sheppard 2005/, and consequently the assessment was primarily founded on ERICA reference organisms.

Table 11-2. Organisms with important ecosystem functions in the Forsmark area. English and scientific names are listed together with the corresponding ERICA reference organisms. Ecosystem indicated by capital letter (F = freshwater, M = marine, T = terrestrial). N.A. = no related species sampled at the site.

English names	Swedish names	Scientific names	ERICA reference organism
Terrestrial			
alder	klibbal	*Alnus glutinosa*	Tree
bottle sedge	flaskstarr	*Carex rostrata*	Grasses and herbs
common frog	vanlig groda	*Rana temporaria*	Amphibia
Norwegian spruce	gran	*Picea abies*	Tree
peat moss	vitmossa	*Sphagnum* spp.	Lichen and bryophytes
pine tree	tall	*Pinus silvestris*	Tree
red fox	rödräv	*Vulpes vulpes*	Mammal
reed	vass	*Phragmites australis*	Grasses and herbs
water vole	vattensork	*Arvicola terrestris*	Mammal
Fresh water			
chara	kransalg	*Chara* spp.	Vascular plant
microphytobenthos	zooplankon		Zooplankton
midge	fjädermygga	*Tanypodinae*	Insect larvae
pike	gädda	*Esox lucius*	Pelagic fish
perch	aborre	*Perca fluviatilis*	Pelagic fish
reed	vass	*Phragmites australis*	Vascular plant
roach	mört	*Rutilus rutilus*	Pelagic fish
ruffe	gärs	*Gymnocephalus cernua*	Pelagic fish
tench	sutare	*Tinca tinca*	Pelagic fish
Marine			
Baltic macoma	Östersjömussla	*Macoma balthica*	Benthic mollusc
bladder wrack	blåstång	*Fucus vesiculosus*	Macroalgae
duck mussel	allmän dammussla	*Anodonta anatina*	Bivalve mollusc
herring	strömming	*Clupea harengus*	Pelagic fish
idothea	gråsugga	*Idothea* spp.	Crustacean
phytoplankton	phytoplankton		Phytoplankton
perch	aborre	*Perca fluviatilis*	Pelagic fish
tench	sutare	*Tinca tinca*	Pelagic fish
zooplankton	zooplankton		Zooplankton

Table 11-3. Economically important organisms in the Forsmark area. English and scientific names are listed together with the corresponding ERICA reference organisms. Ecosystem indicated by capital letter (F = freshwater, M = marine, T=terrestrial).

English names	Swedish name	Scientific names	ERICA reference organism
Terrestrial			
cloudberry (T)	hjortron	*Rubus chamaemorus*	Grasses and herbs
cranberry (T)	tranbär	*Vaccinium oxycoccus*	Grasses and herbs
Norwegian spruce (T)	gran	*Picea abies*	Tree
Peat moss (T)	vitmossa	*Sphagnum sp*	Lichen and bryophytes
Pine tree (T)	tall	*Pinus silvestris*	Tree
Sedges (T)	starr	*Carex sp*	Grasses and herbs
Fresh water			
tench (F)	sutare	*Tinca tinca*	Pelagic fish
Marine			
burbot (M)	lake	*Lota lota*	Benthic fish
common eider (M)	ejder	*Somateria mollissima*	Bird (duck)
eel (M)	ål	*Anguilla anguilla*	Pelagic fish
herring (M)	strömming	*Clupea harengus*	Pelagic fish
lumpsucker (M)		*Cyclopterus lumpus*	Benthic fish
perch (F, M)	aborre	*Perca fluviatilis*	Pelagic fish
pike (F, M)	gädda	*Esox lucius*	Pelagic fish
ringed seal (M)	vikarsäl	*Pusa hispida*	Mammal

11.2.3 No-effect dose rate

The basic quantity for estimating exposure to ionising radiation is the amount of absorbed energy per unit mass, i.e. the absorbed dose. For assessment of radiological effects on biota, the whole-body exposure is considered, and the exposure is related to effects on traits such as survival, growth and reproduction. The sensitivity of the individual organism to exposure is likely to vary between ecosystems and taxonomic groups. Moreover, radiological effects at the population level may be affected by species differences in habitat size, life history strategies and population dynamics. However, data and knowledge are currently not sufficient to derive consistent and robust screening values for separate organism groups, and best practice for judging the level of environmental risk is to contrast estimated dose rates against a generic no-effect dose level /Howard et al. 2010/. In this assessment the no-effect incremental dose rate of 10 μGy h^{-1} was used.

This value is the default screening criterion in the ERICA tool and has been derived from a distribution analysis of species sensitivity on reproductive traits in vertebrates, invertebrates and plants, performed on the basis of chronic exposure data /Andersson et al. 2009/. Howard and co-workers /Howard et al. 2010/ reviewed the numerical criteria for protection of non-human biota, and recommended use of the 10 μGy h^{-1} criteria. Furthermore, this screening value is below the bands of "derived consideration levels" proposed by /ICRP 2008/.

11.2.4 Dose assessments using the ERICA tool

The ERICA tool is a software package that supports the ERICA Integrated Approach to assessing the safety of the environment. The approach provides guidelines on problem formulation, impact assessment and data evaluation. The ERICA tool guides the user through the assessment process, keeps records and performs the calculations to estimate whole body dose rates to selected organisms. The tool considers the majority of the radionuclides included in ICRP Publication 38 /ICRP 1983/, and interacts with the FREDERICA database on radiation effects, which is a compilation of the scientific literature on radiation effect experiments and field studies.

The assessment element is organised in three separate *tiers* with increasing complexity. When the effects are not shown to be negligible in a lower tier, the assessment should continue to the next tier. To permit the use of site-specific organism data (CR and geometries) and the addition of some radionuclides, Tier 2 was used as the entry point in the SR-Site assessment.

Tier 2 assessment

In Tier 2, Risk Quotients (RQ) are calculated for each organism and each radionuclide according to the relationship:

$RQ_i = D_i / D_{lim}$

where D_i = the estimated whole-body absorbed dose to organism *i*, and D_{lim} = the projected no-effect ("screening") dose rate. RQ_i values were summed over all radionuclides to obtain total RQ values for each organism.

The output from the Tier 2 assessments were 1) "expected" RQs obtained by deterministic calculations using mean values for all parameters, and 2) "conservative" RQs (95th percentile, assuming an exponential distribution of dose rates) obtained by multiplying the "expected" RQ by an uncertainty factor.

If all "conservative" RQ's are less than one, the situation is likely to be of negligible radiological concern. If some "conservative" RQ's exceed one, but all "expected" RQs are less than one, the results and assessments needs to be reviewed. Finally, if any "expected" RQ exceeds one, then further assessment using Tier 3 is warranted.

Probabilistic simulations

To examine the effect of parameter uncertainty on the estimate of total absorbed dose rates, probabilistic simulations were carried out with probability density functions (PDF) for the concentration ratios (CR) and mean values for all other model parameters. PDFs for reference organisms were based on data from the ERICA tool. For each radionuclide and organism, the mean values, standard deviation, median, and different percentiles of the dose rates were calculated from the probabilistic simulations.

11.2.5 Representation of organisms

There is an enormous diversity of organisms with respect to size, morphology and habitat choice. To allow dosimetric calculations that cover a wide range of exposure situations, the ERICA tool has made a number of simplifications with respect to the representation of organisms. Thus, the shapes of organisms are approximated by spheres or ellipsoids. In addition, the habitat selection of organisms is assigned to one of ten habitat types, namely: in-soil, and on-soil (including in-air) in terrestrial ecosystems, and in-sediment, on surface-sediment, in water-column, and on water-surface in fresh water and marine ecosystems, respectively. For the SR-Site assessment it was further assumed that organism density was the same as that of water for all evaluated organisms.

11.2.6 Activity concentrations in biota

Plant root uptake from contaminated soil, ingestion of contaminated food and water, and inhalation of contaminated air will result in an internal activity concentration of radionuclides. In the ERICA tool, whole-body activity concentrations in biota are predicted directly from the activity concentrations in the environmental media, using equilibrium concentration ratios (CRs). For terrestrial biota, the CRs are defined as the radionuclide activity concentration in whole-body (Bq kg^{-1} fresh weight) divided by the radionuclide activity concentration in soil (Bq kg^{-1} dry weight) or in air (Bq m^{-3}) for ^{3}H, ^{14}C, ^{32}P and ^{35}S. For aquatic biota, the CRs are defined as the activity concentration in biota whole body (Bq kg^{-1} fresh weight) divided by the activity concentration in filtered water (Bq l^{-1}).

Most CRs estimated in this study are based on measured values of stable element concentrations in biota and environmental media, reported in /Tröjbom and Nordén 2010/. The number of available samples used to calculate CRs were typically limited to three or less on the species level.

11.2.7 Dosimetry

Radionuclides in the environment lead to both internal and external exposure of organisms. In the ERICA tool, the *internal* absorbed dose rate (μGy h^{-1}) in biota is a function of whole-body activity concentrations (see above), size of organism and the type and energy of emitted radiation. Absorbed dose rate from *external* radiation depends in addition on the contamination level in and the properties of the environment. Below is a brief description of the methods used for calculating dose conversion factors in the ERICA tool. A detailed description of the underlying approaches and the data that have been applied in the dosimetric module of the ERICA tool is presented in /Ulanovsky et al. 2008/.

Calculation of Dose Conversion Coefficients

Dose Conversion Coefficients (DCCs) are defined as the internal absorbed dose rates (μGy h^{-1}) per unit activity concentration in an organism (Bq kg^{-1} fw) or as the external absorbed dose rates (μGy h^{-1}) per unit concentration in environmental media (Bq kg^{-1} fw or Bq l^{-1}) /Pröhl 2003/. Dose conversion factors are specific with respect to organism (size and habitat) and radionuclide (type and energy of emitted radiation, decay chain).

For internal exposure, the radioactivity is assumed to be homogenously distributed in the whole body, and individual tissues or organs are not considered. Moreover, the fraction of the emitted energy per transformation in the body that is absorbed (i.e. DCC_{int}) does not depend on properties of the environment. In the derivations of DCCs, α-, β-, and γ-radiation are treated separately and different radiation weighting factors are applied for the radiation types. In this study, the default weighting factors 10, 3 and 1 were used for α-radiation, low-β energy radiation, and γ-radiation plus higher-energy β-radiation, respectively.

For external exposure, DCCs are calculated separately for the different environmental media water, soil/sediments and air. The external dose conversion factor for an organism (DCC_{ext}) is calculated by combining media-specific DCCs according to the fraction of time that an organism spends in each habitat.

The external DCC values depend on radioactive decay properties (which is radionuclide-specific), the geometrical relationship between the source of radiation and the target organism, the composition and shielding properties of materials or media in the environment, and the habitat and size of the organism. For external radiation, only β- and γ-radiations are considered. That is because external exposure of macroscopic organisms by short-range radiation (α and low energy β) is limited due to weak penetration.

For all radionuclides of interest for this study, DCC-values were calculated for reference organisms and for species from the site using the interpolation procedure available within the ERICA tool. The details for these calculations are provided in /Torudd 2010/.

11.2.8 Activity concentrations in environmental media

The basic assumption of the SR-Site assessment is that some degree of failure of the barriers at the repository will lead to a release of radionuclides. The activity concentrations in environmental media that would result from such a release constitute the primary input to the ERICA tool. For each assessed radionuclide (Table 11-1), such input data were obtained by taking the maximum far-field release for the central corrosion case during the simulation period of 1 million years (**SR-Site main report**), and apply it as a constant release rate to the biosphere of Forsmark. The radionuclide model for the biosphere (Chapter 8) was used to run the biosphere simulations through an interglacial (~20,000 years) for all biosphere objects in the Forsmark landscape.

The output from the model was radionuclide concentrations in upper regolith (peat and sediment), air (for C-14), and water (freshwater and marine) as a function of time for each biosphere object. For each radionuclide and environmental media, the maximum values over all biosphere objects during the simulation period were used as input values for calculations of dose rates to biota with the ERICA tool /Torudd 2010/.

11.3 Resulting doses to non-human biota

For all investigated organisms the calculated dose rates were at least four orders of magnitude below the screening no-effect dose level of 10 μGy h^{-1} (Table 11-4). When the uncertainty of the dose rates was taken into account (by using the 95th percentile of the probabilistic simulations or by using the conservative RQ), the dose rates were still far below the no-effect dose rate. That is, for freshwater phytoplankton that received the highest dose rate, the deterministic dose rate was $3 \cdot 10^{-3}$, corresponding to a RQ of $3 \cdot 10^{-4}$. The 95th percentile of the dose rate was below 0.01 μGy h^{-1}, and the conservative risk quota was 10^{-3}. It was noted that the mean values from the probabilistic calculations were almost identical to the deterministic estimates (data not shown), which was expected as the arithmetic mean from the PDF of the CR parameters were used in the deterministic calculations.

Table 11-4. Whole body dose rates for terrestrial, fresh water and marine biota in Forsmark given the release from the central corrosion case. Estimates from deterministic calculations are given together with the 95th percentile from probabilistic simulations. Expected and conservative risk quotients are explained in Section 11.2.4.

Reference organsim	Dose rate (μGy h^{-1})		Risk Quotients	
	Deterministic estimate	95th percentile	Expected	Conservative
Terrestrial				
Amphibia	$2.9 \cdot 10^{-5}$	$5.9 \cdot 10^{-5}$	$2.9 \cdot 10^{-6}$	$8.7 \cdot 10^{-6}$
Bird	$2.7 \cdot 10^{-5}$	$5.9 \cdot 10^{-5}$	$2.7 \cdot 10^{-6}$	$8.1 \cdot 10^{-6}$
Detritivorous invertebrate	$6.4 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	$6.4 \cdot 10^{-6}$	$1.9 \cdot 10^{-5}$
Flying insect	$6.1 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	$6.1 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$
Gastropod	$5.9 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	$5.9 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$
Grasses and herbs	$3.7 \cdot 10^{-5}$	$8.5 \cdot 10^{-5}$	$3.7 \cdot 10^{-6}$	$1.1 \cdot 10^{-5}$
Mammal, large	$2.2 \cdot 10^{-5}$	$4.9 \cdot 10^{-5}$	$2.2 \cdot 10^{-6}$	$6.5 \cdot 10^{-6}$
Mammal, small	$2.5 \cdot 10^{-5}$	$5.2 \cdot 10^{-5}$	$2.5 \cdot 10^{-6}$	$7.6 \cdot 10^{-6}$
Lichen and bryophytes	$6.7 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$6.7 \cdot 10^{-5}$	$2.0 \cdot 10^{-4}$
Reptile	$2.9 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$	$2.9 \cdot 10^{-6}$	$8.6 \cdot 10^{-6}$
Shrub	$7.6 \cdot 10^{-5}$	$2.0 \cdot 10^{-4}$	$7.6 \cdot 10^{-6}$	$2.3 \cdot 10^{-5}$
Soil invertebrate	$6.3 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	$6.3 \cdot 10^{-6}$	$1.9 \cdot 10^{-5}$
Tree	$6.1 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	$6.1 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$
Fresh water				
Bird	$1.6 \cdot 10^{-5}$	$4.4 \cdot 10^{-5}$	$1.6 \cdot 10^{-6}$	$4.9 \cdot 10^{-6}$
Bivalve mollusc	$3.7 \cdot 10^{-4}$	$7.7 \cdot 10^{-4}$	$3.7 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$
Crustacean	$2.7 \cdot 10^{-4}$	$4.8 \cdot 10^{-4}$	$2.7 \cdot 10^{-5}$	$8.1 \cdot 10^{-5}$
Gastropod	$2.7 \cdot 10^{-4}$	$5.3 \cdot 10^{-4}$	$2.7 \cdot 10^{-5}$	$8.2 \cdot 10^{-5}$
Insect larvae	$1.9 \cdot 10^{-3}$	$5.1 \cdot 10^{-3}$	$1.9 \cdot 10^{-4}$	$5.6 \cdot 10^{-4}$
Mammal	$1.8 \cdot 10^{-5}$	$4.3 \cdot 10^{-5}$	$1.8 \cdot 10^{-6}$	$5.4 \cdot 10^{-6}$
Pelagic fish	$1.7 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$
Phytoplankton	$3.4 \cdot 10^{-3}$	$9.7 \cdot 10^{-3}$	$3.4 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$
Vascular plant	$5.2 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$5.2 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$
Zooplankton	$2.2 \cdot 10^{-4}$	$4.9 \cdot 10^{-4}$	$2.2 \cdot 10^{-5}$	$6.5 \cdot 10^{-5}$
Marine				
Benthic fish	$1.1 \cdot 10^{-6}$	$1.8 \cdot 10^{-6}$	$1.1 \cdot 10^{-7}$	$3.4 \cdot 10^{-7}$
Benthic mollusc	$1.9 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$	$1.9 \cdot 10^{-7}$	$5.6 \cdot 10^{-7}$
Bird	$3.2 \cdot 10^{-7}$	$9.0 \cdot 10^{-7}$	$3.2 \cdot 10^{-8}$	$9.5 \cdot 10^{-8}$
Crustacean	$6.3 \cdot 10^{-7}$	$1.2 \cdot 10^{-6}$	$6.3 \cdot 10^{-8}$	$1.9 \cdot 10^{-7}$
Macroalgae	$1.4 \cdot 10^{-6}$	$1.8 \cdot 10^{-6}$	$1.4 \cdot 10^{-7}$	$4.3 \cdot 10^{-7}$
Mammal	$8.5 \cdot 10^{-8}$	$2.2 \cdot 10^{-7}$	$8.5 \cdot 10^{-9}$	$2.5 \cdot 10^{-8}$
Pelagic fish	$3.4 \cdot 10^{-7}$	$1.0 \cdot 10^{-6}$	$3.4 \cdot 10^{-8}$	$1.0 \cdot 10^{-7}$
Phytoplankton	$2.9 \cdot 10^{-6}$	$6.2 \cdot 10^{-6}$	$2.9 \cdot 10^{-7}$	$8.7 \cdot 10^{-7}$
Polychaete worm	$3.0 \cdot 10^{-6}$	$4.6 \cdot 10^{-6}$	$3.0 \cdot 10^{-7}$	$8.9 \cdot 10^{-7}$
Vascular plant	$1.3 \cdot 10^{-6}$	$1.9 \cdot 10^{-6}$	$1.3 \cdot 10^{-7}$	$4.0 \cdot 10^{-7}$
Zooplankton	$3.4 \cdot 10^{-7}$	$6.9 \cdot 10^{-7}$	$3.4 \cdot 10^{-8}$	$1.0 \cdot 10^{-7}$

Dose rates were also calculated for organisms from the site (based on morphology and CR from site data as far as possible) and the detailed results from these analyses are presented in /Torudd 2010/. For most individual species the sample size did not justify inference from these calculations to the safety assessment. Moreover, no substantive difference in calculated dose rates could be detected for ERICA reference organism when CRs from the site were used (as far as possible) as compared to calculations based entirely on generic data. Thus, the use of site data did not appreciably affect the calculated dose rate; primarily because site data was missing for major dose contributing radionuclides.

Comparisons of the concentration ratios (CR) from site data with CR for comparable ERICA reference organisms showed that the site data was reasonably well represented by the ERICA database for well investigated organisms (e.g. terrestrial vascular plants and marine pelagic fish) and elements. However, for organism groups that were less well represented in the database, CR for individual species from the site frequently fell outside the 95% interval of the distribution of the corresponding ERICA reference organism. This pattern was seen for all three ecosystems. Systematic differences could in most cases be attributed to the limited sample size or lack of representative samples in the database, but in a few cases there were indications that CR at the site showed site specific characteristics. For example, the CR for Pb and Cs were systematically lower in vascular plants, rodents and larger herbivores, possibly indicating that the transfer characteristics at the site was not fully captured by the average conditions reflected in the ERICA data. Similarly CR for U was systematically lower by one or two orders of magnitude in freshwater fish and plants at the site, possibly reflecting the naturally elevated concentrations of uranium at the site /Tröjbom and Grolander 2010/.

11.4 Discussion

The dose rates for all investigated ERICA reference organisms were found to be several orders of magnitude below the screening dose rate of 10 µGy h^{-1}. This suggests that the release under the central corrosion case would be of negligible concern for the protection of non-human biota in the Forsmark area. The uncertainty of calculated dose rates did not affect these results significantly.

It is not possible to sample endangered species living in the Forsmark area today, or to get site representative samples from species that are not presently found in the area. Thus, endangered species, species which are of economic or biological importance and species which are important for ecosystem function, were mapped to similar ERICA reference organisms as far as possible. Based on the analyses of these reference organisms, it is inferred that that the species of interest will also be subject to dose rates well below the screening criterion.

The comparison of transfer parameters and the limited effect of size and morphology on absorbed doses /Torudd 2010/, suggest that reference organisms give a sound representation of the species of interest. Moreover substitution of generic parameter estimates with site data did not affect the results in any significant way. Nevertheless, the comparison of transfer parameters high-lighted the importance of collecting sufficient measurements from the site, as the representation of a number of radionuclides and organism groups were limited in generic data, and as consistent differences between site and ERICA data existed.

There are only two scenarios in SR-Site that contribute to a significant release of radionuclides to the biosphere, namely the corrosion scenario and the shear load scenario (Chapter 3 and **SR-Site main report**). The consequences for biota were calculated for the central calculation cases of the corrosion scenario, but the conclusions can be generalised to encompass the whole corrosion scenario and the shear load scenarios. This is because the predicted release rates of dose contributing nuclides in the different release scenarios (and calculation cases) varies with less than an order of magnitude, (see Section 13.5.7 and 13.6.5 in **SR-Site main report**) and calculated dose rates were several orders of magnitude below the screening dose rate. In a similar study relating to the planned repository at Olkiluoto, /Smith and Robinson 2006/ identified some data gaps but concluded that the dose rates predicted for all organism types were several orders of magnitude below those at which population effects would be expected and, accordingly, below those at which effects on the individual may be anticipated. These general results agree with the results obtained in the present study.

The more complete and final study of the Olkiluoto case by /Hjerpe et al. 2010/ was performed using the full ERICA approach and tool, i.e. in a manner directly comparable to the present study. Their results concerning dose rates were similar and they concluded that any radiological consequences of releases from the repository would be negligible. In their study, Hjerpe and co-authors listed several remaining issues which were expected to require further work. Issues that are relevant for the SR-Site assessment include the use of ecosystem models vs. a transfer factor approach in radionuclide transport modeling, management of uncertainties, and difficulties in applying geometry constrain in the assessment of dose to non-human biota.

To some extent, the first issue agrees with the experience from the biosphere assessment in general, and the last two issues are applicable to the SR-Site assessment of non-human biota in particular. For example, in this assessment the maximum environmental concentrations across multiple discharge areas and points in time were cautiously used, instead of explicitly managing the uncertainties in the calculated environmental activity concentrations. Difficulties in the translation of species morphology to ellipsoidal geometries were also encountered for a few organism groups. However, morphology was shown to have little or insignificant effect on calculated dose rates of the organisms used in the assessment /Torudd 2010/.

Conclusion

Given that dose rates for all investigated organisms are far below the screening dose rate of 10 $\mu Gy\ h^{-1}$, and the fact that identified uncertainties were found to have no significant effect on these result, it follows that a potential release from the repository is highly unlikely to cause detrimental effects on the survival and reproduction of individual organisms. This conclusion can be generalised to the two significant release scenarios, and encompasses endangered species, species which are of economic or biological importance, as well as species which are important for ecosystem function. As no effects are expected on the level of the individual organism, effects on the level of populations, communities and ecosystems are also highly unlikely. Thus, from this assessment it is concluded that neither negative effects of the repository on biodiversity, nor sustainable use of natural resources in the Forsmark area are of concern. Nevertheless, SKB recognises that technical refinements of the methods used to assess the safety of non-human biota are ongoing, and SKB will keep the international developments under review and refine the methods of analysis as required.

12 The effect of uncertainties on the landscape dose conversion factors

The final risk estimate is built upon a number of assumptions and modelling results that are associated with different degrees of simplifications, uncertainties and degree of caution. The aim of this chapter is to discuss the end points of the biosphere modelling, the LDFs, and evaluate the consequensces of uncertainties in the light of results from altenative models and the knowledge gathered during the site investigations.

The first section outlines the background, scope and limits of this chapter. Then the three following sections examine the effect of system uncertainties, model uncertainties and parameter uncertainties respectively. The results are summarized and it is concludes that the effects of quantified uncertainties on LDF estimates are limited, and not expected to have any significant effect on assessment end-points. The last section considers methodological improvements for future biosphere assessments.

12.1 Background

Large amounts of site-specific information have been collected in order to better understand transport and accumulation of elements in the biosphere at the site. This understanding underpins conceptual and numerical models, and site data have been used to parameterise the radionuclide model used to calculate environmental concentrations and subsequent human exposure. Uncertainties enter all aspects of the data collection, interpretation, conceptual model formulation and mathematical implementation. In this chapter the effects of uncertainties on the calculated LDFs are examined.

Following the framework outlined by /Galson and Khursheed 2007/ uncertainties were categorised into three types: system uncertainties, model uncertainties and parameter uncertainties (see below). The consequences of uncertainties in LDF were evaluated by exploring the reasonability of assumptions, by formulating and quantitative comparing results with those resulting from alternative assumptions, models and parameters, and by performing Monte-Carlo simulations. The results from Monte-Carlo simulations were also used in sensitivity analyses to identify the parameters contributing most to uncertainty in the LDFs.

The description of uncertainties in the following text is primarily based on modelling of the long-term release during an interglacial. That is, the effect of system, model and parameter uncertainties are evaluated by contrasting the maximum LDF from the interglacial period (referred to as SR-Site LDF below) with an LDF resulting from an alternative model or set of assumptions. However, many of the uncertainties underpinning LDFs for long-term release are shared by the modified LDF for pulse release, since the major difference between the two is in the timing and duration of the release. The reader is referred results and discussions in /Avila et al. 2010/ for the effect of uncertainties that relates specifically to the timing and duration of a pulse release.

For the overall safety assessment, the mean annual dose is calculated by multiplying the radionuclide release to the biosphere with the LDF derived with the radionuclide model (Chapter 8). The impact to non-human biota is calculated using activity concentrations in environmental media delivered from the radionuclide model (Chapter 11), and consequently, many of the uncertainties in the LDF calculations are also relevant for the calculations of dose rates to non-human biota.

The discussions in this chapter are focused on long-lived radionuclides that are expected to contributing most to dose of future human inhabitants. Examples are most frequently drawn from the results of Ra-226 (including daughter nuclides Pb-210 and Po-210) and I-129, and to a lesser extent from Se-79, Np-237, Cs-135, and Cl-36. The first four of these radionuclides where selected because of their expected effect in long-term release (as indicated by the central corrosion case), where as Cs-135, and Cl-36 are primarily expected to contribute to dose in a pulse release (see Section 13.5.4 in **SR-Site Main report**).

12.2 System uncertainties

In the biosphere analysis, system uncertainties refer to uncertainties associated with the development of the biosphere and future human utilisation of natural resources. The handling of these two sources of uncertainty in the biosphere analysis is described and discussed below. The quantitative effects of system uncertainty on LDF used in SR-Site is summarised in Table 12-2 at the end of this section.

12.2.1 Development of the biosphere

The main features of the Forsmark landscape are primarily determined by bedrock topography. It is argued in Section 7.3.3 that the landscape development during the present ice-free period will give an acceptable representation also of the landscape development during future ice-free periods of repeated glacial cycles (see also /Lindborg 2010/).

Geometries of the landscape will change with glacial cycles, as bedrock is eroded the regolith is reworked by glacial and post-glacial processes. However the general geometrical patterns are expected to be similar and the identified biosphere objects span a wide range of sizes and positions in the landscape. Thus it is argued that the geometric properties of future objects will be captured in the variation of identified biosphere objects. Uncertainties with respect to depth and development of regolith layers were treated as parameter uncertainties, and consequently are handled in Section 12.4.2.

State of the biosphere object in relation to the timing and duration of release

The uncertainties with respect to timing and duration of releases reaching biosphere objects have been handled by assuming that the release from the repository will reach the assessed biosphere object (Section 8.1). The degree of cautiousness in this assumption was quantified by calculating LDF for the alternative and perhaps equally likely assumption that the release will only reach the biosphere object after isolation from the sea /Avila et al. 2010/. The simulations showed that accumulation during the sea stage had a significant effect on the maximum LDF on several (but not all) of the examined radionuclides. For example the LDFs for I-129 (Figure 12-1), Se-79, Cs-135 and Np-237 were four, three, two and 14 times lower, respectively, when no radionuclides were released under the sea stage as compared to the SR-Site LDF. For these nuclides the SR-Site handling of this uncertainty was clearly cautious.

Location of release

Uncertainty with respect to which of the biosphere objects will be affected by a release has been handled by assuming that the entire release will reach the biosphere object where the consequences will be the worst (Section 8.1). The degree of cautiousness in this assumption was quantified by calculating LDF for the alternative assumption that all identified biosphere objects are equally likely to receive the release /Avila et al. 2010/.

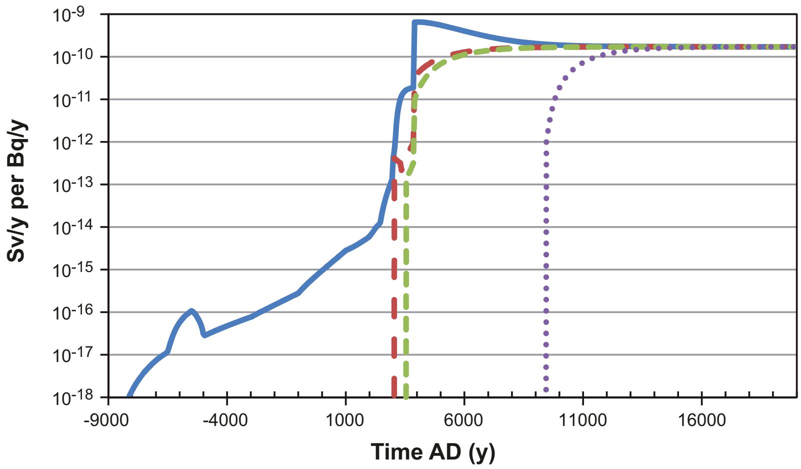

Figure 12-1. *Effect of start and duration of release on LDF for I-129. Annual dose per unit release is shown as a function of release start and time. In the simulations 1Bq/y was released to biosphere object 121_03 at the beginning of the interglacial period (blue line, SR-Site LDF), at the start and end of lake isolation (red and green lines respectively) or at the end of the interglacial period (purple line). Figure from /Avila et al. 2010/.*

The LDF clearly vary between biosphere objects, and the degree of variation depends on the properties of radionuclides (Section 10.2). Thus the difference between the maximum interglacial LDF and the expected value under the alternative assumption (i.e. the arithmetic mean, excluding object 105) was typically a factor two for radionuclides where drinking water was an important pathway for exposure (e.g. Ra-226). For radionuclides where exposure from food was the dominant pathway the LDF under the alternative assumption was between four (Cl-36) and nine (I-129) times smaller then the SR-Site LDF. Thus the handling of this uncertainty was clearly cautious in SR-Site.

Climate conditions – reference climate

In the SR-Site assessment the uncertainty of future climates has been handled by assuming that a reconstruction of the latest glacial cycle, (see *reference glacial cycle* in Section 6.2.1 and **Climate report**) will cover the climatic variations that is expected in the future. According to the reference glacial cycle, the initial period of a temperate climate domain will be followed by a 40,000 year ice free period, where episodes of temperate and periglacial domains will alternate.

A separate LDF was calculated assuming that radionuclides from contaminated groundwater would reach all biosphere objects during this period, but that the climate after the initial interglacial period would prevent agriculture and the use of well water due to deep permafrost (Section 8.7.2). From these simulations it was concluded that the maximum LDF from the period of temperate domain will not be exceeded in the subsequent period with colder climate.

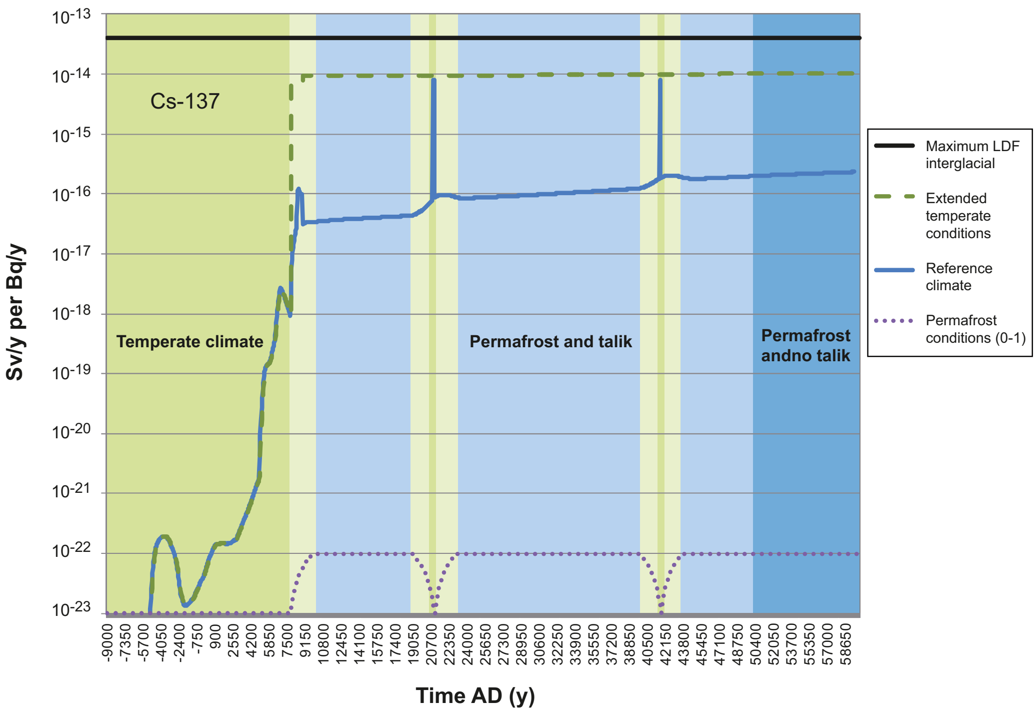

Figure 12-2. Effect of fluctuating periods of temperate and permafrost conditions on LDF for Cs-135 from simulations of object 114. In the simulation the initial 20 ky interglacial was followed by a period where long periods of permafrost are alternated with short periods of temperate climate conditions. The LDF from the simulation (blue line) is contrasted against LDF from constant temperate conditions in the object (dotted line) and the maximum LDF over all biosphere objects from interglacial conditions used in the safety assessment (black line). The spikes in the simulated LDF correspond to short periods of temperate conditions when absence of permafrost allowed use of a deep drilled well. Background colour indicate climate condition (green = temperate, blue = permafrost, light green = transition). In the transition between temperate and permafrost conditions parameters affected by permafrost were averaged according to the dotted line.

However, cold climate and permafrost may effect a number of driving processes and a hydrological description of permafrost conditions in Forsmark suggest that permafrost will prevent discharge of ground water in most biosphere objects /Bosson et al. 2010/. Thus, to evaluate whether the maximum interglacial LDF could be exceeded during fluctuating periods of temperate and permafrost conditions, an alternative simulation was carried out. In this simulation a biosphere object having a potential trough talik (Section 6.1.4.) was simulated allowing key temperature depend parameters (Section 9.3.1) to fluctuate according to the reference glacial cycle /Figure 12-2, Avila et al. 2010/. From these simulations it was concluded that the dose from a unit release during ice free conditions following the initial interglacial was unlikely to exceed the maximum LDF used in SR-Site for examined radionuclides (Ra-226, I-129, Se-79, Cs-135, Np-237 and Cl-36).

Climate conditions – global warming

The temperate domain covers a broad range of mean annual temperatures and precipitation, spanning conditions for a Global warming scenario as predicted by for example /BIOCLIM 2003, Rummukainen 2003/ and /Kjellström et al. 2009/. Conditions characterising global warming have not been assigned a special climate domain or a unique parameterisation in SR-Site surface system modelling. Instead the uncertainty associated with global warming has been handled by calculating maximum LDF for a 40,000 years extension of the initial temperate domain (Sections 8.2.7, Figure 10-1).

The potential effect of a systematic change in parameter values caused by a warmer climate was evaluated for six radionuclides (Ra-226, I-129, Se-79, Cs-135, Np-237 and Cl-36). Sensitivity analysis (see Section 12.4.2) showed runoff to be the only parameters that had any quantitatively important effect on LDF calculations, among the parameters that are expected to be significantly affected by a warmer climate /Löfgren 2010/. Moreover, a warmer climate is associated with an increased runoff /Kjellström et al. 2009/ and for the examined radionuclides an increase in runoff was associated with a decrease in LDF. Thus, the uncertainties associated with a warmer climate were not expected to have a significant effect on the maximum LDF for most radionuclides. For radionuclides with LDFs that would potentially be affected (e.g. I-129 and Cl-36), the uncertainty was handled by the cautious use of a temperate parameter value /Avila et al. 2010/.

Chemical evolution

Most of the easily weathered calcite in the upper regolith of the Forsmark area is likely to be dissolved and washed out within a period of some thousands of years (Section 6.2.6). This means that the influence of the calcium-rich deposits on the terrestrial and limnic ecosystems will be reduced over time, with possible consequences for retention in soil and biological uptake /Tröjbom and Grolander 2010/.

The uncertainty of potential effects of an outwash of calcite was handled as parameter uncertainty in the biosphere analysis. That is, the uncertainty of parameters that describe retention (Kd) and biological uptake (CR) covers conditions with and without the influence of calcite. Moreover, the site data used representing Kd and CR was based on samples from the two SKB sites Forsmark and Laxemar-Simpevarp. There is no influence of calcite in Laxemar-Simpevarp and thus the differences in parameter values between site were used to estimate the potential effect of calcite outwash. The difference in Kd and CR parameters between the two site were small as compared to the natural variation at the sites (Nordén et al. 2010), and consequently it was concluded that the uncertainty associated with future lack of influence of calcite was appropriately handled as parameter uncertainty.

12.2.2 Use of natural resources by future human inhabitants

Occupancy of potentially contaminated areas

The uncertainties with respect to the degree that future humans will inhabit contaminated areas and the extent to which they will be dependent of the natural resources in the object has been handled by cautious or even conservative assumptions. Below follows a discussion on why the assumption that a representative individual of the most exposed group spend all of her/his time in the contaminated area, and get her/his full supply of food and water from the biosphere object are a cautious assumption in a cultural and landscape use perspective.

When agriculture is not possible, (as is assumed in a biosphere object where intrusion of salt water is still frequent), most lakes and wetlands will support no more than one or a few individuals. Non-agricultural communities existing in the past or today are typically non-stationary, and it is hard to see why future inhabitants of such cultures would restrict their foraging for food to one isolated lake with a surrounding wetland in the Forsmark area. In addition, during the terrestrial phase the production in most biosphere objects could only support a fraction of the yearly energy demand of a family sized group. It is possible that a family group or a small community living in the coastal area can be fully supported by the fish production corresponding to the size of the sea basin of a biosphere object. However these groups would be catching fish primarily from migrating stocks. Consequently, it is likely that individuals that feed only on natural food would obtain only a fraction of their diet from a contaminated discharge area, and thus contaminated food would be diluted considerably.

Sustainable agricultural is made possible only for a period of 50–100 years on drained organic soils, which may provide the only arable land in several biosphere objects /Lindborg 2010/. In contrast, the thick and partly continuous layers of clay and sand in the central parts of Öregrundsgrepen can be sustainably cultivated for thousands of years. Thus, a more realistic scenario for a future self-supporting society in the area is that the mainly low contaminated central parts of Öregrundsgrepen will be intensively cultivated and contribute the major part of the food consumed, even to the most exposed group. Some of the small biosphere object may be cultivated during limited periods in time and complement the food produced in the more suitable agricultural areas in Öregrundsgrepen. However even for self-sustained agricultural community it seems more likely that the biosphere objects will primarily be utilised for extensive collection of naturally produced food. Thus, it is concluded that the assumption of a representative individual of the most exposed group to spend all time in the contaminated area and get his/her full supply of food and water from this biosphere object seems improbable given the availability of non-contaminated land in the future landscape and the organisation of present and historical societies.

Consumption of contaminated drinking water

The exposure from contaminated well water has been calculated by assuming that the release of radionuclides is intersected by a well drilled in bedrock. The activity concentration in the well water has been calculated by dividing the release rate (1Bq/year) by the well capacity, cautiously assuming that the release is completely captured by the wells annual recharge. The release into the well is made independently of the release into the biosphere object of 1Bq/year. For radionuclides where contaminated water and food are both important exposure pathways this handling is cautious as compared to assuming that the release would transect a well or reach a biosphere object (as assumed in previous biosphere assessments). However, the effect of this handling on LDF calculations will not exceed a factor two as compared to the alternative handling.

The uncertainty of what type of water source that will be used for drinking in the contaminated area has been handled by assuming that it is equally likely that humans and livestock will use surface water and water from a well drilled in bedrock. Under this assumption, the well water is the dominating exposure pathway by two orders of magnitude (or more) for short lived radionuclides ($\lambda < 100$ years). However, for longer lived radionuclides the well is a less important pathway for exposure (Table 10-1).

The degree of cautiousness in this assumption was quantified by calculating LDF for the alternative assumption that no release would reach a well drilled in bedrock /Avila et al. 2010/. From this comparison, it was clear that for radionuclides expected to contribute to dose, Ra-226 was the only radionuclide to be affected by the handling of the uncertainty associated with the use of contaminated well water. For Ra-226 the LDF decreased by a factor two when well water was disregarded.

Irrigation with contaminated water

In the Forsmark area, stream or lake water will be readily available in most biosphere objects and drainage water can be stored for periods of draught. This also apply to a warmer climate than today as runoff is expected to increase at the site with increased temperatures /Kjellström et al. 2009/. Irrigation with well water is therefore considered to be unlikely in the area /Löfgren 2010/, and consequently for LDF calculations it was assumed, that vegetables are irrigated with contaminated surface water (Section 8.5.1). However as irrigation with water from a well drilled in bedrock cannot be excluded, this uncertainty was examined by calculating LDFs under the alternative assumption that well and surface water are equally likely to be used for irrigation /Avila et al. 2010/.

Irrigation considering well water increased activity concentrations in vegetables somewhat for most examined radionuclides, but the effects on radionuclides expected to contribute to dose was typically below a factor two. From this comparison it was clear that the handling of the uncertainty associated with the use of well water for irrigation did not affect the LDF for these radionuclides, with the exception for Ra-226. For Ra-226 the LDF increased by a factor two when well water was considered for irrigation.

Long term irrigation

In organic soils that originate from drained wetlands in the Forsmark area is expected to be productive for agriculture only during a limited time (Section 8.3.3), and consequently long term use of arable land has not been considered in the LDF calculations. However, future shallow wetlands Öregrundsgrepen can probably be drained relatively easily, and the underlying minerogenic deposits can be sustainably cultivated for thousands of years.

In an alternative simulation it was assumed that initially uncontaminated deposits of glacial and post-glacial clay in Öregrundsgrepen were cultivated and irrigated for 10,000 years with contaminated surface water. The simulations showed that resulting activity concentrations in vegetables was typically two orders of magnitude lower than those resulting from draining and cultivating a wetland in an adjacent contaminated discharge area. That is, the accumulation of radionuclides in the wetland is much higher than accumulation resulting from irrigation. From these simulations it was concluded that the consequences of disregarding contamination through long-term irrigation were insignificant /Avila et al. 2010/.

Land use and diet

No specific diet was pre-specified for the LDF calculations in SR-Site. Instead it was assumed that the human inhabitants utilize all available food sources in a biosphere object, and that the contribution of food types to the diet is proportional to the production capacity of the food types (Section 8.3.2). More over it is assumed that most of the wetland will be drained and cultivated when agriculture is possible, and the uncertainty associated with the use of the contaminated land was handled by assigning an equal probability of all considered land use. Consequently the diet during periods when agriculture is possible will be dominated by root crops, cereals and vegetables, with minor contributions from meat, milk and natural food (Table 12-1).

The effect of uncertainty with respect to human land use on LDF was examined by two Monte-Carlo simulations. Human diet of the first simulation was varied according to randomly allocation of land for production of different agricultural crops or natural food, and to uncertainty in the productivity of each food type. In the second simulation, uncertainty in activity concentration (due to parameter uncertainty) was added /Avila et al. 2010/.

The simulations showed that for radionuclides expected to contribute to dose, the uncertainty in the activity concentration in the food types caused an order of magnitude larger uncertainty in dose than uncertainty introduced by land use and food productivity combined (Figure 12-3). Consequently uncertainty with respect to human diet had a small effect on dose from food ingestion, and the differences between SR-Site calculations and the expected value from including uncertainty with respect to land use and productivity was within a factor two. It was concluded from these simulations that the handling of the uncertainty with respect to human land use and productivity of food types had no significant influence on SR-Site LDFs.

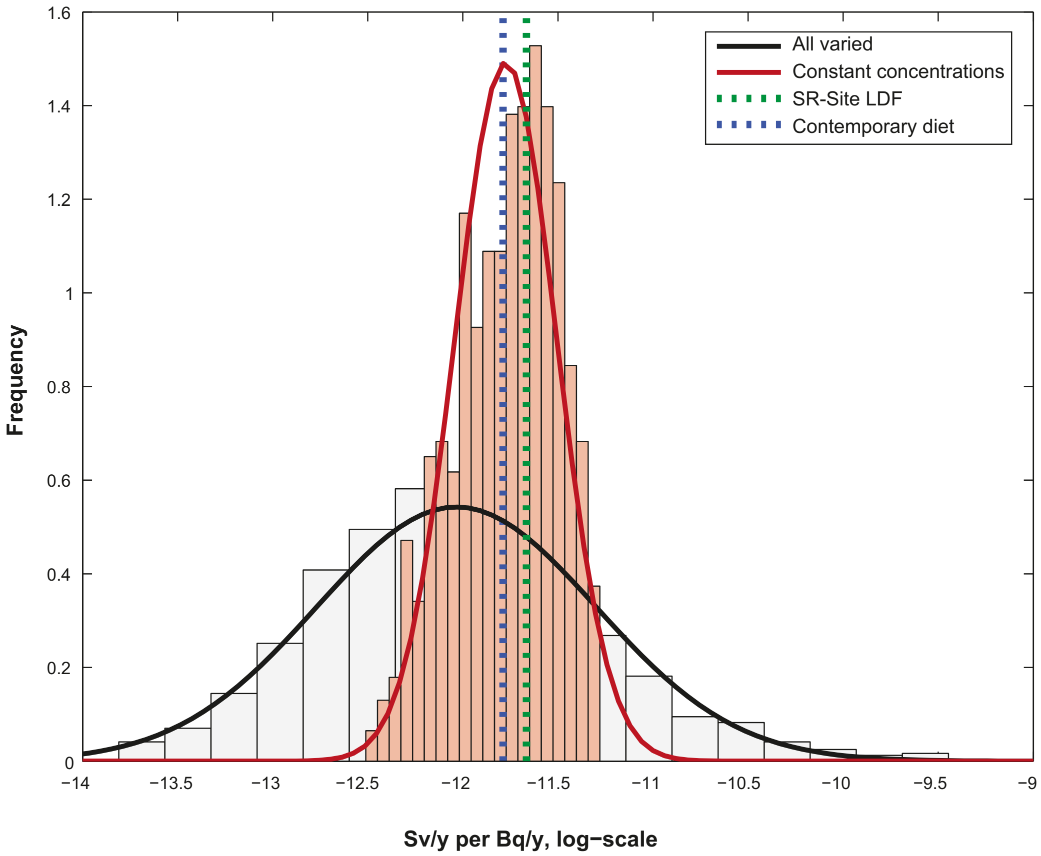

Figure 12-3. *Distribution of dose from Ra-226 (and daughter radionuclides) originating from ingestion of contaminted food. Results were obtained from two Monte-Carlo simulations: Red line corresponds to dose distribution resulting from uncertainty in land use and food productivity. Black line corresponds to dose distribution resulting from uncertainty in land use, food productivity and activity concentration in food. The green vertical line shows the dose corresponding to SR-Site LDF. The purple vertical lines shows the value corresponding to a diet based on contemporary food statistics.*

Table 12-1. Productivity and potential diet for food items used in the SR-Site assessment. Modern diet was derived from national food statistics /Avila et al. 2010/.

	Production			Diet from Food Statistic	
	Productivity	Relative Production			
	(kgC m^{-2} y^{-1})	Without agriculture[a]	With agriculture[a]	(kgFW y^{-1})	Relative
Milk	0.169		4.3%	115[b]	12%
Meat	0.011		0.3%	72	14%
Vegetables	0.135		34%	51	3%
Tuber	0.127		32%	84	14%
Cereal	0.114		29%	71	45%
Fruit				23.5	2%
Fish	$2.7 \cdot 10^{-4}$	48.3%	0.3%	27	4.2%
Crayfish	$3.1 \cdot 10^{-5}$	5.5%	0.04%	1.7	0.2%
Berries	$1.3 \cdot 10^{-4}$	23.2%	0.03%	4.25	3%
Mushrooms	$1.2 \cdot 10^{-4}$	21.5%	0.03%	1.3	0.03%
Game	$8.3 \cdot 10^{-6}$	1.5%	0.002%	25	5%

[a] equal land and lake area,

[b] unit is litre per year.

The LDFs used in SR-Site were also contrasted against the dose from contaminated food that would result from a diet derived from contemporary Swedish food statistics (further described in /Avila et al. 2010/). The differences in LDFs for nuclides expected to contribute to dose was typically within a factor two. However, for Np-237, which gave peak exposure from natural foods, the SR-Site LDFs was an order of magnitude larger than the LDF from the alternative diet, as it was not diluted by uncontaminated agricultural products. These results supported the conclusion that the handling of the uncertainty with respect to human diet, land use and productivity of food types did not significantly affect SR-Site LDFs.

Table12-2. Quantative effects of system uncertainties on maximum LDF from the interglacial period (SR-Site LDF). Source of uncertainty listed together with handling in the SR-Site assessment, and alternative model/assumption. Comparisons were done for six radionuclides (Ra-226, I-129, Np-237, Se-79, Cs-135, and Cl-36). A difference within a factor two between SR-Site LDFs and LDFs calculated with an alternative approach was considered non-significant.

Source of uncertainty	SR-Site handling	Alternative model/assumptions	SR-Site handling compared to alternative
Development of the biosphere			
State of biosphere object in relation to the timing and duration of the releases.	All release to one object. Maximum LDFs over the full interglacial period.	Simulations with different timing and duration of release.	Cautious. Ra-226 not affected.
Location of release	Maximum LDF over all potential discharge areas	All biosphere objects equally likely to recieve the full release	Cautious
In reference climate Interglacial is the 20 k year followed by alternating periods of permafrost and temperate conditions.	Maximum LDF from the interglacial period represent the worst case during the 70 k year simulation period.	Simulations with alternating conditions after the intial 20 k year interglacial period.	SR-Site handling supported. LDF from alternative model did not exceed SR-Site LDF.
Human utilization of natural resources			
Consumption of contaminated drinking water	Contaminated surface and well water used for drinking	Drinking water from surface water only (no deep well)	Ra-226 cautious. No significant difference other nuclides.
Irrigation, source of contaminated water	Surface water from biosphere object used for irrigation	Irrigation with contaminated surface and well water	Ra-226 non-cautious. No significant difference other nuclides.
Long term irrigation	Contaminated organic soil cultivated for 50 years	Inorganic soils irrigated for thousands of years	SR-Site handling supported, (contribution of long term irrigation insignificant).
Land use and productivity	Different use of wetland for food production equally likely	Land use and productivity randomly varied	No significant difference.
Diet	Diet proportional to production capacity in biosphere object	Diet from contemporary Swedish food statistics	Np-237 cautious. No significant difference other nuclides.

12.3 Model uncertainties

Model uncertainties refers to uncertainties arising from an incomplete knowledge or lack of understanding of ecosystems and the processes important for transport and accumulation at the site, and their representation in simplified models.

For example, complex ecosystems are represented in the radionuclide model by ten compartments. These are considered internally homogeneous, and radionuclides entering a compartment are assumed to become mixed within time scales of thousands of years (Section 8.4). The lower regolith is associated with very slow hydrological flows and thus the assumption of mixing may be questioned. Consequently the effect of a simplified model representation was evaluated by a finer discretisation (see 12.3.1 Representation of lower regolith for a summary). A thorough examination of the uncertainties associated with the simplified representation of the biosphere with the radionuclide model, including a discussion on the assumptions of the internal homogeneity of compartments, are presented in /Avila et al. 2010/.

Soil retention and biological uptake of radionuclides are complex processes. These have been represented in the biosphere assessment by simple equilibrium parameters (for a description of CR and Kd see Sections 9.2.6 and 9.2.7 respectively). The uncertainties associated with this highly stylised and simplified approach are handled by using large intervals for parameter values spanning a wide range of environmental conditions, and consequences of this for the uncertainty of LDF are discussed in Secetion 12.4.2. The general assumptions and limitations of the Kd and CR approaches, in relation to the natural variation at the site, are discussed in details in /Nordén et al. 2010/, and their implications for dose calculations are further examined in /Avila et al. 2010/.

In the following sections, model uncertainties have been divided into uncertainties associated with the model discretisation and vertical transport respectively. The handling of these uncertainties are described and discussed, and the quantitative effects of model uncertainty on LDF are summarised in Table 12-3.

12.3.1 Discretisation

Size of the biosphere object

Several characteristics of the biosphere objects (including area of sub-catchment, timing of emergence from the sea and depth of regolith layers) affect the transport and accumulation of radionuclides. Some of these are related to the size of the object. For example, the steady state activity concentration in surface water is primarily determined by the watershed area of the object, and the steady state concentration in the wetland peat is influenced by the size of the sub-catchment /Avila et al. 2010/.

The biosphere objects which yields the highest environmental activity concentrations are objects with small sub-catchments and no inflow of surface water from upstream watersheds (Figure 12-4). These objects can typically support 80 individuals from agriculture , and the most extreme object has a local drainage area which is only three times as large as the lake/wetland area (0,24 km^2). In theory smaller biosphere objects, with smaller sub-catchments, could sustainably support a group of approximately 10–20 individuals. However, a thorough analysis of the Forsmark landscape fails to identify any discharge areas with a local drainage area less than 0.24 km^2 and a reasonable likelihood of persistent release from the repository /Lindborg 2010/.

The basin of one of the original biosphere objects (121) was partitioned into three separate biosphere objects in order to represent discharge directly into a stream or a wetland without going through a lake stage. One of these objects, 121_03, turned out to be small with respect to both area of the sub-catchment and watershed. Thus to examine the effect of this subdivision of a biosphere object, the LDF was calculated for the original undivided biosphere object. The LDF of most radionuclides was lower when the undivided object 121 was used. However, as several other small biosphere objects were included in the assessment and the contribution from the well is independent of the size of the objects, the effect on the maximum LDF was small. Among radionuclides expected to contribute to dose, only I-129 and Se-79 were significantly affected the division of object 121 (by a factor two and three respectively).

Representation of lower regolith

The lower regolith is represented by a single compartment in the radionuclide model. As the vertical flow rates associated with the lower regolith are small, a single-compartment model will tend to underestimate the time for break-through and over estimate dispersion of radionuclides in the regolith.

The effect of discretisation was examined by alternative models in which the lower regolith compartment was split into a varying number of compartments, stacked on top of each other /Avila et al. 2010/. The retention of low-sorbing radionuclides was not affected by the model discretisation. For radionuclides with a moderate or high Kd, the retention increased by orders of magnitude with finer discretisation. However, this had a limited effect on the calculated LDFs as contamination from well water was unaffected by retention in the lower regolith. Thus it was concluded that the uncertainty

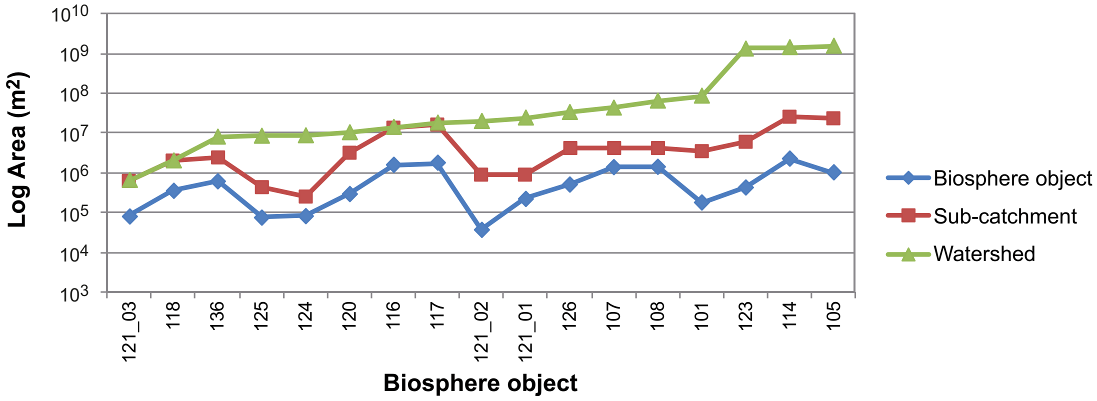

Figure 12-4. *The size of biosphere objects and their sub-catchment and watershed. Objects are sorted in ascending order of the watershed size and their position in the landscape is shown in Figure 7-11.*

associated with the representation of the lower regolith layer had no significant effect on the LDF for most nuclides expected to contribute to dose. Moreover, for radionuclides that were significantly affected by the discretisation (e.g. the LDF of Cs-135 decreased with a factor five), the single-compartment representation lead to cautious LDF estimates, as compared to estimates from higher discretised alternative models.

Contamination through surface water

The LDFs used in the dose assessments were derived from simulations in which a constant release rate (see above) was applied to the lower regolith layer of each biosphere object separately, disregarding the effects of contamination of downstream objects. This was considered and appropriate approach for finding maximum doses in the landscape over the simulation period. The effect of this simplified representation of contamination was examined by alternative simulations where the full landscape configuration (Figure 7-13) was captured, accounting for indirect contamination through surface water (see /Avila et al. 2010/ for details).

Results from a simulation of chain of biosphere objects are presented in Figure 12-5. In this simulation radionuclides were released to object 136, and objects downstream were contaminated through flow of surface water. For this, and all other possible chains of biosphere objects, the LDF was highest in the first object of the chain that received radionuclides directly into the lower regolith. For most objects and radionuclides, the LDF from an indirect release was typically an order of magnitude lower than that from a direct release. It was concluded that the simulations that only consider direct release to each biosphere object will give a realistic or cautious values of LDF for individual objects, as compared to results with more complex models where all objects and connections are explicitly modelled. Moreover the maximum LDF (over all biosphere objects) where identical for landscape chains and the simplified representation used in the biosphere analysis.

12.3.2 Vertical transport

Diffusion

Vertical transport of radionuclides in the radionuclide model is driven by both advection and diffusion. There are uncertainties associated with the description of diffusion in situations when vertical water fluxes vary both in time and space. To quantify the relative contribution of diffusion to the vertical transport of radionuclides and how it affected the LDF estimates, simulations with an alternative model disregarding diffusion were carried out /Avila et al. 2010/. Results from this analysis showed LDFs to be insensitive to the presence of diffusion in the model and the difference between LDFs including or excluding diffusion was within a factor two. Therefore, it is concluded that uncertainties associated with the representation of diffusion in the radionuclide model has no significant effect on the SR-Site LDFs.

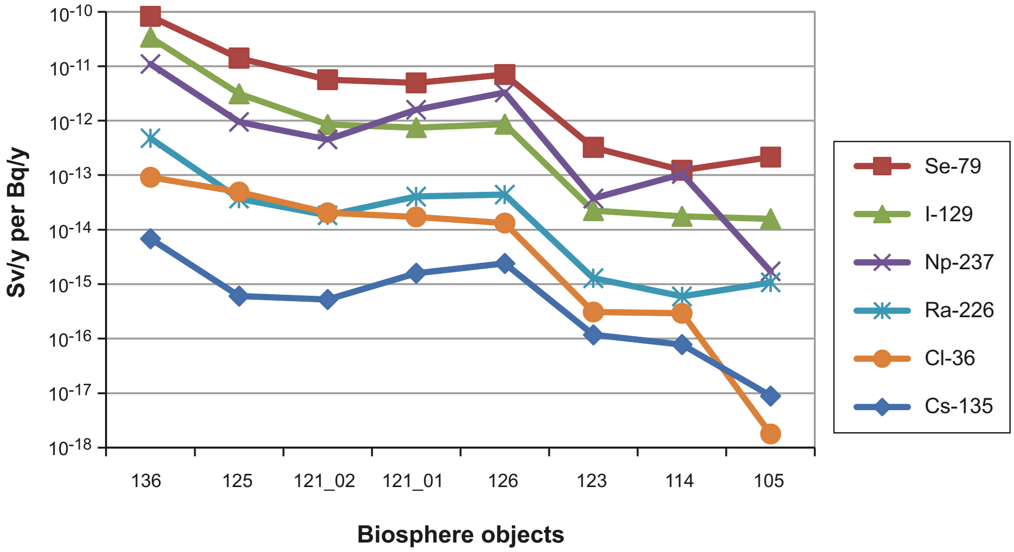

Figure 12-5. *LDFs from one chain of biosphere objects. Radionuclides were released at a constant rate to the lower regolith of biosphere object 136. Biosphere objects downstream were contaminated through surface water. LDFs are maximum values from an interglacial period. Biosphere objects appear in order of the chain from left to right (see Figure 7-11). Figure from /Avila et al. 2010/.*

Advective transport from the lower regolith

The parameter describing upward hydrological flux from the lower regolith increase by a factor five when the biosphere object develops from the sea stage to the lake/terrestrial stage. As a constant release rate has been applied to the biosphere in the simulations, an increased flow rate will be associated with a proportional decrease in the steady state inventory of radionuclides with a long half-life. Thus, in the model, radionuclides may potentially be flushed out from the lower regolith when the biosphere object is under transgression.

However, groundwater flow and transport from the geosphere to the biosphere is also expected to change when the site develops from submerged to terrestrial conditions. For example, in the MARFA flow transport simulations that illustrate the effect of varying flow conditions on final risk estimates, the flow scaling factor for submerged conditions is a factor five smaller than the corresponding factor for terrestrial temperate conditions (Section 13.5.6 in **SR-Site main report**). No flush of radionuclides would be expected if this change in release rate was factored in to the biosphere simulations.

To illustrate how a potential flush associated with the change in vertical hydrological fluxes from the lower regolith affected the LDF, two simulations were carried out with a constant flux from the lower regolith during the whole simulation period. One with low flux, corresponding to the flux in the sea stage and one with a higher flux, corresponding to flux in the terrestrial stage /Avila et al. 2010/. These simulations also allow estimating the sensitivity of the LDF to the value of the flux from the lower regolith. The alternative simulations showed that assumptions on flow rate had a limited effect on LDF calculations. Of nuclides expected to contribute to dose, Cs-135 was the only one to be significantly affected by the alternative parameterisation. That is, SR-Site LDF was a factor two larger for Cs-135 than the estimate assuming a constant low flux from the lower regolith. Thus, it was concluded that the handling of the uncertainty associated with flux rates from the lower regolith during coastline passage did not have a significant effect on the SR-Site LDFs.

Table 12-3. Quantitative effects of model uncertainties on maximum LDF from the interglacial period (SR-Site LDF). Source of uncertainty listed together with handling in the SR-Site assessment, and alternative model/assumption. Comparisons were done for six radionuclides (Ra-226, I-129, Np-237, Se-79, Cs-135, and Cl-36). A difference within a factor two between SR-Site LDFs and LDFs calculate with an alternative approach was considered non-significant.

Source of uncertainty	SR-Site handling	Alternative model/assumptions	SR-Site handling compared to alternative
Discretisation			
Size of biosphere object	Size of biospher object equals size of sea / lake basin. Basin 121 diveded into three biosphere objects.	Basin 121 one biosphere object	I-129 and Se-79 cautious. No significant difference other nuclides.
Reprsentation of lower regolith	Represented by a single compartment.	Represented by multiple stacked layers	Cs-135 cautious. No significant difference other nuclides.
Contamination may reach an object from direct release or by surface water from another object	Contamination from neighbouring objects disregaded.	Simulations of all biosphere objects conceted according to the landscape configuration	SR-Site handling supported. Maximum LDF from alternative model identical to SR-Site LDF.
Vertical transport			
Representation of diffusion	Both advection and diffusion represented in model.	Transport by diffusion excluded	No significant difference
Advective transport from the lower regolith	Advective transport increases from sea to lake/terrestrial stage	Constant high advection	No significant difference.
		Constant low advection	Cs-135 cautious. No significant difference other nuclides.

12.4 Parameter uncertainties and sensitivity analysis

Site-specific data, generic data, and expert judgement were used to determine best estimate values, and to characterise the uncertainty in parameter estimates with probability density functions (Chapter 9). For each selected radionuclide, probabilistic simulations were performed by applying Monte-Carlo simulations for the biosphere object which showed the highest LDF value in the deterministic simulations. The results from these simulations were also used in sensitivity analyses to identify the parameters contributing most to uncertainty in the LDFs.

Not all parameters were treated probabilistically in the evaluation of LDF uncertainties. Parameters that represent habits and properties of the exposed individuals and future use of the biosphere were kept constant for the uncertainty analysis calculations. In line with international recommendations /ICRP 2006/, fixed, slightly conservative values were chosen for these parameters. For instance, the uncertainties in inhalation rates, water ingestion rates and food ingestion rates were not included in probabilistic simulations. Some parameters that occur in the model as time series do not vary independently of each other and were therefore excluded from the probabilistic simulations. Instead, their effect on LDFs were quantified by systematically varying parameters together, preserving their correlation structure /Avila et al. 2010/.

12.4.1 Uncertainty analysis

The uncertainty analysis was carried out to estimate the effects of parameter uncertainties on LDFs. This was done by propagating uncertainties in input distributions through the model to develop distribution functions for the LDFs.

LDF-distributions were derived for the point in time when the median of the distribution reached its peak value for each examined radionuclide. The derived distributions were approximately log-normal for most examined radionuclides, with a 90% confidence interval typically spanning two orders of magnitude (Figure 12-6). The LDFs were generally close to the median of the probabilistic simulations, and the LDFs used in the safety assessment thus reflect the central tendency, or the typical outcome, when parameter uncertainties are considered. However, it is the arithmetic mean value from the probabilistic simulations that represents the expected outcome if the parameter uncertainties were to be taken into account.

The arithmetic means from the probabilistic simulations were systematically higher than the median value due to the approximately log-normal distribution of LDFs. The difference between the deterministic LDFs and the arithmetic mean was within a factor three for most radionuclides, including nuclides expected to contribute to dose (i.e. Ra-226, I-129, Se-79, Cs-135, Np-237 and Cl-36). For a few radionuclides, inclusion of parameter uncertainties resulted in an expected value that was an order of magnitude larger than the LDF used in the safety assessment (e.g. Tc-99, Th-230, U-238 and Zr-93). However, the potential release of these radionuclides to the biosphere is expected to be insignificant (**SR-Site main report**). This is discussed in more detail in /Avila et al. 2010/.

From the analysis of time dependent parameters, it was shown that uncertainty associated with bounding assumptions on biomass and productivity for aquatic primary producers, and on water retention for sea and coastal basins, had an insignificant effect on the LDF /Avila et al. 2010/.

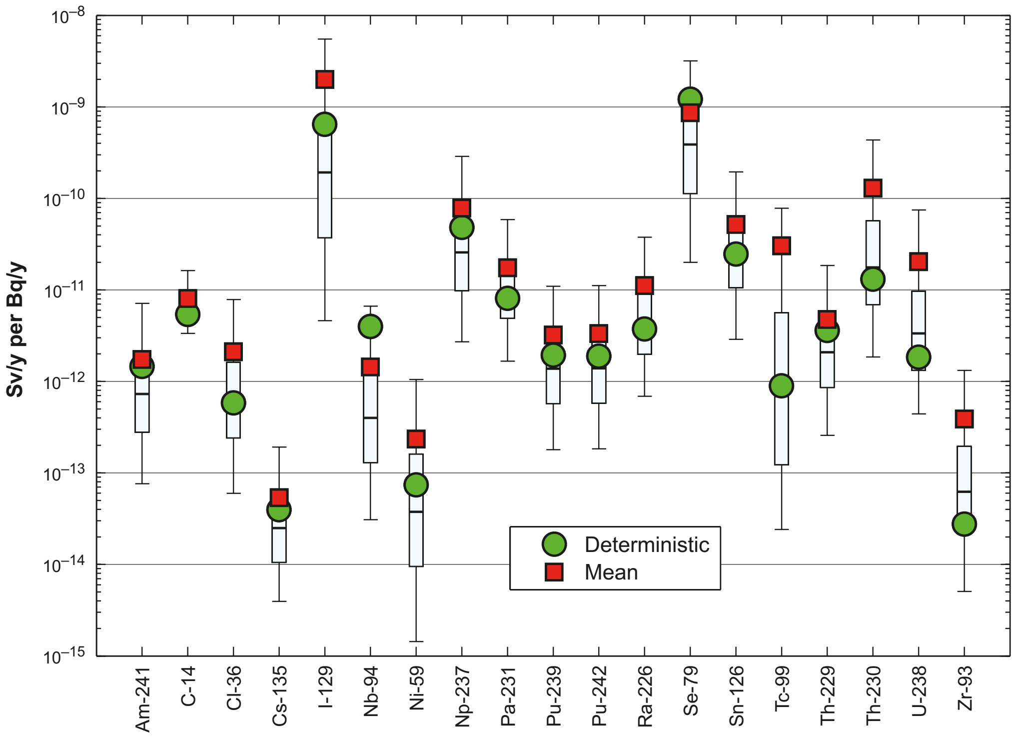

Figure 12-6. *Effects of parameter uncertainty on maximum LDF estimates. LDF distributions were derived from Monte-Carlo simulations (see text). The mean (square) from the simulations are contrasted against the SR-Site LDF (circle). The box represents the 25th percentile, the median and the 75th percentile of the LDF distribution from the simulation, and whiskers represents the 90 percent confidence interval. (Figure from /Avila et al. 2010/.)*

12.4.2 Sensitivity analysis

The Monte-Carlo simulations described above were also used in a sensitivity analysis. This analysis aimed to identify individual parameters with a strong influence on the assessment endpoint, and examine to what extent the importance of these parameters varied with the development of a biosphere object. The results were focused on LDF variation with respect to the uncertainty of individual parameters (i.e. not with respect absolute or proportional changes), and thus the results identify parameters or processes where most benefit would be gained from improved understanding or measurements.

The results below were derived from regression analysis of first order effects on a logarithmic scale. However, several other methods were applied to understand the effect of individual parameters on the assessment endpoint. Details on all methods and the results are presented in /Avila et al. 2010/. It was clear from the sensitivity analyses that the importance of a parameter on LDF varied with the development of the biosphere objects. This was not unexpected as major process rates and pathways change throughout the development of an object. For example, for Ra-226 uncertainty in the properties of regolith layers and fish productivity caused the majority of uncertainty in the LDF during the sea stage. Where as to uncertainty in well capacity and parameters describing plant uptake dominating LDF uncertainty during the terrestrial stage (Figure 12-7).

Althrough sensitivity analyses were carried out for the full simulation time, it is the maximum LDF throughout the interglacial period that is used to assess the safety of future human inhabitants (Chapter 10). The Ra-226 LDF reaches its maximum in the terrestrial stage at the end of the temperate domain (9400 AD, Table 10-1). At this point in time, uncertainty in well capacity explains 48% of LDF uncertainty, and the corresponding numbers for plant uptake (CR) of Ra-226 and its daughter Pb-210 is 6% and 20%, respectively (Figure 12-8). Uncertainty in the parameter describing retention in the low regolith layer (Kd_regolow) explains an additional 5% of LDF uncertainty. The standardized regression coefficients from the sensitivity analysis of first order effects indicate both the importance and direction of the effects of a parameter on LDF. Thus as expected, the LDF for Ra-226 would decrease with an increase in well capacity or in the Kd of the low regolith layer. Similarly it would increase with an increase in plant uptake (see wellCapac, kD_regoLow[Ra-226], cR_soilToVegetab[Pb-210] and cR_soilToVegetab[Ra-226] in Figure 12-8a).

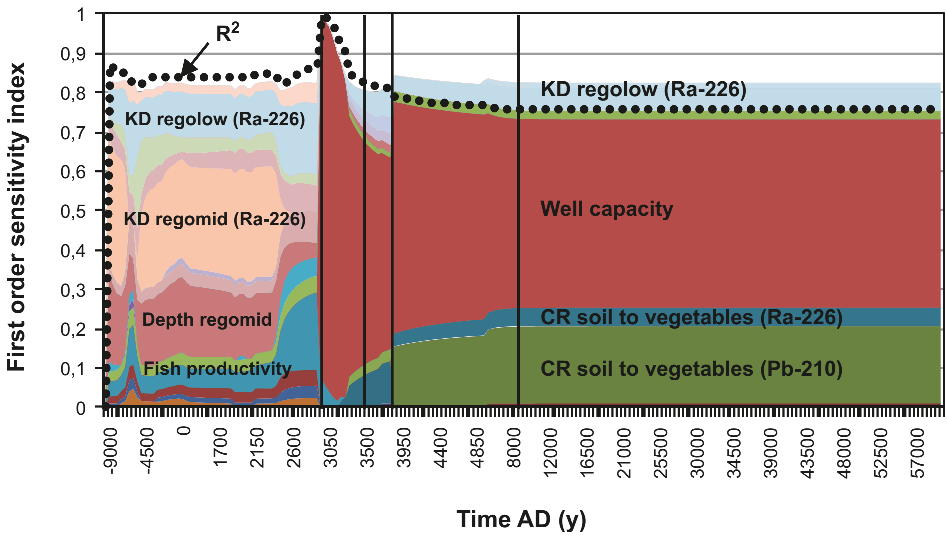

Figure 12-7. *Effects of parameter uncertainty on LDF uncertainty for Ra-226 as a function of time. The first order sensitivity index indicates the proportion of uncertainty in LDF that is explained by uncertainty in each of the parameters. The dotted line shows the fraction of the total parameter uncertainty in LDF that is explained by first order effects of the model parameters. The vertical lines represents (from left to right) the start and end of lake isolation, the time when the wetland can first be converted to arable land and the end of the interglacial period, respectively. The analysis is based on the fit of a regression model to the results from Monte-Carlo simulations of biosphere object 121_03. The sensitivity analysis was carried out on a logarithmic scale. Figure from /Avila et al. 2010/.*

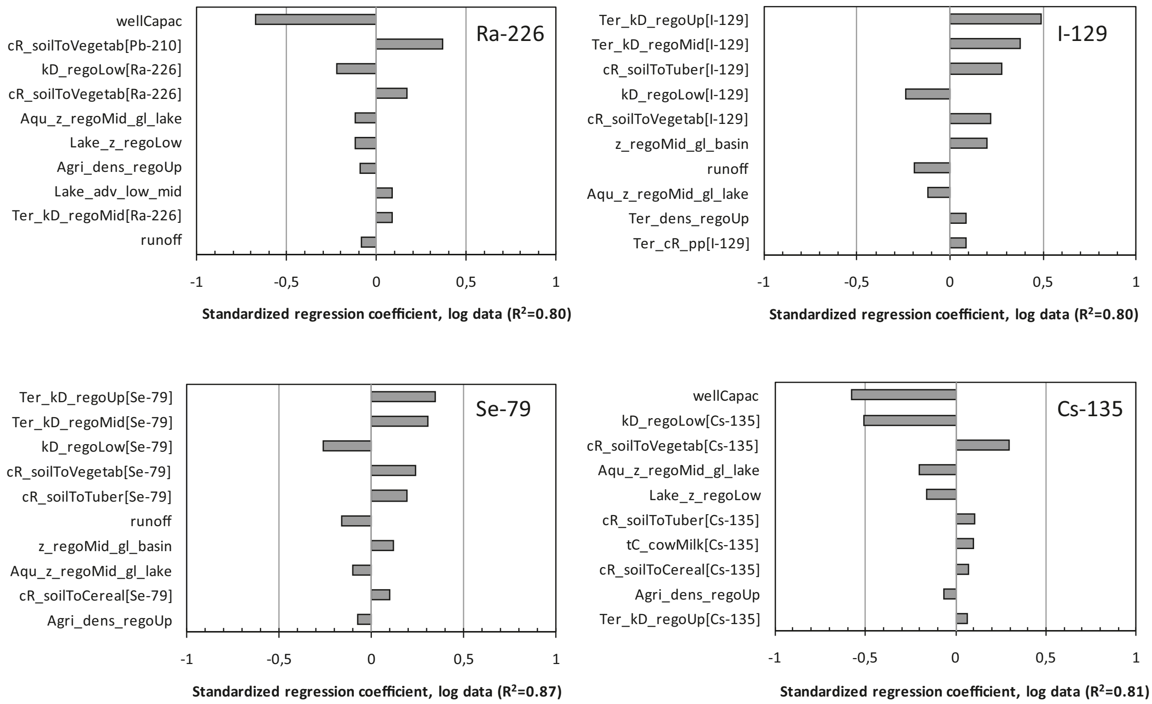

Figure 12-8. *Effects of parameter uncertainty on uncertainty in maximum LDF for four radionuclides. The size and direction (negative or positive) of vertical bar reflects the effects of uncertainty in individual parameters on LDF uncertainty. The R^2 value indicates the fraction of the total uncertainty in LDF that is explained by first order effects of the model parameters. Parameter name are explanied in Appendix 2. The results are based on Monte-Carlo simulations in biosphere objects 121_03 (Ra-226, I-129, Se-79) and 124 (Cs-135), respectively. Figure from /Avila et al. 2010/.*

As a rule, parameter uncertainty associated with the dominating exposure pathway was the major source of LDF uncertainty, and consequently the relative importance of parameters for LDF uncertainty varied with radionuclide properties (for examples of dominating exposure pathways for expected dose contributing radionuclides see Table 10-1). Detailed results on the source of uncertainty of individual radionuclides and the influence on individual parameters on LDF uncertainty are presented and discussed in /Avila et al. 2010/.

Uncertainty in parameters that describe retention in regolith layers (Kd) and plant uptake (CR) explained a large fraction of LDF uncertainty for many radionuclides. For medium sorbing nuclides with long half-life (e.g. I-129 and Se-79) the uncertainty of these parameters clearly dominated LDF uncertainty (see e.g. parameters names with kD or cR i Figure 12-8). An increase in plant uptake and retention in the upper and the mid regolith layers was always associated with an increase in LDF, whereas an increase in the retention of the low regolith layer was associated with a decrease in LDF (Figure 12-8, Avila et al. 2010).

The primary reason for the large impact of Kd and CR values on LDF, was that the distribution of these parameters was typically very wide. That is, as these parameters were estimated from combining site and literature data they covered a broad range of environments. As systematic variation due to for example climate, geographic location, type of ecosystem or measurement techniques were not partitioned out before site and literature data were combined, the derived PDFs for these parameters are likely to overestimate the natural variation expected at the site /Tröjbom and Nordén 2010/. Thus it is expected that model uncertainty could be significantly reduced if the uncertainties in these parameters could be limited to reflect natural variation at the site. It may also be possible to reduce uncertainties for some radionuclides by describing sorption and plant uptake by alternative modelling approaches which are less sensitive to parameter uncertainties.

The development of biosphere objects are captured by several parameters that vary systematically in time (Table 7-2). To assess the sensitivity of LDF to variation in the predicted landscape development, alternative parameter sets were derived by systematically varying key process rates in the coupled regolith-lake development model (see Chapter 5 in /Brydsten and Strömgren 2010/ for details). From this analysis it was concluded that LDF for nuclides expected to contribute to dose, was insensitive to changes in the predicted landscape development /Avila et al. 2010/.

12.5 Overall uncertainty

The LDFs obtained from the biosphere assessment are best estimates for a representative individual in the most exposed group from deterministic simulations. These deterministic simulations are the combined result of process understanding, the most precise description of the site available and relevant assumptions on the use of natural resources by future human inhabitants.

The effect of uncertainties on the calculated LDFs was examined in this chapter. Uncertainties were divided into three categories for this analysis ; system uncertainties, model uncertainties and parameter uncertainties. The consequences of uncertainties in LDF calculations were carried out by discussions of the reasonability of assumptions, by formulating and quantitatively exploring alternative assumptions, models and the parameters, and by performing Monte-Carlo simulations.

The philosophy of the biosphere assessment has been to make estimations of landscape dose conversion factors as realistic as possible, based on the knowledge of present-day conditions at Forsmark and of the past and expected future development of the site. From the summary of quantitative effects of system and model uncertainties (Tables 12-2 and 12-3, respectively) it is evident that the handling of these types of uncertainties has been balanced for the examined radionuclides. /Avila et al. 2010/.

The effect of parameter uncertainties on LDF calculations were assessed with both systematic and random variation of model parameters. From these assessments it was concluded that uncertainties in parameters which reflected landscape development had limited effect on LDF estimates. However, from the Monte-Carlo simulations it was clear that parameter uncertainty was the major source of LDF uncertainty, and that the effects of examined system and model uncertainties fell within the 90 percent confidence interval corresponding to parameter uncertainties (Avila et al. 2010, Figure 12-9). Moreover it was noted that the handling of parameter uncertainties was not cautious as the expected value from the probabilistic simulations were systematically higher than the LDFs used in the safety assessment.

The LDFs are based on best estimates of all available parameters, i.e. they reflect typical values representing available knowledge from the site and literature. Though a great effort was put into the process to derive meaningful PDFs (see Section 9.1), information from the site was occasionally insufficient, resulting in PDFs reflecting the span reported in the literature rather than the natural variation expected on the site. Moreover, the Monte-Carlo sampling did not incorporate dependence between parameters (e.g. a negative correlation between CR for plants and Kd for soil), and the sampling was not designed to give precise estimates in presence of long-tailed distributions. These and other limitations in probabilistic simulations are discussed in /Avila et al. 2010/. Nevertheless, the difference between deterministic calculations and expected values from the probabilistic simulations gives an indication of the potential impact of parameter uncertainties. Thus if the final risk estimates are close to the regulatory limits, (as compared to difference between LDFs and the expected value from the Monte-Carlo simulation), it would be reasonable to make an effort to reduce the parameter uncertainty of dose contributing radionuclides.

A representative individual of the most exposed group is assumed spend a life time in the discharge area where the environmental concentrations lead to the highest dose, and to get his or her full supply of food and water from the contaminated area. A fairly sized group of individual (>40) can be sustainably supported by agriculture from a transformed wetland in any of the biosphere objects. However, the assumption that a representative individual of the most exposed group should be totally dependent on resources from a small area seems improbable given the availability of non-contaminated land in the future landscape and the organisation of present and historical societies (Section 6.1.8). Though no attempt has been made to quantify a reasonable degree of dilution that would result from the consumption of non-contaminated food and water due to e.g. trading or migration, the assumption on the behaviour of future human inhabitants are inherently cautious or even conservative.

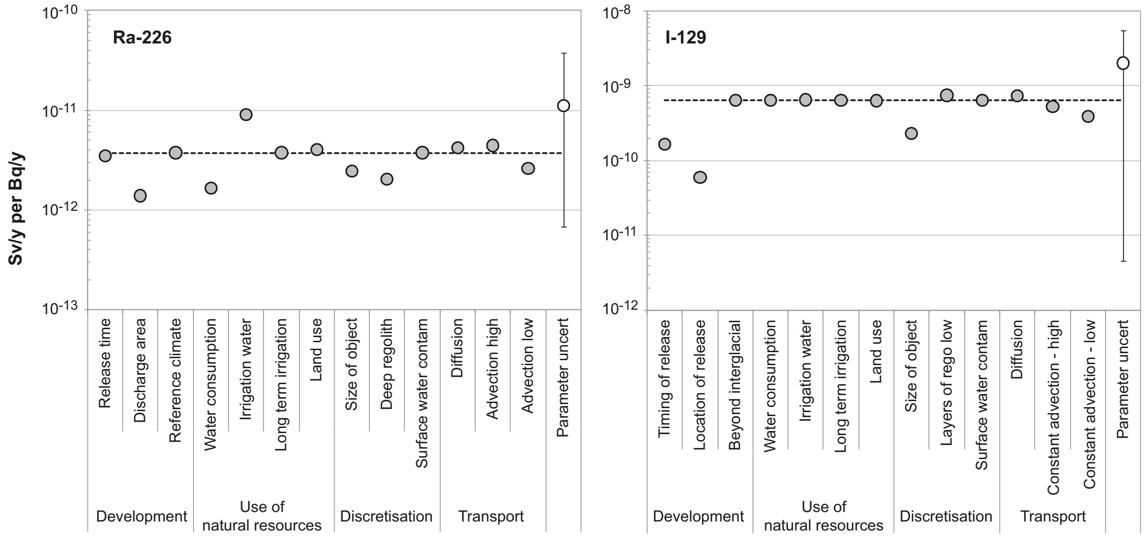

Figure 12-9. *Uncertainties of LDF for Ra-226 and I-129. Grey circles represents LDFs calculated with alternative assumptions/models, where as white circle represents the expected value taking parameter uncertainties into account (whiskers represents the 90 percent confidence interval).The dotted line represents the maximum LDF from the interglacial period.*

Extensive analyses were carried out to characterise which parameters have a strong influence on the assessment endpoint (see /Avila et al. 2010/ summarized above). The sensitivity analyses demonstrated that the influence of individual parameters on LDFs varied between radionuclides and depended on the development of the landscape. The analyses highlighted that a large proportion in LDF uncertainty can be attributed to parameters describing the partitioning of radionuclides between the solid and liquid phases (i.e. Kd) and biological uptake (i.e. CR). For most radionuclides, a combination of generic and site data was used to estimate these parameters, indicating the potential benefit of additional site measurements that would reveal systematic natural variation and reduce measurement errors. Alternatively, LDF uncertainty could be reduced by describing sorption and uptake of radionuclides with models that are less sensitive to parameter uncertainties.

Conclusion

A systematic evaluation of the effects of uncertainties on the SR-Site LDFs demonstrated that the handling of system and model uncertainties was balanced. Site representative values were used for model parameters, and their uncertainties were not handled in a cautious way, where as the definition of the most exposed group was clearly cautious. However, the effect of quantified uncertainties was limited and is therefore not expected to have a significant effect on the assessment endpoint. Thus taken together we are confident that the maximum LDFs used in SR-Site are robust estimates for the most exposed group, reflecting process understanding and the most precise description of the site available.

Nevertheless, SR-Site biosphere recognises that there is a potential to reduce uncertainties, in particular with respect to processes describing the partitioning of radionuclides between the solid and liquid phases (i.e. Kd) and biological uptake (i.e. CR). Thus if the final risk estimates are close to the regulatory limits, it would be reasonable to make an effort to reduce the uncertainty associated with these processes, at least for dose contributing radionuclides.

12.6 Feedback for future Site investigations and the biosphere RD&D program

In the above analysis several areas where benefit from improved understanding or measurements would reduce uncertainty in dose calculations were identified. Implications from these findings for future site investigations and for the biosphere research and development programme (RD&D programme) are briefly discussed below.

The LDF calculations for long-term release are based on the assumptions that the release from the repository will reach the biosphere objects where the consequences for human inhabitants will be worst. Moreover, the release is assumed to reach an object at a constant rate for the entire assessment period. Although these assumptions are not unrealistic with respect to geo-hydrological predictions, they were shown to be cautious (Table 2-2). Thus, reducing uncertainties with respect to the location and timing of the release would result in more reliable dose estimates.

Along these lines, SKB plans to re-examine the possibility to represent the release to the biosphere with a probability weighted function that captures the timing and location of deep groundwater discharge according to relevant geo-hydrological predictions. For near future calculation scenarios, the release from the geosphere is used as a direct and time-dependent input to the radionuclide model (Section 10-4). An advantage of this approach is that it allows estimates of total dose that corresponds to a most exposed group which is well defined in time and space. A similar approach could be used to long-term release. Thus, the possibility to complement the unit release approach with a realistic release term that accounts for the relevant driving hydrology will be further investigated (see e.g. MARFA simulations with flow scaling, Section 13.5.6 in **SR-Site Main Report**).

A major part of the quantified uncertainty in LDF could be attributed to parameters describing the partitioning of radionuclides between the solid and liquid phases (Kd) and by parameters describing biological uptake (CR). A high uncertainty in parameter estimates of Kd and CR could often be attributed to the lack of site data, and in these cases the parameter uncertainty reflects the variation in the data reported to international databases rather than natural variation expected at the site. Consequently, a better coverage of concentration measurements of a few elements (including Ra and I) is desirable for all environmental media, and there is a need to obtain concentrations of all elements in agricultural products and soils similar to those expected in a future Forsmark landscape.

In order to predict sorption and biological uptake in the future when environmental conditions may be different from today, it is important to increase our understanding of the processes that are likely to affect Kd and CR at the site. A better process understanding may be achieved by identification of systematic variation in element concentrations and ratios at the site (and similar sites), with respect to for example type of ecosystem, soil and sediment conditions, and to background fluxes due to e.g. plant uptake, mineralisation, deposition and weathering. Studies of element pools and fluxes offer an important perspective on element transport and retention at larger scales, and results from studies at the catchment and landscape levels will be continued, and possibly used to validate the assumptions and approaches used in the assessment model.

It may also be possible to describe sorption and/or biological uptake by alternative modelling approaches that are less sensitive to parameter uncertainties. Hence, the coming RD&D program will also aim at developing assessment tools that explicitly describe biological uptake as a function of physiological processes /Kumblad and Kautsky 2004 /. For primary producers this means that both active and passive uptake will be considered accounting for bioavailability of radionuclides and competition between radioactive and stable isotopes /e.g. Avila 2006/. Similarly, uncertainty in Kd values for specific radionuclides may be reduced by explicitly modelling radionuclide transport as a function of known chemical processes as in reactive transport models / Piqué et al. 2010/.

The assumptions on the behaviour of future human inhabitants are inherently cautious or even conservative. Further literature reviews of present and historic self-sustained communities will aim to replace a cautious approach by reasonable assumption on human habits associated with sustainable land use in a cultural and landscape context.

Finally, the analysis of non-human biota high-lighted the importance of collecting sufficient measurements from the site, as the representation of a number of radionuclides and organism groups are limited in generic data on non-human biota.

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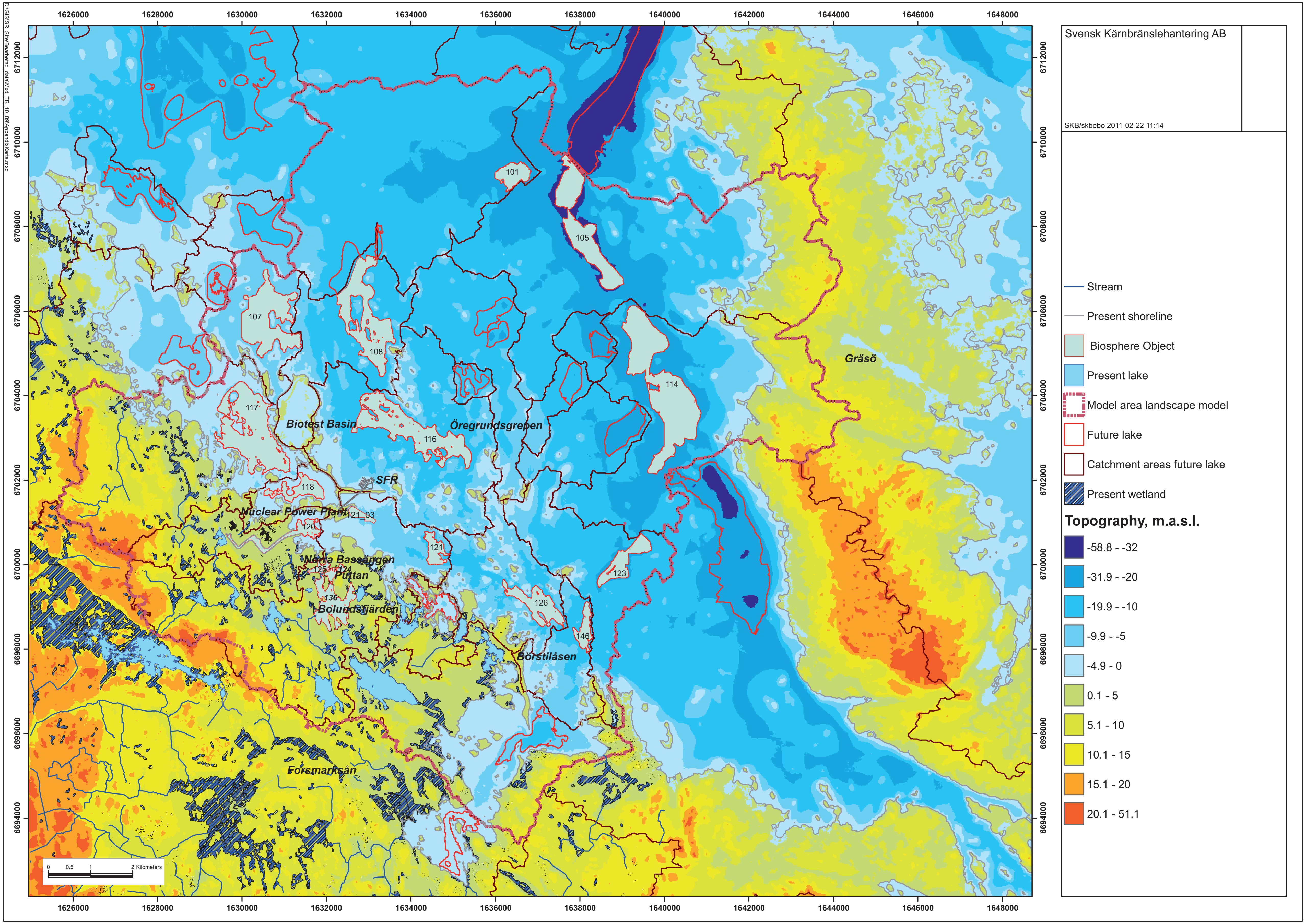

Figure A-1. *Map over the Forsmark area today. Numbers within biosphere objects show object id-number. The sizes of biosphere objects shown on the map represent sizes during the lake and terrestrial stages in the landscape succession (see Figure 7-8 for object sizes during the marine stage). The basin of biosphere object 121 was subdivided into 3 separate objects, of which biosphere object 121_03 is shown on the map. See Figure 6-6 for the location of the planned repository.*

Appendix 2

Glossary of terms and acronyms used in the SR-Site biosphere assessment

Term	**Definition**
abiotic	Non-living physical or chemical component or process.
autotroph	Organism that utilises photosynthesis or chemosynthesis to build up organic carbon.
basin	In the SR-Site terminology, a basin is the drainage area of a biosphere object (e.g. lake), minus the drainage area of any upstream object. When the basin is below sea level, the basin equals the biosphere object.
biosphere	That part of the environment normally inhabited by living organisms.
biosphere object	A part of the landscape that potentially will receive radionuclides released from a repository.
biotic	Living ecosystem component or process involving living organisms.
climate cases	SR-Site describes climate cases, which are possible future climate developments at Forsmark.
climate domain	A climatically determined environment with a specific set of characteristic processes of importance for repository safety.
CR (concentration ratio)	The CR is used to calculate uptake of radionuclides by biota and is defined as the element-specific concentration ratio between the concentrations in biota, and in the surrounding media (soil or surface water).
conceptual model	A qualitative description of important components and their interactions.
deterministic analysis	Analysis using, for key parameters, single numerical values (taken to have a probability of 1), leading to a single value for the result.
DEM (digital elevation model)	The DEM describes topography and bathymetry of a certain area. The DEM is a central data source for the site characterisation, and is used as input to most of the descriptions and models produced for the surface system.
discharge points /area	The area where deep groundwater reaches the ground surface.
dose	Dose, as used in SR-site refers to the mean annual dose of the most exposed group. The calculated dose accounts for retention of radionuclides in the human body and exposure from daughter radionuclides, as well as radiation sensitivities of different tissues and organs.
dose rate to biota	Dose rate to biota represents mean absorbed dose rates in the whole body of a given radionuclide and is expressed in uGy h^{-1}.
ecosystem model	Conceptual or numerical representation of an ecosystem, divided into compartments, and its included processes.
effective dose	(or effective dose equivalent). A measure of *dose* designed to reflect the *risk* associated with the *dose*, calculated as the weighted sum of the *dose equivalents* in the different tissues of the body.
ERICA tool	Computer software used to obtain activity concentrations and radiological effects on different types of non-human biota.

exposure	The act or condition of being subject to irradiation. (*Exposure* should not be used as a synonym for *dose*. *Dose* is a measure of the effects of *exposure*.) External exposure. Exposure to radiation from a source outside the body. Internal exposure. Exposure to radiation from a source within the body.
functional group	A group of organisms with a common function in the ecosystem, e.g. primary producers, filter feeders etc.
geosphere	Those parts of the lithosphere not considered to be part of the *biosphere*. In *safety assessment*, usually used to distinguish the subsoil and rock (below the depth affected by normal human *activities*, in particular agriculture) from the soil that is part of the *biosphere*.
glacial cycle	A period of c. 120,000 years that includes both a glacial (e.g. the Weichselian) and an interglacial.
GPP (gross primary production)	Total fixation of carbon by photosynthesis, including respiration (cf. net primary production, NPP).
heterotroph	Organism that uses organic compounds produced by autotrophs.
hydrodynamic model	The hydrodynamic model gives outputs of annual mean flows between adjacent marine basins and water retention time for each individual basin.
hydrological model	Hydrological modelling performes simulation of surface and near surface water flow. Each model run have different environmental settings as input parameters. The hydrological modelling utilises GIS, as well as MIKE SHE and ConnectFlow as numerical modelling tools.
infilling	Infilling describes the combined process of sedimentation and organogenic deposition, turning lakes into wetlands.
interglacial	A warm period between two glacials. In SR-Site an interglacial is defined as the time from when the ice sheet retreats from the area (time of deglaciation) to the time for the first occurrence of permafrost.
Kd	Soil/liquid partition coefficients are defined as the ratio between the element concentrations in the solid and liquid phases.
landscape development model	A model at landscape level that describes the long-term development of a landscape. The model is used to describe time-dependent properties of the biosphere objects that are input parameters to the Radionuclide model.
landscape model	In SR-Site, the landscape model is a description of where biosphere objects are situated in the landscape and how they are hydrologically interconnected.
LDF (landscape dose conversion factor)	The LDF is a radionuclide-specific dose conversion factor, expressed in Sv/y per Bq/y. The LDF represents the mean annual effective dose to a representative individual from the most exposed group, resulting from a unit constant release rate, or alternatively per unit released in a single pulse to the biosphere of a specific radionuclide. The LDF relates a unit release rate to dose.
mass balance model	The mass balance model calculates the total sum of major sources and sinks for individual chemical elements in the landscape.
most exposed group	In SR-Site, the expression *most exposed group* refers to the group of individuals subjected to the highest exposure during any time period.
NEP (net ecosystem production)	The sum of gross primary production and ecosystem respiration.

NPP (net primary production)	The balance between gross primary production and plant respiration (cf. gross primary production, GPP).
PANDORA	The Matlab/Simulink toolbox used for implementation of the SR-Site radionuclide model.
probabilistic analysis	Mathematical analysis of stochastic (random) events or processes and their consequences.
radionuclide model	Model used to calculate radionuclide inventories in different compartments of the biosphere, radionuclide fluxes between the compartments and radionuclide concentrations in environmental media (soil, water, air and biota). Exposure calculations for humans to estimate LDF's are included in the radionuclide model, whereas exposure of non-human biota is calculated separately. The radionuclide model utilises PANDORA and Ecolego modelling tools.
regolith	All matter overlying the bedrock are collectively denominated regolith. This includes both minerogenic and organogenic deposits as well as antropogenic landfills.
RDM (regolith depth model)	The RDM interpolates observation points of analysed vertical distribution of regolith into 3-dimensional regolith extension.
RLDM (coupled regolith-lake development model)	The RLDM is divided into a marine module that predicts the sediment dynamics caused by waves, and a lake module that predicts infilling of lakes. The model forecasts regolith distribution and thickness of different strata at time-steps.
sub-catchment	The drainage area of a biosphere object minus the drainage area of the inlets to the object.
terrestrialisation	The transfer of an aquatic ecosystem (marine or limnic) to a terrestrial ecosystem.
watershed	The drainage area of a biosphere object.

Appendix 3

Parameters for calculations of environmental concentrations

Parmeter Name	Description	Unit	Type	Report	Source File
Physical constant					
Half_life	Radionuclide half-life.	year	Nuclide specific	TR-10-07	ParametersES.xls
Landscape geometry					
Aqu_area_obj	Water area in the lake basin.	m^2	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
area_subcatch	Area of the subcatchment.	m^2	Site Specific	TR-10-05	ParametersSS.xls
area_wshed	Watershed area.	m^2	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
depth_aver	Average water depth.	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
depth_max	Maximum water depth.	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
growth_rego	Average accumulation rate of sediment calculated for lake and marine bottoms.	m/year	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
res_rate	Resuspension rate.	kg DW/ (m^2year)	Site Specific (Time Series)	TR-10-05	ParametersTS.xls
sed_rate	Sedimentation rate.	kg DW/ (m^2year)	Site Specific (Time Series)	TR-10-05	ParametersTS.xls
Ter_area_obj	Area with peat in the lake basin.	m^2	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
threshold_agriculture	Point in time when wetland is 2 m above sea level.	year	Site Specific	TR-10-05	ParametersSS.xls
threshold_end	Point in time when ingrowth of wetland stops.	year	Site Specific	TR-10-05	ParametersSS.xls
threshold_start	Point in time when lake isolation starts.	year	Site Specific	TR-10-05	ParametersSS.xls
threshold_stop	Point in time when lake isolation is completed.	year	Site Specific	TR-10-05	ParametersSS.xls
Regolith					
Agri_z_regoUp	Depth of the agricultural upper regolith layer	m	Generic	TR-10-01	ParametersUC.xls
Aqu_dens_regoMid_gl	Density of glacial clay in the middle layer of the regolith.	kg DW/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Agri_dens_regoUp	Density of the agricultural upper regolith layer.	kg DW/ m^3	Site Specific	TR-10-01	ParametersSS.xls
Agri_poro_regoUp	Porosity of the agricultural upper regolith layer.	m^3/ m^3	Site Specific	TR-10-01	ParametersSS.xls
Aqu_dens_regoMid_pg	Density of the postglacial sediments in aquatic middle layer of regolith.	kg DW/ m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_dens_regoUp	Density of the aquatic upper layer of the regolith	kg DW/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_poro_regoMid_gl	Porosity of the glacial clay in aquatic middle regolith layer.	m^3/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_poro_regoMid_pg	Porosity of postglacial sediments in aquatic middle regolith layer.	m^3/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_poro_regoUp	Porosity of the aquatic upper regolith layer.	m^3/m^3	Site Specific	TR-10-02 TR-10-03	ParametersSS.xls
Aqu_z_regoMid_pg	Depth of postglacial clay in aquatic middle regolith layer under sea, lake or stream	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
Aqu_z_regoMid_gl_lake	Average depth of glacial deposits in lake.	m	Site Specific	TR-10-05	ParametersSS.xls

Parmeter Name	Description	Unit	Type	Report	Source File
dens_regoLow	Density of the lower regolith layer (till).	kg DW/m^3	Site Specific	TR-10-01 TR-10-02 TR-10-03	ParametersSS.xls
Lake_z_regoLow	Depth of the lower regolith (till) in the lake/terrestrial stage.	m	Site Specific	TR-10-05	ParametersSS.xls
Lake_z_regoUp	Depth of the upper regolith layer in the lake basin.	m	Site Specific	TR-10-02	ParametersSS.xls
poro_regoLow	Porosit of the lower regolith layer (till).	m^3/m^3	Site Specific	TR-10-01 TR-10-02 TR-10-03	ParametersSS.xls
Sea_z_regoLow	Average depth of glacial till in sea basin	m	Site Specific	TR-10-05	ParametersSS.xls
Sea_z_regoUp	Depth of the upper regolith layer in sea.	m	Site Specific	TR-10-03	ParametersSS.xls
Ter_dens_regoMid_gl	Density of the glacial clay in terrestrial middle regolith layer.	kg DW/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_dens_regoMid_pg	Density of the postglacial clay in terrestrial middle regolith layer.	kg DW/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_dens_regoUp	Density of the terrestrial upper regolith layer (peat).	kg DW/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_growth_rego	Growth of wetland relative water area.	m^2/ (m^2year)	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
Ter_poro_regoMid_gl	Porosity of the glacial clay in terrestrial middle regolith layer.	m^3/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_poro_regoMid_pg	Porosity of the post glacial clay in terrestrial middle regolith layer.	m^3/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_poro_regoUp	Porosity of the terrestrial upper regolith layer (peat).	m^3/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_z_regoMid_pg	Depth of the post glacial clay in terrestrial middle regolith layer (covered by peat).	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
Ter_z_regoUp	Depth of the terrestrial upper regolith layer (peat).	m	Site Specific (Time Series)	TR-10-05	Parameters_TS_ all_basins.xls
z_regoMid_gl_basin	Depth of the glacial clay of the aquatic middle layer in the sea basin.	m	Site Specific	TR-10-05	ParametersSS.xls
Aquatic ecosystem					
Aqu_biom_pp_macro	Biomass of macroflora and macrofauna (macroalgae, macrophytes, benthic macro-fauna) in lake.	kg C/m^2	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_biom_pp_plank	Biomass of pelagic biota (i.e. phytoplankton bacterioplank-ton, zooplankton and fish) in lake.	kg C/m^2	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_biom_pp_ubent	Biomass of microphytobenthos and benthic bacteria in lake.	kg C/m^2	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_degass_C	Carbon degassing rate. Release of carbon from lake water surface to atmosphere.	kg C/ (m^2year)	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_prod_pp_macro	Net productivity of the benthic macrocommunity, i.e. the net primary production minus respiration of macrofauna and flora, in lake.	$year^{-1}$	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_prod_pp_plank	Net productivity of the pelagic community, i.e. net primary production by phytoplankton minus respiration by zoo-plankton, bacterioplankton, and fish, in lake.	$year^{-1}$	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Aqu_prod_pp_ubent	Net productivity of the benthic microscopic community, i.e. net primary production by micro-phytobenthos minus respiration by benthic bacteria in lake.	$year^{-1}$	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls

Parmeter Name	Description	Unit	Type	Report	Source File
gasUptake_C	Uptake of carbon from atmosphere to lake water (mainly CO_2).	kg C/ (m^2year)	Site Specific (Time Series)	TR-10-02 TR-10-03	ParametersTS.xls
Lake_conc_DIC	Concentration of dissolved inorganic carbon in lake water.	kg C/m^3	Site Specific	TR-10-02	ParametersSS.xls
Lake_conc_PM	Concentration of particulate matter in lake water.	kg DW/m^3	Site Specific	TR-10-02	ParametersSS.xls
prod_edib_cray_Lake	Production of edible crayfish in the lake.	kg C/ (m^2year)	Site Specific	TR-10-02	PostProcessing ParametersSS.xls
prod_edib_fish_Lake	Production of edible fish in the lake.	kg C/ (m^2year)	Site Specific	TR-10-02	PostProcessing ParametersSS.xls
z_min_prod_edib_cray-fish_Lake	Minimum lake depth for crayfish production.	m	Site Specific	TR-10-02	PostProcessing ParametersSS.xls
z_min_prod_edib_fish_Lake	Minimum lake depth for production of edible fish.	m	Site Specific	TR-10-02	PostProcessing ParametersSS.xls
prod_edib_fish_Sea	Production of edible fish in the sea.	kg C/ (m^2year)	Site Specific	TR-10-03	PostProcessing ParametersSS.xls
Sea_conc_DIC	Concentration of dissolved inorganic carbon in sea water.	kg C/m^3	Site Specific	TR-10-03	ParametersSS.xls
Sea_conc_PM	Concentration of particulate matter in sea water.	kg DW/m^3	Site Specific	TR-10-03	ParametersSS.xls
Terrestrial Ecosystem					
conc_C_atmos	Concentration of carbon in the atmosphere above the terrestrial ecosystem	kg C/m^3	Generic	TR-10-01	ParametersUC.xls
frac_C_atmos	Fraction of decomposed carbon that is mineralised (leaving as CO_2 to the atmosphere)	–	Site Specific	TR-10-01	ParametersSS.xls
frac_mush_Herbiv	Fraction of mushrooms in the diet of terrestrial herbivores.	–	Generic	TR-10-01	ParametersUC.xls
prod_edib_berry	Production of edible berries.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_game	Production of edible game meat.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_mush	Production of edible mush-rooms.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
Ter_biom_pp	Biomass of terrestrial primary producers.	kg C/m^2	Site Specific	TR-10-01	ParametersSS.xls
Ter_conc_C_regoUp	Concentration of dissolved inorganic carbon in the upper terrestrial regolith (peat).	kg C/m^3	Site Specific	TR-10-01	ParametersSS.xls
Ter_conc_Dust	Concentration of dust in air.	kg DW/m^3	Generic	TR-10-01	ParametersUC.xls
Ter_decomp	Decomposition rate.	1/year	Site Specific	TR-10-01	ParametersES.xls
Ter_degass_C	Degassing rate of dissolved inorganic carbon in the ter-restrial ecosystem.	kg C/ m^2 year	Site Specific	TR-10-01	ParametersSS.xls
Ter_prodBiom_pp	Net primary production per unit biomass in the terrestrial ecosystem.	kg C/(kg C year)	Site Specific	TR-10-01	ParametersSS.xls
Ter_z_mixlay	Height of the mixing layer in the terrestrial ecosystem.	m	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
Ter_z_roughness	Height above ground below which the wind speed is zero due to vegetation.	m	Generic	TR-10-01	ParametersUC.xls
vel_wind	Wind velocity.	m/year	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
Agri_conc_Dust	Concentration of dust in the atmosphere on agricultural land.	kg DW/m^3	Generic	TR-10-01	PostProcessing ParametersSS.xls
conc_C_meat	Concentration of carbon in meat.	kg C/kg FW	Generic	TR-10-07	ParametersUC.xls
conc_C_milk	Concentration of carbon in milk.	kg C/kg FW	Generic	TR-10-07	ParametersUC.xls
densMilk	Density of the milk.	kg FW/l	Generic	TR-10-07	ParametersUC.xls

Parmeter Name	Description	Unit	Type	Report	Source File
ingRate_food_meat	Fodder ingestion rate for meat cattle.	kg C/d	Generic	TR-10-07	ParametersUC.xls
ingRate_food_milk	Fodder ingestion rate for milk producing cattle.	kg C/d	Generic	TR-10-07	ParametersUC.xls
ingRate_soil_Cow	Soil ingestion rate for cattle.	kg DW/d	Generic	TR-10-07	ParametersUC.xls
ingRate_water_meat	Water ingestion rate for meat cattle.	m^3/d	Generic	TR-10-07	ParametersUC.xls
ingRate_water_milk	Water ingestion rate for milk producing cattle.	m^3/d	Generic	TR-10-07	ParametersUC.xls
leaf_areaIndex	Ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows.	m^2/ m^2	Generic	TR-10-01	ParametersUC.xls
leaf_StoreCapac	Storage capacity of intercepted water on leaf surface.	m^3/ m^2	Generic	TR-10-01	ParametersUC.xls
numb_irrig	Number of irrigation events.	$year^{-1}$	Generic	TR-10-01	ParametersUC.xls
prod_edib_cereal	Production of edible cereals.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_meat	Production of edible meat (relative fodder consumption).	kg C/kg C	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_milk	Production of edible milk (relative fodder consumption).	kg C/kg C	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_tuber	Production of edible root crop, e.g. potato.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_edib_vegetab	Production of edible vegeta-bles.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
prod_fodder	Production of fodder on agricultural land.	kg C/ (m^2year)	Site Specific	TR-10-01	PostProcessing ParametersSS.xls
vol_irrig	Volume of irrigation water used each year.	m/year	Generic	TR-10-01	ParametersUC.xls
Surface Hydrology and water exchange					
Flooding_coef	Gross lateral flux of water from lake/stream to wetland, nor-malised by the net lateral flux from wetland to lake/stream.	unitless or (m^3/year)/ (m^3/year)	Site Specific	TR-10-01 TR-10-02	ParametersSS.xls
Lake_adv_low_mid	Total advective flux from regoLow (till) to regoMid (gla-cial and post glacial deposits) for the lake/terrestrial stage.	m/year	Site Specific	TR-10-01 TR-10-02	ParametersSS.xls
Lake_Aqu_adv_mid_ up_norm	Advective flux in the aquatic object between the sediment and the water during lake stage, normalised by the net lateral advective flux from wetland to lake/stream.	–	Site Specific	TR-10-02	ParametersSS.xls
Lake_fract_Mire	Fraction of the upward flux from regoLow (till) that is directed to the terrestrial part of the biosphere object.	–	Site Specific	TR-10-01 TR-10-02	ParametersSS.xls
runoff	Total annual runoff.	m/year	Site Specific	TR-10-01 TR-10-02 TR-10-03	ParametersSS.xls
Sea_adv_low_mid	Total advective flux from regoLow (till) to regoMid (gla-cial and post glacial deposits) for the sea stage.	m/year	Site Specific	TR-10-03	ParametersSS.xls
Ter_adv_mid_up_norm	The advective flux from rego-Mid (glacial and post glacial deposits) to regoUp (peat) in the terrestrial ecosystem. normalised by the net lateral flux from terrestrial ecosystem to lake/stream.	–	Site Specific	TR-10-01 TR-10-02	ParametersSS.xls
wat_ret	Average water retention time in the sea basin.	year	Site Specific (Time Series)	TR-10-03	Water_retention. xls
wellCapac	The water volume capacity of a well.	m^3/year	Site Specific	TR-10-01	PostProcessing ParametersSS.xls

Parmeter Name	Description	Unit	Type	Report	Source File
Distribution coefficients and diffusivity					
kD_regoLow	Distribution coefficient for lower regolith layer (till).	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Lake_kD_PM	Distribution coefficient for particulate matter in lake/stream.	m^3/kg DW	Element Specific	TR-10-07	ParametersSS.xls
Lake_kD_regoMid	Distribution coefficient for particulate matter in lake/stream.	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Lake_kD_regoUp	Distribution coefficient for the middle regolith layer in lake/stream.	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Sea_kD_PM	Distribution coefficient for particulate matter in sea.	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Sea_kD_regoMid	Distribution coefficient for the middle regolith layer in sea (glacial clay and post glacial sediments combined).	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Sea_kD_regoUp	Distribution coefficient for the upper regolith layer in sea.	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Ter_kD_regoMid	Distribution coefficient for the terrestrial middle regolith layer (glacial clay and post glacial sediments combined).	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
Ter_kD_regoUp	Distribution coefficient for the terrestrial upper regolith layer (peat).	m^3/kg DW	Element Specific	TR-10-07	ParametersES.xls
diffcoef	Diffusion coefficient.	m^2/year	Element Specific	TR-10-02	ParametersES.xls
Concentration ratios, retention and release					
cR_foodToHerbiv	Concentration ratio from food to terrestrial herbivores.	kg C/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_soilToCereal	Concentration ratio from soil to cereals.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_soilToMush	Concentration ratio from soil to mushrooms.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_soilToTuber	Concentration ratio from soil to tubers.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_soilToVegetab	Concentration ratio from soil to vegetables.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_watToCray_Lake	Concentration ratio from water to crustacean in the lake.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_watToFish_Lake	Concentration ratio from water to fish in the lake.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
cR_watToFish_Sea	Concentration ratio from water to fish in the sea.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Lake_cR_pp_macro	Concentration ratio from water to macrophytes/macroalgae in lake/stream.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Lake_cR_pp_plank	Concentration ratio from water to macrophytes/macroalgae in lake/stream.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Lake_cR_pp_ubent	Concentration ratio from water to phytoplankton in lake/stream.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Sea_cR_pp_macro	Concentration ratio from water to macrophytes/macroalgae in sea.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Sea_cR_pp_plank	Concentration ratio from water to phytoplankton in sea.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
Sea_cR_pp_ubent	Concentration ratio from water to microphytobenthos in sea.	m^3/kg C	Element Specific	TR-10-07	ParametersES.xls
tC_cowMeat	Transfer coefficient from intake of radionuclides in fodder and water to cow meat.	d/kg FW	Element Specific	TR-10-07	ParametersES.xls

Parmeter Name	Description	Unit	Type	Report	Source File
tC_cowMilk	Transfer coefficient from intake of radionuclides in fodder and water to cow milk.	d/l	Element Specific	TR-10-07	ParametersES.xls
Ter_cR_pp	Concentration ratio for terrestrial primary producers.	kg DW/kg C	Element Specific	TR-10-07	ParametersES.xls
coefRetent	Fraction of leaf intercepted radionuclides that is adsorbed to edible parts of vegetables during irrigation.	–	Element Specific	TR-10-07	ParametersES.xls
Ter_df_decomp	Discrimination factor during decomposition.	–	Element Specific	TR-10-07	ParametersES.xls
Human characteristics					
AverTime	The time interval over which concentration in agricultural soil is averaged over.	y	Generic	TR-10-07	ParametersUC.xls
expTime	Time spent outdoor (time for exposure from external radiation).	h/year	Generic	TR-10-07	ParametersUC.xls
ingRate_C	Human food ingestion rate.	kg C/year	Generic	TR-10-07	ParametersUC.xls
ingRate_wat	Human water ingestion rate.	m^3/year	Generic	TR-10-07	ParametersUC.xls
inhalRate	Human inhalation rate of volume air.	m^3/h	Generic	TR-10-07	ParametersUC.xls
Dose coefficients					
dosCoef_ext	Dose coefficient from external exposure.	Sv/h*Bq/m^3	Element Specific	TR-10-07	ParametersES.xls
dosCoef_ing_food	Dose coefficient from ingestion of food.	Sv/Bq	Element Specific	TR-10-07	ParametersES.xls
dosCoef_ing_water	Dose coefficient from ingestion of water.	Sv/Bq	Element Specific	TR-10-07	ParametersES.xls
dosCoef_inhal	Dose coefficient from inhalation.	Sv/Bq	Element Specific	TR-10-07	ParametersES.xls