Technical Report

TR-14-06

Biosphere synthesis report for the safety assessment SR-PSU

Svensk Kärnbränslehantering AB

November 2014

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1404-0344
SKB TR-14-06
ID 1429516

Biosphere synthesis report for the safety assessment SR-PSU

Svensk Kärnbränslehantering AB

November 2014

Keywords: Assessment context, Biosphere object, Climate, Discharge areas, Exposure pathways, Features, events and processes (FEP), Landscape development, Landscape dose conversion factors (LDF), Land use, Most exposed group, Non-human biota (NHB), Radionuclide transport, Safety assessment, Sensitivity analysis, SFR, Site description, Surface ecosystems, Uncertainty analysis.

Preface

This report presents a synthesis of biosphere analyses undertaken in an assessment of long-term safety of the low- and intermediate-level waste repository SFR in Forsmark. The report forms part of the SR-PSU safety assessment, which supports SKB's licence application to extend SFR.

A number of authors have contributed to the various sections of the report, as listed in Section 1.1.

The report has been reviewed by Jordi Bruno, Ari Ikonen and Mike Thorne.

Stockholm, November 2014

Fredrik Vahlund
Project leader SR-PSU

Abstract

This report presents the biosphere part of the SR-PSU safety assessment, which means that the report is focused on the surface systems where humans and non-human biota potentially could be exposed to radionuclides released from the SFR repository. The report summarises and analyses the data, process descriptions and models that have been used to develop and parameterise models for calculating radionuclide transport, exposure and resulting doses in the biosphere, including the support for various simplifications and assumptions made in this process of model development and parameterisation.

The focus of the present report is on models and data used in the biosphere component of the modelling chain employed in the overall safety assessment calculations, but it also contains some modelling results not presented elsewhere. This modelling was performed with the aim of investigating processes, properties and parameters specifically associated with the biosphere, without having the influence of other parts of the system confounding the interpretations. Most chapters of this report summarise background reports produced within the SR-PSU biosphere modelling project, which means that more detailed descriptions are provided in those background reports.

Following a general introduction and descriptions the methodological and regulatory background to the work, the actual model descriptions begin with a summary of relevant parts of the site descriptive model (SDM) describing the present conditions at Forsmark. This presentation includes central underlying models such as the digital elevation model (DEM) and the regolith depth and stratigraphy model (RDM). These models provide important geometrical descriptions used not only within the biosphere modelling but also in other parts of the safety assessment. The SDM is the basis for the development of models describing future conditions.

The first part of the description of future developments in Forsmark deals with climate and the associated shoreline displacement, as expressed by the SR-PSU climate cases, and their implications for processes and ecosystems in the Forsmark area. The site-specific coupled regolith-lake development model (RLDM) is an important tool for the modelling of landscape succession and possible future geometrical-geological conditions. In the next step, human land use is introduced and analysed, with emphasis on the conditions for agriculture in potential future Forsmark landscapes. The results of the coupled analysis of natural conditions and effects of human interventions are formulated as a time-dependent landscape development model (LDM).

The LDM is used in combination with results of hydrogeological modelling and information on present and future geometrical conditions to develop a model for biosphere objects. Thereby, areas where groundwater potentially carrying radionuclides from SFR discharges are identified and described. The resulting model for biosphere objects under temperate climate conditions, which is used in the majority of the safety assessment calculations, consists of seven biosphere objects. However, one biosphere object (referred to as object 157_2) receives most of the potentially radionuclide-containing water from the repository, and hence is the object of main interest in the safety assessment.

The SR-PSU biosphere objects are of two main types: objects that have a lake stage in their succession, which means that they go from sea (bay) to lake to wetland and then possibly are developed further into agricultural land, and objects without a lake stage in their succession. The object of main interest in the safety assessment (object 157_2) is of the type that lacks a lake stage. The modelling of radionuclide transport under periglacial climate conditions considers two biosphere objects, of which one is included also in the modelling of temperate climates.

One major step is the analysis of features, events and processes (FEPs) and exposure pathways, and the formulation of calculation cases. The FEP and exposure analysis utilises and combines external input in the form of recommendations and requirements with the site-specific knowledge from data and models, in order to identify and describe what is relevant and needs to be included in the model calculations of transport, exposure and doses. The analysis of potentially most-exposed groups results in the identification of four potentially exposed populations representing four alternative land use variants considered in the modelling. Exposure routes for these four populations in natural and agricultural systems are identified, and the exposure analysis also includes an identification of non-

human biota endpoints based on an analysis of organism types in terrestrial, marine and limnic ecosystems. The exposed populations are assessed in seven biosphere calculation cases (BCC), which are mapped to the main calculation cases considered in the safety assessment.

After the identification and description of what needs to be modelled, the development of a numerical compartment model for calculating radionuclide transport and doses in the Forsmark biosphere is presented. Modelled biosphere objects on land are subdivided into one mire part and one aquatic part, where the aquatic part decreases in size with time due to infilling. Objects that lack a lake stage (such as object 157_2) consist solely of a mire during the whole model period after the marine stage. The general vertical subdivision of the model is based on the geological layers identified and described in the RDM and the RLDM. The description of models is completed by a summary of the data used in the parameterisation of the radionuclide transport model.

The report presents modelling results for a constant unit radionuclide release rate (one becquerel per year), i.e. results expressed in terms of radionuclide inventories and activity concentrations in different media and associated doses to humans and dose rates to non-human biota. The unit release results for doses to humans are presented in the form of landscape dose conversion factors (LDFs). These results are used to make comparisons with previous safety assessments, and to provide a detailed analysis for selected radionuclides, including an evaluation of sources of uncertainty. For non-human biota, dose rates to various types of organisms in different ecosystems (marine, freshwater and terrestrial) are presented. Finally, the effects of assumptions and uncertainties in the biosphere modelling are synthesised and discussed, including an evaluation of their implications for the overall safety assessment.

Sammanfattning

Denna rapport presenterar biosfärsdelen av säkerhetsanalysen SR-PSU, vilket innebär att den är fokuserad på de ytnära system där människor och andra organismer kan exponeras för radionuklider som eventuellt läcker ut från SFR-förvaret i Forsmark. I rapporten sammanställs de data, processbeskrivningar och modeller som har använts för att beskriva platsen och utveckla och parametrisera modeller för beräkningar av radionuklidtransport och exponering. Vidare analyseras resultat från stiliserad modellering och information som stöder de förenklingar och antaganden som gjorts i samband med modellutveckling och parametrisering redovisas.

Rapportens viktigaste funktion är att ge en samlad och sammanfattande redovisning av modeller och data som utgör biosfärsdelen av den modellkedja som används för beräkningar av radionuklidtransport och doser i SR-PSU. Flertalet kapitel i rapporten utgörs därför av sammanfattningar av underlagsrapporter, i vilka de detaljerade beskrivningarna av modelleringsaktiviteter och resultat ges. Utöver detta innehåller rapporten en redovisning av resultat från modelleringar med så kallade enhetsutsläpp, vilka inte presenteras i någon underlagsrapport. Denna stiliserade modellering genomfördes i syfte att undersöka effekterna på radionuklidtransport av processer, egenskaper och parametrar som specifikt beskriver förhållandena i biosfären, utan inverkan av andra delar av systemet som skulle kunna komplicera tolkningarna.

Efter en allmän introduktion och redovisningar av arbetets bakgrund vad gäller metodik och lagstiftning, inleds själva modellbeskrivningarna med en presentation av relevanta delar av den platsbeskrivande modell (”site descriptive model”, SDM) som beskriver dagens förhållanden i Forsmark. Denna presentation innefattar viktiga underlagsmodeller såsom höjdmodellen (”digital elevation model”, DEM) och jordlagermodellen (”regolith depth and stratigraphy model”, RDM). Dessa modeller utgör centrala geometriska beskrivningar som används inom flera modelleringsdiscipliner. Beskrivningen av dagens Forsmark utgör utgångspunkten för framtagandet av modeller som beskriver de framtida förhållandena i området.

Första delen av beskrivningen av det framtida Forsmark handlar om klimatet och strandlinjeförskjutningen. Dessa beskrivs i enlighet med projektövergripande klimatfall, vilkas inverkan på processer och ekosystem i området diskuteras. Den platsspecifika utvecklingsmodellen för jordlager och sjöar (”regolith-lake development model”, RLDM) är ett viktigt verktyg i modelleringen av landskapets succession och möjliga framtida geometriska förhållanden. Därefter introduceras människans markanvändning, varvid förutsättningarna för olika typer av markanvändning i framtida Forsmarkslandskap analyseras. Resultaten av den kopplade analysen av naturliga förhållanden och mänsklig påverkan formuleras i termer av en landskapsutvecklingsmodell (”landscape development model”, LDM), där fem varianter av framtida landskapsutveckling beskrivs.

LDM används sedan tillsammans med resultat från hydrogeologisk modellering och information om nuvarande och framtida geometriska förhållanden för att identifiera och beskriva utvecklingen av de områden i landskapet där radionuklider från SFR kan nå ytekosystemen. Dessa områden kallas biosfärsobjekt och används i säkerhetsanalysens modellering av radionuklidtransport och stråldoser. Sammanlagt sju stycken biosfärsobjekt ingår i beräkningarna för tempererade klimatförhållanden, vilket är den typ av klimat som används i de flesta av säkerhetsanalysens beräkningsfall. De hydrogeologiska analyserna visar dock att huvuddelen det utströmmande grundvatten som har passerat förvaret sannolikt kommer att hamna i ett av objekten. Det konstateras därför att detta biosfärsobjekt, som betecknas objekt 157_2, är av störst intresse för säkerhetsanalysen.

Biosfärsobjekten i SR-PSU är av två huvudtyper: objekt som går igenom ett sjöstadium i sin succession, vilket betyder att de går från hav (havsvik) till sjö till våtmark och sedan möjligen används som jordbruksmark efter dränering, och objekt som saknar sjöstadiet i sin succession. Biosfärsobjektet som är av störst intresse i säkerhetsanalysen (objekt 157_2) är av den typ som saknar sjöstadium och kännetecknas av att varken vattendrag eller större sammanhängande ytvatten uppstår där efter havsstadiet. För modelleringen av radionuklidtransport och stråldoser under periglaciala klimatförhållanden identifieras två biosfärsobjekt, av vilka ett används även i modelleringen av tempererade klimat.

Viktiga steg i modelleringsprocessen är analysen av egenskaper, händelser och processer (”features, events and processes”, FEP) som kan påverka landskapsutvecklingen, transport och ackumulation av radionuklider i biosfären, och analysen av exponeringsvägar. Dessa analyser är grunden till formuleringen av de beräkningsfall som illustrerar effekter av de radionuklider som eventuellt når ytekosystemen. Analyserna av FEP och exponering använder en kombination av externa krav och rekommendationer och modelleringsteamets samlade kunskap om platsen för att identifiera och beskriva vad som är relevant och ska inkluderas i beräkningarna av transport, exponering och doser. Fyra typer av mest exponerade grupper identifierades. Dessa grupper representerar fyra olika markanvändningsalternativ (varav tre utgörs av olika former av jordbruk) och för varje grupp kartlades relevanta exponeringsvägar. Exponeringsanalysen innefattar också exponering av andra organismer än människan i terrestra, marina och limniska ekosystem. De exponerade populationerna utgör grund för formuleringen av de biosfärsberäkningsfall som ingår i den övergripande säkerhetsanalysen.

Efter identifieringen och beskrivningen av det som behöver modelleras, presenteras den numeriska beräkningsmodell som används vid beräkningarna av radionuklidtransport och doser i biosfären. I modellen delas biosfärsobjekt under landperioden upp i en terrester del (våtmark/myr) och en akvatisk del (sjö), där den akvatiska delen minskar i storlek med tiden till följd av sedimentation och igenväxning. Biosfärsobjekt som saknar sjöstadium (exempelvis objekt 157_2) går direkt från ett havsstadium till ett våtmarksekosystem. Den vertikala indelningen av beräkningsmodellen i olika lager baseras på de geologiska beskrivningarna i RDM (dagens förhållanden) och RLDM (framtiden). Rapportens modellbeskrivningar avslutas med en summering av de data som använts för att parametrisera radionuklidmodellen för biosfären.

I rapporten presenteras modelleringsresultat från beräkningar med randvillkor i form av ett konstant enhetsutsläpp till biosfären (en Bq per år) av studerade radionuklider. Resultaten omfattar beräknade inventarier och aktivitetskoncentrationer i olika medier (vatten, jord och luft) och delar av ekosystemen, samt doser till människa och dosrater till andra organismer. Dosresultaten för enhetsutsläpp presenteras i form av doskonverteringsfaktorer och jämförs med motsvarande resultat från tidigare säkerhetsanalyser. En detaljerad utvärdering av resultaten för fyra utvalda radionuklider (kol-14, klor-36, molybden-93 och nickel-59) redovisas också. För andra organismer än människan, presenteras dosrater till olika typer av organismer i terrestra, marina och limniska ekosystem. Slutligen redovisas en analys och diskussion av effekterna av antaganden och osäkerheter på biosfärsmodelleringen, samt en värdering av deras betydelse för den övergripande säkerhetsanalysen.

Contents

1 Introduction

1.1 The SR-PSU project

The final repository for short-lived low- and intermediate-level radioactive waste, SFR 1, is located in Forsmark in the Östhammar municipality (Figure 1-1), in the immediate vicinity of the Forsmark nuclear power plant (Figure 1-2). A map of the Forsmark area is presented in Appendix 1. The SFR 1 repository consists of a set of disposal chambers situated in rock at ca 60 m depth beneath the sea floor, and is built to receive and after closure serve as a passive repository for low- and intermediate-level short-lived radioactive waste. The radioactive waste stored in SFR includes operational waste from Swedish nuclear power plants and from the interim storage facility for spent nuclear fuel, Clab, as well as radioactive waste from other industries, research institutions and medical care.

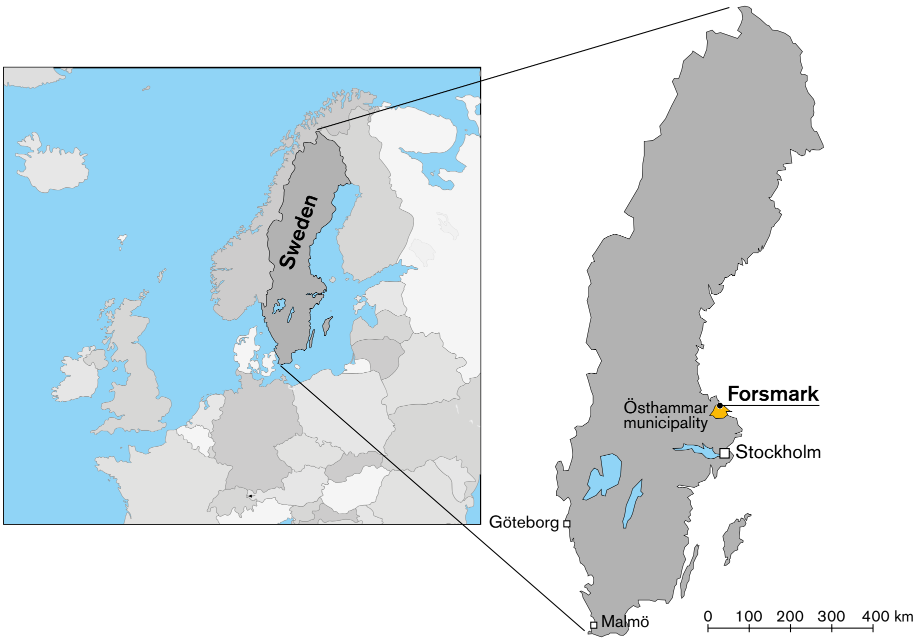


Figure 1-1. Location of the Forsmark site in Sweden (right) and in context with the countries in Europe (left). The site is situated in the Östhammar municipality, which belongs to the County of Uppsala.

Figure 1-2. The surface part of the SFR facility in the Forsmark harbour with the Forsmark nuclear power plant in the background.

In order to be able to also store decommissioning waste from the Swedish nuclear power plants in SFR, an extension of the repository, referred to as SFR 3, is planned. An SFR repository extension called SFR 2 was included in earlier plans for disposal of reactor core components and internal parts. However, according to present plans a separate repository (SFL) will be built for disposal of these types of waste (SKB 2013a).

As a part of the license application for the extension of SFR, the Swedish Nuclear Fuel and Waste Management Company (SKB) has performed the SR-PSU project. The objective of SR-PSU is to assess the long-term radiological safety of the entire future SFR repository, i.e. both the existing SFR 1 and the planned SFR 3. SR-PSU is reported in a series of SKB reports, which includes a main report, here referred to as the **SR-PSU Main report**, and a set of main references. These include, among others, the reports denoted as **Climate report**, **Radionuclide transport report**, **FEP report**, **FHA report** and **Biosphere synthesis report** (the present report) in the SR-PSU reporting (see Section 1.2). In addition to these main references, the safety assessment is based on a large number of background reports and other references.

The biosphere is a key part of the system considered in a safety assessment of a nuclear waste repository. This is where the consequences of potential future radionuclide releases from the repository arise, and hence near-surface radionuclide transport and dose calculations are performed within the framework of the biosphere assessment. This report belongs to the sub-project of SR-PSU called SR-PSU Biosphere. SR-PSU Biosphere mainly describes the information needed to calculate effects on humans and the environment in the case of a radionuclide release from SFR. The calculated effects are then used to show compliance with regulations related to future repository performance for time spans up to 100,000 years after closure. Because of the uncertainties associated with the prediction of future development of the site in this time frame, a number of calculation cases are analysed to describe a range of possible site developments.

The SR-PSU Biosphere project is divided into the following tasks:

1. Identification of features and processes of importance for modelling radionuclide dynamics in present and future ecosystems in Forsmark.
2. Description of the site and its future development with respect to the identified features and processes.
3. Identification and description of areas in the landscape that may be affected by releases of radionuclides from the existing repository and its planned extension.
4. Calculation of the radiological exposure to a representative individual of the most exposed group of humans in the future Forsmark landscape, and the radiological exposure to the environment.

The SR-PSU biosphere assessment builds on previous safety assessments for the existing and planned nuclear waste repositories in Sweden. Between 2002 and 2008, SKB performed site investigations for a repository for spent nuclear fuel in Forsmark. Data from these site investigations were used to produce a comprehensive, multi-disciplinary site description (SKB 2008a). This description has been used as a basis for understanding and modelling the site and its development.

The SFR repository has been in operation since 1988 and a number of safety assessments have been performed for the repository since SKB received permission to start building SFR 1 in 1983, including the SAFE project (Lindgren et al. 2001, Kautsky 2001) and SAR-08 (SKB 2008b). In addition, safety assessments have been performed for a planned repository for spent nuclear fuel, i.e. within the SR-Can (SKB 2006a) and SR-Site (SKB 2011) projects, for which SKB handed in an application in 2011. This implies that the SR-PSU biosphere assessment is based on knowledge gathered from site data, site modelling and the previous safety assessments, together with modelling performed and data collected during the SR-PSU project.

The work done within the SR-PSU Biosphere project has been conducted by a number of people. Many of the project participants have been involved from the site investigation, via the site characterisation and modelling tasks, through to the SR-PSU safety assessment; several members of the project group also have experience from previous safety assessments for SFR and for the planned repository for spent nuclear fuel. The project members in alphabetic order, their roles and affiliations are listed in Table 1-1.

Table 1-1. Project members of SR-PSU Biosphere in alphabetical order and their roles in the project.

Boris Alfonso, Facilia AB	Numerical modelling of impacts on non-human biota.
Eva Andersson, SKB	Project manager SR-PSU Biosphere, process descriptions, limnic ecosystems.
Karin Aquilonius, Studsvik Nuclear AB	Marine ecosystems.
Rodolfo Avila, Facilia AB	Radionuclide modelling and dose assessment.
Sten Berglund, HydroResearch AB	Hydrology and near-surface radionuclide transport, editor of the present report.
Lars Brydsten, Umeå University	GIS (geographical information system) analysis, regolith dynamics and lake development modelling.
Per-Anders Ekström, Facilia AB	Numerical modelling of radionuclide transport and doses.
Christin Eriksson, DHI Sverige AB	Oceanography.
Sara Grolander, Sara Grolander Miljökonsult AB	Distribution coefficient (K_d) and concentration ratio (CR) analysis, parameter report editor.
Fredrik Hartz, Hartz Technology AB	GIS analysis and landscape development.
Thomas Hjerpe, Facilia AB	FEP handling.
Ben Jaeschke, SKB	Non-human biota.
Emma Johansson, SKB	Hydrology.
Ulrik Kautsky, SKB	Overall biosphere coordinator at SKB, scientific and method development.
Sven Keesmann, SKB	Radionuclide model report.
Tobias Lindborg, SKB	Site modelling and landscape development.
Anders Löfgren, EcoAnalytica	Terrestrial ecosystems.
Sara Nordén, SKB	Non-human biota, K_d and CR analysis.
Veronika Rensfeldt, Facilia AB	K_d and CR analysis.
Peter Saetre, SKB	Radionuclide model development, data evaluation, synthesis.
Mona Sassner, DHI Sverige AB	Hydrology.
Gustav Sohlenius, SGU	Regolith and future land use.
Viktor Smide, Hartz Technology AB	GIS analysis and illustrations.
Mårten Strömgren, Umeå University	GIS analysis, landscape development.
Mats Tröjbom, MTK AB	K_d and CR analysis, water chemistry.
Kent Werner, EmpTec	Hydrology, wells, water resources management.
Per-Gustav Åstrand, Facilia AB	Numerical modelling of radionuclide transport and doses.

1.2 The SR-PSU report hierarchy

The SR-PSU project is reported in a series of SKB reports, which includes a main report and a set of main references that are referred to by abbreviated names in the SR-PSU reporting. The main references and the names used (bold, in text) when referring to them in this and other SR-PSU reports are shown in Figure 1-3 and listed in Table 1-2. In addition to the main references, the safety assessment is based on a large number of background reports and other references.

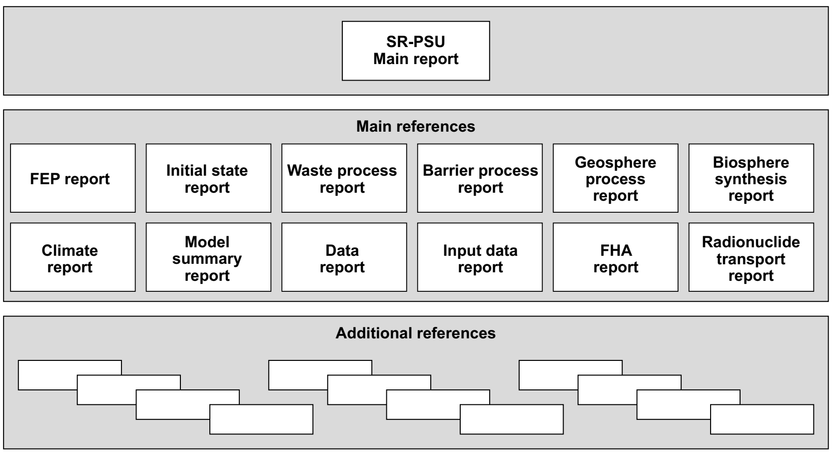


Figure 1-3. *Relationship between reports produced in the SR-PSU safety assessment.*

Table 1-2. The SR-PSU Main report and main references to it produced within SR-PSU. FEP stands for features, events and processes and includes FEP for all disciplines in the assessment (e.g. waste, geosphere and climate). FHA is short for future human actions.

Report number	Short name used when referred to in the text	Full title
TR-14-01	SR-PSU Main report	Safety analysis for SFR. Long-term safety. Main report for the safety assessment SR-PSU.
TR-14-02	Initial state report	Initial state report for the safety assessment SR-PSU.
TR-14-03	Waste process report	Waste form and packaging process report for the safety assessment SR-PSU.
TR-14-04	Barrier process report	Engineered barrier process report for the safety assessment SR-PSU.
TR-14-05	Geosphere process report	Geosphere process report for the safety assessment SR-PSU.
TR-14-06	Biosphere synthesis report	Biosphere synthesis report for the safety assessment SR-PSU.
TR-14-07	FEP report	FEP report for the safety assessment SR-PSU.
TR-14-08	FHA report	Handling of future human actions in the safety assessment SR-PSU.
TR-14-09	Radionuclide transport report	Radionuclide transport and dose calculations for the safety assessment SR-PSU.
TR-14-10	Data report	Data report for the safety assessment SR-PSU.
TR-14-11	Model summary report	Model summary report for the safety assessment SR-PSU.
TR-14-12	Input data report	Input data report for the safety assessment SR-PSU.
TR-13-05	Climate report	Climate and climate-related issues for the safety assessment SR-PSU.

Table 1-3 presents the background reports produced within SR-PSU Biosphere. For these reports, conventional references are used in the present report (e.g. "Strömgren and Brydsten (2013)" for the DEM report); however, the short names/descriptions are in some cases used in the biosphere work and reporting, and are therefore listed in the table together with references and titles. The relationships between the background biosphere reports and the main references are shown in Figure 1-4. The present report, the **Biosphere synthesis report**, is one of the main references listed in Table 1-2. The report is a summary and synthesis of the biosphere assessment; see Section 1.3 for an overview of the work performed and Section 1.4 for a description of the role and contents of the report. As indicated in Figure 1-4, it is based on input from a large number of background reports and provides input to the **SR-PSU Main report**.

Table 1-3. Biosphere background reports produced within SR-PSU Biosphere; FEP stands for features, events and processes.

Report number	Short description and reference in text	Full title
R-12-03	DEM report, Strömgren and Brydsten (2013)	Digital elevation model of Forsmark. SR-PSU Biosphere.
R-13-01	K_d and CR report, Tröjbom et al. (2013)	K_d and CR used for transport calculations in the biosphere in SR-PSU.
R-13-18	Biosphere parameter report, Grolander (2013)	Biosphere parameters used in radionuclide transport modelling and dose calculations in SR-PSU.
R-13-19	Surface hydrology report, Werner et al. (2013a)	Hydrology and near-surface hydrogeology at Forsmark – synthesis for the SR-PSU project. SR-PSU Biosphere.
R-13-20	Hydrological data report, Werner et al. (2013b)	Meteorological, hydrological and hydrogeological monitoring data from Forsmark – compilation and analysis for the SR-PSU project. SR-PSU Biosphere.
R-13-22	RDM report, Sohlenius et al. (2013a)	Depth and stratigraphy of regolith at Forsmark. SR-PSU Biosphere.
R-13-27	RLDM report, Brydsten and Strömgren (2013)	Landscape development in the Forsmark area from the past into the future (8500 BC to 40,000 AD).
R-13-43	Biosphere process definition report, SKB (2013b)	Components, features, processes and interactions in the biosphere.
R-13-46	Biosphere radionuclide model report, Saetre et al. (2013a)	The biosphere model for radionuclide transport and dose assessment in SR-PSU.
R-14-02	Biosphere FEP handling report, SKB (2014)	Handling of biosphere FEPs and recommendations for model development in SR-PSU.

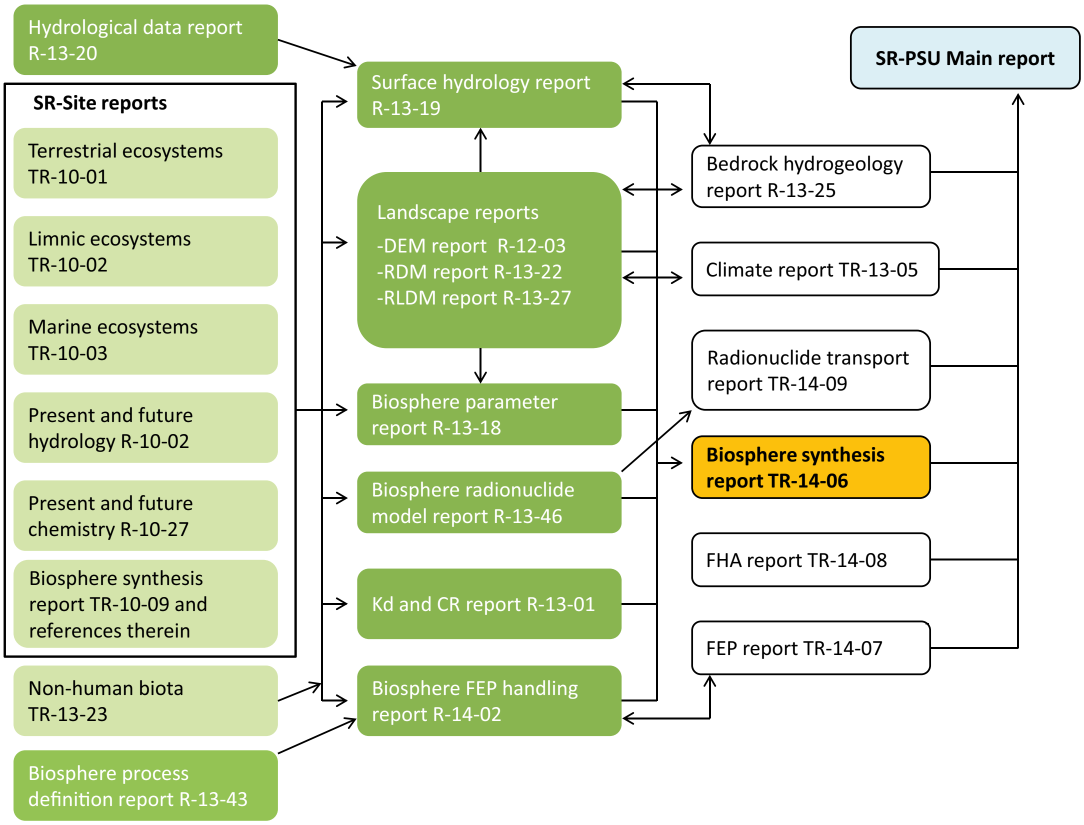


Figure 1-4. *Relationship between reports produced in the SR-PSU Biosphere project (dark green boxes). The present report is marked in orange and bold. Supporting documents produced within other biosphere projects at SKB are shown as light green boxes, whereas other reports in the SR-PSU project are shown in white except the* ***SR-PSU Main report,*** *which is shown in blue.*

1.3 Overview of the biosphere assessment

1.3.1 Site description and process understanding

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 the development of scenarios describing future conditions at the Forsmark site, is summarised and synthesised in Lindborg (2008, 2010), Söderbäck (2008), SKB (2010) and in a series of papers in a special issue of the AMBIO journal (e.g. Lindborg et al. 2013, Berglund et al. 2013a, b, Saetre et al. 2013b). The SR-PSU biosphere modelling is based on these earlier works and additional studies focused on specific subject areas (e.g. hydrology), parameters (e.g. distribution coefficients) or issues (e.g. transport of radiocarbon, C-14) performed in connection with SR-PSU.

As in the previous safety assessments, emphasis was in SR-PSU put on improving the understanding of features, processes and parameters where uncertainties are likely to have a large influence on estimates of exposure. This includes updated descriptions of landscape development (Brydsten and Strömgren 2013, Chapter 5 of the present report), present and future hydrology and hydrodynamics (Werner et al. 2013a, Karlsson et al. 2010, Chapters 3 and 4 of the present report), and the distribution coefficients (i.e. K_d and CR values) that quantify radionuclide retention in the transport model employed in the safety assessment (Tröjbom et al. 2013, Chapter 9 of the present report).

The identification and handling of features and processes that are important for transport and accumulation of radionuclides in the environment are also of importance to the assessment of impacts on human health and the 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-PSU safety assessment to reflect the current understanding of ecosystem processes and radionuclide behaviour at the investigated site (SKB 2013b, 2014).

1.3.2 Discharge areas and biosphere objects

The discharge of groundwater in future landscapes has been used to identify areas that may be directly affected by radionuclides released from the SFR repository. These areas are referred to as biosphere objects, and extensive work has been performed in this and previous safety assessments to obtain detailed descriptions of the ecosystems that are likely to develop in these areas (Andersson 2010, Aquilonius 2010, Löfgren 2010), and of their successional development (Brydsten and Strömgren 2010, 2013). Transport within and between biosphere objects has been modelled (Werner et al. 2013a, Karlsson et al. 2010) and the present retention of elements in regolith and in biota in similar environments at the site has been characterised (Tröjbom et al. 2013). 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 (Grolander 2013).

1.3.3 Radionuclide modelling

Transport and accumulation of radionuclides that could potentially be released to biosphere objects was simulated with a radionuclide transport model implemented in the Ecolego software (Saetre et al. 2013a). 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. For the safety assessment, the exposure of the most exposed group was calculated using modelled time-variant releases from the repository (**Radionuclide transport report**). However, for the purposes of understanding biosphere processes, calculations based on simplified inputs to the biosphere were also carried out. That is, transport and accumulation in the biosphere was assessed assuming a constant release, and the results of these calculations are presented herein. Environmental activity concentrations were used to assess the potential for radiological impacts on the environment.

1.4 This report

This report is the main document for reporting the biosphere analyses performed within the SR-PSU safety assessment, and as such it provides the background information for conclusions on the biosphere communicated in the **SR-PSU Main report**. The report gives the context of the biosphere assessment, 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 are assessed. All information necessary for a detailed review and for a reconstruction of the work done can be found in the background reports, which communicate primary analyses and results (Figure 1-4).

The main contents of each chapter of the present report are described below. Where applicable, the main references providing the basis for the chapter are also given.

Chapter 1 (this chapter) gives a short background to the SR-PSU safety assessment, and an introduction to the SR-PSU Biosphere work, including a brief description of the framework and workflow of the project and a list of the persons involved in the biosphere part of the safety assessment.

Chapter 2 puts the biosphere analyses into the context of the SR-PSU 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-PSU safety assessment is put in relation to international recommendations.

Chapter 3 provides a description of the present-day conditions at Forsmark. The site description focuses on features and processes that are important for transport and accumulation of radionuclides. The chapter is structured in terms of descriptions of the Forsmark landscape with respect to topography, regolith, climate, hydrology, coastal oceanography, chemistry, ecology and utilisation of the landscape by humans. The main inputs to this chapter are the most recent site descriptions of Forsmark, i.e. SDM-Site (SKB 2008a) and SDM-PSU (SKB 2013c), and the references given therein.

Chapter 4 describes the long-term development of the site in terms of the main driving forces, i.e. climate and climate-related processes, and their effects on the processes and systems considered in the description of present site conditions (Chapter 3). A summary of the SR-PSU climate cases, based on the **Climate report**, is given, followed by short descriptions of possible future development of biosphere processes and systems. These descriptions are based on results from SR-Site (Lindborg 2010, SKB 2010) and additional modelling performed for SR-PSU (e.g. Strömgren and Brydsten 2013, Brydsten and Strömgren 2013, Werner et al. 2013a).

Chapter 5 describes the landscape development modelling, which essentially integrates the descriptions of present site conditions (Chapter 3) and future development of processes and systems (Chapter 4) with an analysis of possible future land uses under different conditions and assumptions in terms of climate and human utilisation of the area. The modelling results in a set of landscape development variants presented as maps of future Forsmark for selected combinations of climate and land use, and which are used as a basis for the development of biosphere transport models.

Chapter 6 presents the modelling of biosphere objects. This modelling starts with the identification of the areas in the landscape that are most likely to be affected by potential future releases of radionuclides from the SFR repository, i.e. the biosphere objects. The identification uses modelled discharge areas of groundwater that has passed through the repository at different times in the future, as obtained from results of hydrogeological modelling (Odén et al. 2014). This is followed by a presentation of the principles for delineating biosphere objects and how they are connected in the landscape. Finally, a description of the resulting model for biosphere objects is given. This part of the biosphere assessment is similar to SR-Site in terms of principles and methodology (see Lindborg 2010), and the description in the present report is therefore focused on differences from the previous assessment.

Chapter 7 includes a description of the handling of biosphere FEPs (features, events and processes), an exposure pathway analysis describing the different exposure routes considered for humans and the environment, and finally a description of the biosphere calculation cases considered in the assessment. This chapter is based on new background reports related to FEPs produced for SR-PSU (SKB 2013b, 2014).

Chapter 8 gives a brief presentation of the mathematical model, the underlying 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 quantifies exposure of humans and non-human biota from these media through relevant pathways. This chapter summarises the detailed descriptions of radionuclide models for different ecosystems and assumptions related to their application that are provided in Saetre et al. (2013a).

Chapter 9 presents the input parameters that are needed to calculate radiological exposures. 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. This chapter is based on the background report by Grolander (2013).

Chapter 10 presents and discusses the results of transport and dose calculations performed for the purposes of the biosphere assessment, i.e. not the results of the overall safety assessment (they are presented in the **SR-PSU Main report**). The focus is on the analysis of transport and accumulation of radionuclides in the biosphere and the associated processes, parameters and uncertainties. The results in Chapter 10 are therefore derived from model calculations based on simplified boundary conditions (i.e. constant unit releases) that make it possible to distinguish the processes and parameters of the biosphere from the rest of the system. Effects of selected assumptions and uncertainties are illustrated and unit-release results are compared to the corresponding results from earlier safety assessments.

Chapter 11 synthesises and discusses the results of the biosphere analysis, including an evaluation of assumptions and how they may affect the final results. The starting point of the discussion is the identification and analysis of selected radionuclides presented in Chapter 10, which is extended and generalised to a discussion on simplifying assumptions and main uncertainties affecting calculated activity concentrations and doses in the environment and potential food resources.

The present report contains several terms and acronyms that either are rarely used outside SKB or can be regarded as specialised terminology within one or several of the modelling disciplines involved in the reported work. In order to facilitate the readability of the report, terms and acronyms are listed in Appendix 2.

2 Assessment context

This chapter gives the background to the biosphere part of the SR-PSU 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 the long-term safety of a repository for radioactive waste. After that, a description of how the SKB biosphere analysis and dose assessment relate 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 brief account of the assessment philosophy.

2.1 Assessment purpose

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

- to assess the long-term radiological safety of the SFR repository, including both the existing SFR 1 and the planned extension SFR 3 (see the **SR-PSU Main report**),
- to provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.

For the biosphere part of the assessment, the general purpose is to determine the radiological significance of potential future releases of radionuclides from SFR 1 and 3 into the surface environment at Forsmark, and to consider such releases in relation to Swedish regulatory requirements for radioactive waste disposal.

2.2 Preconditions for the SR-PSU safety assessment

2.2.1 Repository system

SFR 1 was built to receive, and after closure serve as a passive repository for, low- and intermediate-level radioactive waste. SFR 1 was built between 1983 and 1988 and has been operating to store operational waste since 1988. The low- and intermediate-level waste in SFR 1 consists of operational waste from the Swedish nuclear power plants and from the interim storage facility for spent nuclear fuel, Clab, as well as similar radioactive waste from other industries, research institutions and medical care (**SR-PSU Main report**).

The disposal chambers are situated in rock beneath the sea floor, and are covered by about 60 metres of granitiod rock, a few metres of regolith and 6–10 m seawater (Kautsky 2001). The disposal chambers contain different types and amounts of waste (see further the **Initial state report)**. The underground part of the facility is reached via two tunnels, whose entrances are near the surface facility (Figure 2-1). The planned extension SFR 3 will function in the same way as the existing repository, but the rock vaults will be situated at a depth of about 120 m. In addition to similar wastes as those held at SFR 1, reactor vessels from Swedish boiling water reactors are also planned to be stored in SFR. Therefore, the additional tunnel entrance has to be built large enough to enable transport and storage of the larger reactor vessels (Figure 2-1).

2.2.2 Site context

This section gives a brief summary of the site context. More detailed descriptions are given in Chapter 3 (Present conditions), Chapter 4 (Site development processes), and Chapter 5 (Landscape development).

Forsmark is located on the coast of the Baltic Sea (Bothnian Sea) in the County of Uppsala within the Municipality of Östhammar, about 120 km north of Stockholm, Sweden (Figure 1-1). The existing and planned extension of SFR is situated in the vicinity of the nuclear power plant in Forsmark. The surroundings show small-scale topographic variations of less than 20 metres (Figure 2-2).

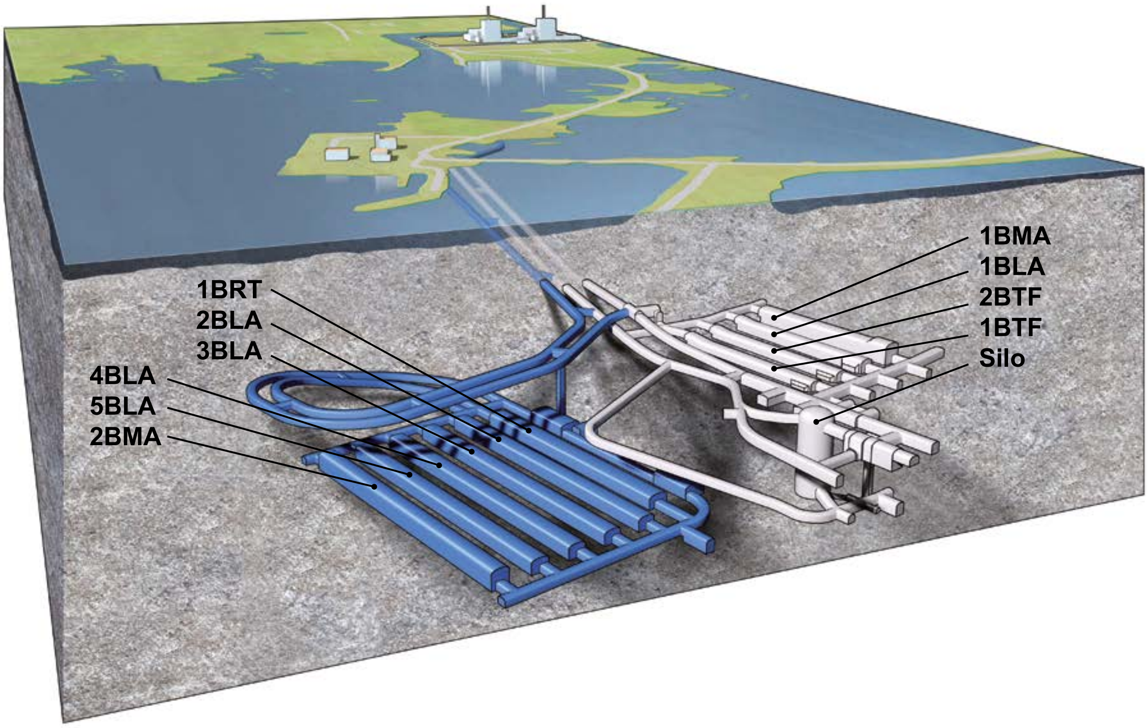


Figure 2-1. *Illustration of the SFR repository. White represents the existing repository SFR 1, and blue is the planned extension SFR 3. The tunnels to the repository extend to the surface buildings (centre of picture). The dimension and functions of the rock vaults (BMA, BLA, BTF and RTF) and Silo and the different types of waste are described further in the* ***Initial state report****.*

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 (see Chapter 3). The coastline consists of sheltered shallow bays and small islands. The coast is exposed to 600 km of open sea towards the northeast, which creates fast water turnover and a long fetch for wave action (Brydsten 2009). Thus, 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.

Most parts of the landscape are covered by a thin regolith layer, dominated by till. The mean regolith thickness in the Forsmark area is c. 4 m in terrestrial areas and 8 m in marine areas (Chapter 3 and Sohlenius et al. 2013a). The regolith thickness on the sea floor above the SFR repository is 1–4 m. 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 3). The land use outside the controlled area around the nuclear power plant and SFR is dominated by recreational hunting and fishing. Such practices may contribute to the diet of some inhabitants; however, 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 in this area was dominated by forestry, especially when supplying the iron-works at Forsmark with charcoal, and by small-scale farming and fishing.

Figure 2-2. The coastal area in Forsmark, characterised by small altitudinal differences, shallow coastal bays and recently isolated small lakes and wetlands.

2.2.3 Release scenarios and source terms

The two main safety principles of SFR are: 1) limited quantity of radioactivity in the waste, and 2) retardation. The repository will eventually lose its containment capacity and isolation will be lost. Limited amounts of waste and long retardation of releases will keep the risk for humans and the environment low. There are a number of scenarios identified to evaluate the predicted release from SFR (**SR-PSU Main report**).

The activity of the expected inventory is listed in the **Initial state report**. A substantial amount (98%) of the activity decays away during the first thousand years. The activity in the waste is dominated by Ni-63 during the first 600 years and thereafter by Ni-59 and C-14. The potential radiotoxicity of the radionuclides is influenced by the type and energy of radiation they emit and by their mobility. Modelling results presented in the **SR-PSU Main report** show that the radiotoxicity is initially dominated by Am-241, and that this toxicity has decreased to 1% of that at closure after about 5,000 years.

In SR-PSU, radionuclide transport and dose are calculated with a series of models. The near-field model describes radionuclide release from the waste packages and the repository. The far-field model is used to describe transport in the water phase in the geosphere, from the repository to the biosphere. The radionuclide model for the biosphere is used to describe transport and accumulation in the biosphere and to evaluate exposure (see the **Radionuclide transport report** for an overview of radionuclide transport models and calculations).

Potential areas of radionuclide release from the geosphere to the biosphere are simulated in the hydrogeological analysis, which describes where and when in the landscape the discharge of deep groundwater that has passed through the repository could be expected (Odén et al. 2014). Accordingly, the analysis of discharge includes both a spatial and a temporal dimension. These discharge simulations are used to identify areas in the surface ecosystems where potential doses to humans and non-human biota are calculated. The near-field, far-field, and biosphere radionuclide models are combined in the assessment model (see the **Radionuclide transport report**) to calculate dose to humans and the environment for different release scenarios, further described in Chapter 7.

2.3 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 the environment, and other requirements of special interest for the biosphere assessment, which are given in SSMFS 2008:37, are summarised below.

2.3.1 Time frames

The regulations (SSM 2008a) require that a safety assessment for a repository's protective capability should be assessed quantitatively in detail for the first thousand years after repository closure. For a longer time period, the assessment of the repository's protective capability shall be based on various possible sequences for the development of the repository's properties, its environment and the biosphere. In the general advice of the regulation (SSM 2008a), it is clarified that for a repository of SFR type the longer time frame should at least cover the period of time until the expected maximum consequences in terms of risk and environmental impact have taken place, although for a maximum time period of up to one hundred thousand years. The arguments for the selected limitations of the risk analysis should be presented (SSM 2008a).

2.3.2 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 No. 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.

2.3.3 Most exposed group

The most exposed group cannot be described 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 large 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."*.

2.3.4 Effects on the environment

For the protection of the environment, no risk criteria exist in the Swedish legislation. However, SSM (2008a) states in §6 and 7: *"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. Biological effects of ionising radiation in the habitats and ecosystems concerned shall be described. The report shall be based on available knowledge on the ecosystems concerned and shall take particular account of the existence of genetically distinctive populations such as isolated populations, endemic species and species threatened with extinction and in general any organisms worth protecting."*

"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."

2.3.5 Scenarios

The regulations give some information on scenarios that should be included in a safety assessment for radioactive waste repositories. Paragraph 10 in SSMFS 2008:37 and the general advice for Section 9 in SSMFS 2008:21 are of specific interest for the identification of biosphere calculation cases. In these, the following statements are found:

SSMFS 2008:37 § 10 *"The description shall include a case based on the assumption that the biospheric conditions prevailing at the time when an application for a licence to construct the repository is submitted will not change. Uncertainties in the assumptions made shall be described and taken into account when assessing the protective capability."*

SSMFS 2008:37, general advice *"Taking into consideration the great uncertainties associated with the assumptions concerning climate evolution in a remote future and to facilitate interpretation of the risk to be calculated, the risk analysis should be simplified to include a few possible climate evolutions. A realistic set of biosphere conditions should be associated with each climate evolution."*

General advice of SSMFS 2008:21, Section 9 *"Based on an analysis of the probability of occurrence of different types of scenarios in different time periods, scenarios with a significant impact on repository performance should be divided into different categories*:

- *main scenario,*
- *less probable scenarios,*
- *other scenarios or residual scenarios.*

The main scenario should be based on the probable evolution of external conditions and realistic, or where justified, conservative assumptions with respect to the internal conditions."

Thus the regulatory guidelines point out that there should be at least one calculation case where the biosphere conditions of today prevail into the future, and that realistic assumptions should be applied for the description of the biosphere.

2.4 Relationship to international experience

The Swedish programme for handling and storage of spent nuclear waste has a substantial history of working with international organisations and other national agencies with interests in 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.

2.4.1 Background to international cooperation in biosphere assessments

The Swedish programme has offered opportunities for peer review of various aspects of its safety assessment methods, going back as far as 1984 (Swedish Ministry of Industry 1984). The reviews 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 (SSI, later becoming the Swedish Radiation Safety Authority SSM) 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,
- 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 as well as in the first safety assessments of SFR, 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 1996a).

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 benchmark, or point of reference, with 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 1996b).

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 (IAEA 2003). 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 in six Task Groups, including the participation of SKB experts and support organisations.

2.4.2 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 a focus on site-specific assessments, which reflects the progress in 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. BIOPROTA is designed to support the 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, for example, been involved in projects related to geosphere biosphere interactions (GBIZ) and C-14 behaviour in the environment and non-human biota assessments (e.g. Bergström et al. 2006, Leclerc-Cessac et al. 2006, Limer et al. 2012, Jackson et al. 2014).

SKB also participated in the IAEA programme Environmental Modelling for RAdiation Safety (EMRAS II), contributing to the working group 3 activities on the dose implications for environmental change. SKB continues to work within the follow-up project MOdelling and DAta for Radiological Impact Assessments (MODARIA), especially within working group 6 on developing a common framework for addressing environmental change in long-term safety assessments of radioactive waste disposal facilities, with a special focus on climate change and its consequences.

2.4.3 Application of the BIOMASS methodology in SR-PSU

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-PSU. Since the start of the SKB programme, iteration has affected all parts in the process and thus the steps identified in IAEA (2003) are not necessarily taken in the same order, but rather in parallel.

Define the assessment context

This Chapter 2 sets out the assessment context for the biosphere within SR-PSU. 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; which are needed to make the assessment coherent,
- provide a clear record of the purpose of making each of the calculations.

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 shore level at Forsmark, are addressed in Chapter 5. These changes have substantial implications for the information needed to address the assessment endpoints, and influence the importance of various biosphere processes and potentially relevant exposure pathways (Chapter 7), the identification of discharge areas and the development of these over time (Chapter 6), 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 3) and how it is expected to develop as a result of environmental change (Chapters 4 and 5). 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 development (see, e.g. Lindborg 2008, 2010, Aquilonius 2010, Andersson 2010, Löfgren 2010).

Consideration of potentially exposed groups

It is not possible to reliably predict human behaviour so far into the future as is required for the demonstration of safety. IAEA (2003) proposes the following approach:

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

This approach has been adopted by SKB. An exposure pathway analysis has been performed (Chapter 7). The exposure pathways identified as potentially important have been included in a number of exposed populations, identified from historically self-sustainable communities. The use of several exposed communities can then be used as bounding cases to ensure that the most exposed group is used in the calculations.

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 6. Similarly to IAEA (2003), interaction matrices were used to develop an understanding of how these objects exist together over the area and ecosystems of interest (Chapters 3 and 7). A systematic approach was used to check the inclusion, or justified exclusion, of potential FEPs (Chapter 7). Two stages were then adopted to model development: firstly, the development of potential discharge areas within the Forsmark landscape was modelled (Chapters 5 and 6) and secondly the movements of radionuclides within the evolving biosphere objects were modelled. The radionuclide model used in SR-PSU is based on the SR-Site radionuclide model, but has been developed to answer questions of special interest for SR-PSU, for example to represent C-14 transfers in the biosphere. The radionuclide model is described in Chapter 8.

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

2.5 Summary of earlier SKB work

The methodology for assessment of radiological effects on humans and the environment from a repository for spent nuclear waste has developed considerably during the last few decades and SKB have been deeply involved in this development. A number of biosphere assessments have been performed by SKB, the development of which have regularly been reported in the RD&D Programme, with SKB (2013a) being the latest report. A review of the first c. 25 years of work on biosphere assessments is found in Edlund et al. (1999). A safety report for SFR was submitted in 1987 but has since then been updated by the safety assessments Safe and SAR-08 (cf. below). In parallel, SR-97, KBS-3, SR-Can, and SR-Site have been produced as safety assessments of a planned repository for spent nuclear fuel. Although safety assessments for the low- and intermediate- level waste repository SFR and for spent nuclear fuel differ in several aspects, the biosphere is assumed to have the same development and functioning and therefore the development of the approach to biosphere assessment has been driven by both kinds of assessments.

2.5.1 KBS-3

Already when the KBS-3 report (SKBF/KBS 1983) 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 2.4.

2.5.2 SFR 1

The post closure safety of the SFR 1 repository was analysed for the first time in the 1980s. The results and the review that was undertaken by the authorities led to a study that dealt explicitly with the problems of C-14 (Hesböl et al. 1990). This early analysis contained a detailed assessment of the biosphere dealing with the landscape at different spatial dimensions ranging from the local ecosystems to regional, intermediate and global scales. The details and knowledge from this biosphere assessment were state-of-the-art in terms of implementing a safety assessment for a real site and a real repository. The knowledge from this assessment has been the firm basis for the continuation of the biosphere modelling in the following biosphere assessments up to SR-Site (see Sections 2.5.3 to 2.5.9).

2.5.3 SR-97

With the SR-97 assessment (SKB 1999a), a spatially distributed model was introduced and site-specific data were used to parameterise the model (Bergström et al. 1999). The biosphere was subdivided into different ecosystems, and ecosystem-specific dose conversion factors (EDFs) were calculated (Nordlinder et al. 1999). Several important issues were identified. One of them was the gap 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 were 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 (Lindborg and Schüldt 1998). 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 were obtained from other sources. The lack of understanding of forest ecosystems contaminated by groundwater discharge was identified.

2.5.4 SFL 3-5

In parallel to the work with SR-97 a preliminary assessment of a deep repository for intermediate-level and long-lived waste (SFL 3-5) was presented (SKB 1999b). Mainly the biosphere assessment from SR-97 was used to calculate the dose from high-level and intermediate-level wastes other than spent fuel (see SKB 1999b).

It was necessary to expand the list of radionuclides, for example, with Mo-93. The results showed that long-lived and mobile radionuclides like Cl-36 and Mo-93 are important. It also showed that the site and biosphere conditions are important if the repository should fulfil the regulatory limits.

It is interesting to note that the highest dose conversion factors in these calculations were obtained with the ecosystems peat, well and agricultural land. Drinking water was a dominant exposure pathway for actinides in the well, but for the bioavailable nuclides such as chlorine, iodine and caesium isotopes, doses from consumption of food from agricultural land contaminated directly by groundwater exceeded those from a well. Thus, it was emphasised that it is necessary to expand the biosphere assessment beyond the traditional well scenario. This assessment also demonstrated that for some repositories a more realistic approach is needed with fewer conservative assumptions.

2.5.5 SAFE

SR-97 was followed by the renewed assessment of the SFR facility called SAFE (Andersson et al. 1998) for which the biosphere activities are summarised in Kautsky (2001). 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 and near-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 confirmed later in SR-Site. The implication of this is that discharge areas are not randomly distributed among the surface ecosystems, but are instead concentrated to specific ecosystems.

The biosphere assessment in SAFE was made using the discharge flux directly, 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 concentration factors, for example, 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 PANDORA tool (see next sections). 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 and improved for SR-PSU.

The SAFE assessment was also the first time that the draft version of the SSM regulations (SSM 2008a) was 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 the authorities reinforced this conclusion. The SAFE project was the foundation for the biosphere group that has since then continued and extended its work for SR-Site and SR-PSU.

2.5.6 SR-Can interim assessment

The development of the safety assessment for the HLW (high-level waste) repository included several preparatory steps. One was a test safety assessment "SR-Can interim" (SKB 2004). This was then followed by SR-Can, and later by SR-Site.

In SR-Can interim, the first version of the landscape model was implemented using a newly 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 development of 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 needs for 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, because most parameters are time dependent.

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.

2.5.7 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 (SKB 2006a). The biosphere work was summarised in two reports, representing the two sites then under consideration (SKB 2006b, c). 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 would 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 fitted 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 8) 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 of SR-Can pointed out several issues. Major concerns were about discretisation of the biosphere, the distribution of the discharge points, and the assessment of the 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 later safety assessments. 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 Chapter 1 in this report).

2.5.8 SAR-08

SAR-08 (SKB 2008b) was the previous safety assessment for SFR. For all radionuclides except C-14, similar landscape models as those used for SR-Can were used and biosphere ecosystem models for sea, lake, mire, and well similar to those used in SAFE were used in this assessment. The major step forward was the updated models for C-14. These models were based on the so-called 'specific activity approach'. The main assumption behind these models is that the long term environmental behaviour of C-14 is modulated by the environmental cycles of stable carbon (C-12) and that isotopic equilibrium between C-14 and C-12 is achieved with a constant isotopic ratio (specific activity), i.e. the same specific activity is observed in all environmental compartments. The specific activity is defined as the activity concentration of C-14 in a medium, expressed in Bq g^{-1} or Bq m^{-3}, divided by the stable carbon content in the same medium, expressed in g C g^{-1} or g C m^{-3}. Furthermore, several other realistic and cautious assumptions were made for deriving simplified equations for calculating C-14 specific activities. The dose assessment and radionuclide model is described in Bergström et al. (2008) and Avila and Pröhl (2008).

The review conducted by SSM pointed out several issues that could be improved for future assessments. Major concerns were about the discretisation and resulting size of the biosphere objects, and how accumulated radionuclides were transferred to later ecosystems in the succession. SSM also asked for clearer documentation of how identified FEPs are included in the biosphere assessment.

2.5.9 SR-Site

SR-Site (SKB 2011) was the safety assessment that was contained in the application for a license to build a deep repository for spent nuclear fuel at Forsmark. An overview of the different biosphere activities and reports was given in the synthesis report (SKB 2010). This was the first assessment to utilise the extensive information from the site. Especially for the biosphere assessment it was a large step forward. The process understanding and extraction of parameter values were presented in three volumes covering the marine (Aquilonius 2010), freshwater (Andersson 2010) and terrestrial ecosystems (Löfgren 2010).

The thorough modelling of near-surface hydrology was the basis of the current understanding of the water turnover at the site (Bosson et al. 2010) and the analysis of the landscape development (Lindborg 2010) formed a firm basis to describe how the succession of objects in the landscape affects important parameter values of the dose assessment. In this assessment, a new radionuclide model was applied (Avila et al. 2010). The model contains all the landscape elements in a single model, which enables a continuous dose calculation during landscape development. This removes the artefacts due to the step-wise replacements of biosphere objects, as was done in earlier assessments. The model also included the possibility to handle stable isotopes to deal with isotopic dilution.

The safety report is currently being reviewed by the authorities, but an early review by OECD-NEA declared that the analysis and discussion of biosphere modelling in SR-Site was excellent and state-of-the-art (OECD/NEA 2012). The understanding from SR-Site and the new model tools and parameters values are the basis for SR-PSU; the main part of the intellectual capital is also reused in SR-PSU.

2.6 Biosphere assessment implementation and 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 addition, SKB's ambitions and long term goals are also an important part of the context when the biosphere model is to be implemented. However, in a safety assessment the initial ambitions and goals have to be balanced with the uncertainties as to the future Forsmark landscape and its inhabitants. In SR-PSU the outcome of this is founded on a few guiding principles that can be seen as the biosphere assessment philosophy.

The main purpose of the biosphere assessment is to allow estimations of the radiological risk for humans and the environment that reflect a robust description of the biosphere and a credible handling of associated uncertainties. Thus, we have aimed to make the transport model of natural ecosystems as realistic as possible, with respect to model structure, primary transport pathways, landscape development and the associated parameters. However, the uncertainties with respect to the characteristics of future human inhabitants of the area are large. Thus, the description of exposure has been based on an analysis of potential exposure pathways, rather than on an attempt to explicitly predict living conditions and habits of generations to come in the Forsmark area. Following this approach, ecosystems created by humans have a more simplified representation than natural ecosystems, and exposed populations are to be interpreted as credible bounding cases with respect to the identified exposure pathways.

2.6.1 Transport modelling

The structure of the radionuclide transport model of natural ecosystems is founded on the model developed in the SR-Site assessment (SKB 2010). That is, the starting point has been a model designed to simulate the transport and fate of radionuclides that are discharged into connected ecosystems that evolve in the Forsmark landscape. In SR-PSU the model has been further developed to incorporate features of C-14 cycling, and the model structure has been supported by a FEP-analysis that explicitly considers features of the ecosystems at the site. In the model, radionuclide fluxes are linked to natural processes (e.g. fluxes of water, solids or gas, diffusion and plant uptake), to make it possible to derive parameters from conditions measured or modelled at the site.

The use of real site data means that model assumptions and parameter values can easily be traced back to the site description. Moreover, using a representative data set, where the measured parameters are sampled at the same site during the same time period, gives internally consistent datasets. Thus, it is possible to make a scientifically underpinned and coherent assessment that is relevant for Forsmark.

The assessment is based on substantial knowledge of present-day conditions at Forsmark and its Holocene history. For the current situation, the uncertainty in assumptions and parameters describing the succession of natural ecosystems is relatively low (Chapter 10). However, uncertainties in biosphere properties in the future increase gradually with time, and thus it is inevitable that some cautious assumptions have to be introduced to handle these uncertainties (Chapter 10).

2.6.2 Most exposed group and calculation cases

There are no prescriptions in the Swedish regulations concerning assumptions on future human behaviour and land use (see Section 2.3.3). As uncertainties connected with future human inhabitants are vast, SKB deem it undoable to assign characteristics and habits that are likely to provide realistic estimates of the actual characteristics and habits of humans in the far future. Instead we have performed an exposure-pathway analysis to identify all relevant pathways of exposure. Following international recommendations (ICRP 2007), we then constructed a number of exposed groups which we argue are credible bounding cases, reflecting land use and habits that are reasonable and sustainable with respect to the Forsmark area as well as human physiological requirements (see Chapter 7).

One of the identified exposed groups represents the use of natural ecosystem for living space and food and water supplies. However, all other exposed groups represent land uses where cultivation plays a central part in the exposure pathways. For these scenarios we have used stylised representations of transport and accumulation in cultivated soil, in combination with bounding assumptions with respect to land use which result in exposure from radionuclides accumulation in regolith, from radionuclides taken up in aquatic and terrestrial plants (through fertilisation), or from radionuclides in ground or surface water (through irrigation).

2.6.3 Non-human biota

There has been a substantial development of the framework aiming at protection of other biota than humans that post-dates the basis for SSMFS 2008:37 (SSM 2008a). There are no risk criteria for non-human biota (NHB) but the ERICA methodology, applied in the current assessment, proposes a screening dose rate at the ecosystem level of 10 $\mu Gy\ h^{-1}$ (Beresford et al. 2007, Brown et al. 2008), which has been further endorsed by the EU PROTECT project (Andersson et al. 2009). The screening dose rate represents a threshold, above which it is possible that negative effects could occur to populations of non-human biota. If a dose rate in an assessment exceeds the screening dose rate, then a more detailed investigation of exposure parameters and uncertainties, and/or some investigation into the radiosensitivity of specific organisms, should be performed.

It is worth mentioning that this screening dose rate is well below the screening dose rates used by some others, for instance the US Department of Energy (US DOE 2002), see also IAEA (1992) and UNSCEAR (1996). US DoE suggests using a screening dose rate of 400 μGyh^{-1} for native aquatic animals, and screening dose rates of 400 and 40 μGyh^{-1} for terrestrial plants and terrestrial animals, respectively. ICRP recommends the lower band of the derived consideration reference level (DCRL) as a benchmark against which the acceptability, in terms of environmental impacts, of planned activities may be gauged (ICRP 2014). Consideration is therefore also given to relevant DCRLs where these are more restrictive than the generic ERICA screening value. The development of the non-human biota framework at SKB is further described in Jaeschke et al. (2013). Handling of dose rates to non-human biota in SR-PSU is described in Chapter 7 and results are presented in Chapter 10.

2.6.4 Time frames

The biosphere assessment for SR-PSU is not subdivided into different time frames. Instead, it is modelled in a continuum, but three main time periods are identified as relevant for different purposes, namely the first thousand years after closure, the period between 1,000 and 10,000 years after closure and the period between 10,000 and 100,000 years. The first 1,000 years are specified by the regulations as of special importance with requirements for detailed analysis (see Section 2.3.1). The period between 1,000 and 10,000 years after closure (i.e. until 12,000 AD) is considered a relevant limiting time in the present biosphere description, since at about that time succession has turned all objects considered in the biosphere analyses (see Chapter 6) into terrestrial areas (wetlands, forests or agricultural land). It is also consistent with the latest time steps studied in the hydrological analyses producing discharge points for the biosphere modelling (Odén et al. 2014) and water fluxes that are used in the radionuclide transport and dose calculations (Werner et al. 2013a). Furthermore, this is also approximately the time when the sea leaves the model area (see Chapter 4), which implies a transition from landscape development affected by both shoreline displacement and climate change to a period between 10,000 and 100,000 years over which biosphere development is dominated by climate changes.

2.6.5 Biosphere calculation cases

Although the biosphere transport model as far as possible has been founded on realistic assumptions, SKB realises that there are a vast number of processes acting in the surface system affecting the development of the biosphere, and that it is not possible to identify one most likely development of the biosphere. However, the regulatory guidelines point out that there should be at least one calculation case where the biosphere conditions of today prevail into the future, and that realistic assumptions should be applied for the description of the biosphere (SSMFS 2008:37). Thus, as there are available data and good knowledge of present conditions at the site, the present conditions have been chosen to represent the base calculation case for the biosphere.

Other climatic conditions and biosphere developments are covered in separate calculation cases. There are separate calculation cases for climatic conditions expected as a consequence of, for example, extended global warming, a talik under permafrost conditions, and the retreat of an inland ice sheet, far in the future. There are also biosphere calculation cases addressing uncertainties with respect to the discharge of radionuclides from the geosphere to the biosphere, and cases that illustrate the consequences of exposure to groundwater in the geosphere or in the repository. In the safety assessment, a number of scenarios are assessed to evaluate repository safety under different climate evolutions, and to illustrate the functioning of the repository. In each such scenario, calculation cases for transport of radionuclides in the repositories and the geosphere are combined with biosphere calculation cases and the resulting risks are reported in the **SR-PSU Main report**. The biosphere calculation cases are described in Chapter 7 together with information on which SR-PSU main calculation case they are applied in.

2.6.6 Dose and risk estimates

In SR-PSU the risks to humans and dose to non-human biota are estimated from environmental concentrations that are the endpoints from a chain of connected transport models. The transport model chain includes the repository, the geosphere and the biosphere. In this model chain, radionuclide activity is simulated to propagate through the integrated repository-geosphere-biosphere system as a function of time (see Section 2.2.3).

However, since the results from the entire model chain are available late in the assessment, the radionuclide model calculations presented in this report use a unit release rate (1 Bq y^{-1}) to examine features of transport and accumulation of radionuclides in the biosphere model (Chapter 10). Thus, we have used a limited set of radionuclides to demonstrate how different properties (such as adsorption, bioaccumulation and volatilization) affect the transport and fate of key radionuclides (Chapter 10). The doses and dose rates from a unit release correspond to the landscape dose conversion factor (LDF) used to represent the biosphere in previous assessments (e.g. SAR-08 and SR-Site). The maximum LDF values over all examined exposed populations and times are compared with results from previous assessments, and used to contrast the outcomes of the different assumptions on the biosphere used in separate calculation cases (Chapter 10). Moreover, the unit release approach is used to evaluate the effects of object delineation, and to screen out a few exposure pathways that do not contribute significantly to exposure of future human inhabitants.

The LDFs calculated in this report are best estimates for the most exposed groups from deterministic simulations, given a constant release rate. These deterministic simulations are the combined result of process understanding, the most precise description of the site available and relevant assumptions on land use and human habits. In addition, the effects of parameter uncertainties and model sensitivities to variations in input parameter values have been addressed through probabilistic simulations, and separate biosphere simulations have illustrated uncertainties with respect to the size and properties of the biosphere object have been illustrated by separate biosphere simulations. However, calculations for a unit release rate cannot be used unguided to make precise inferences with respect to the consequences from a specific release, as the activity concentrations of radionuclides reaching the biosphere is likely to vary over time in a non-synchronized manner. Thus, for conclusions with respect to potential dose and risk, the reader is referred to the results from the model chain, which are presented and discussed in the **SR-PSU Main report** and in the **Radionuclide transport report**.

3 Site description – present-day conditions at Forsmark

This chapter provides a brief description of present-day conditions at Forsmark, in terms of topography and regolith (Section 3.1), hydrology and chemistry (Section 3.2), marine, limnic and terrestrial ecosystems (Sections 3.3 to 3.5), wells and water resources management (Section 3.6), and human population and land use (Section 3.7). Most data and models for the description of the surface systems presented in the site descriptive model for the PSU project, SDM-PSU (SKB 2013c), were produced as part of SDM-Site (SKB 2008a), i.e. the site description for the repository for spent nuclear fuel at Forsmark. As is described in the following sections, data and/or models for some disciplines have been updated subsequent to SDM-Site or SDM-PSU.

On the maps in this and the following chapters, coordinates are given in the coordinate systems RT 90 2,5 gon V/0:15 (X, Y) and RHB 70 (Z). This means that vertical (Z) coordinates are expressed in terms of elevation (m) above the RHB 70 datum (0 m elevation).

3.1 Topography and regolith

The present ground surface in the Forsmark region is a part of the sub-Cambrian peneplain in south-eastern Sweden. This peneplain represents a relatively flat topographic surface with a gentle dip towards the east that formed more than 540 million years ago (SKB 2008a). The Forsmark area is characterised by a small-scale topography at low altitude (Figure 3-1). Most of the area studied in detail in connection with the site investigations for the planned spent nuclear fuel repository is below 20 metres above the current sea level (Johansson 2008).

Figure 3-1. *The Forsmark area seen from southeast, with the only larger arable land area, Storskäret, in the foreground and the Forsmark nuclear power plant in the background. The yellowish areas along the shoreline are reed belts.*

The whole area is located below the highest coastline associated with the last glaciation and large parts of the area emerged from the Baltic Sea only during the last 2,000 years (see Chapter 4). Despite the relatively small variations in surface topography, the upper surface of the bedrock is found to undulate over small distances. This implies that variations in regolith thickness partly even out the bedrock undulations (SKB 2008a).

A DEM (digital elevation model), which is an update of a previously developed DEM (Strömgren and Brydsten 2008), has been developed in the SR-PSU project to describe the topography of the Forsmark area (Figure 3-2). The DEM, which has a horizontal resolution of 20 m, is a central data source for the site characterisation, and it is used as input to hydrogeological descriptions and models, and most of the descriptions and models of the surface system. In the terrestrial areas, the DEM is based on aerial photographs taken from an altitude of 2,300 m. In the marine areas, the DEM is constructed using a combination of nautical charts, supplementary depth probing and marine-geological surveys. A detailed description of the DEM is provided in Strömgren and Brydsten (2013).

The DEM displayed in Figure 3-2 confirms that elevation differences are small in the terrestrial parts of the Forsmark area, especially near the coastline, and also in the marine areas in the vicinity of SFR. Prominent topographical features of the landscape are glacial landforms like eskers. The highest observed point is at 50 m elevation and is located in the southwestern part of the DEM area. A deep trough (Gräsörännan) runs in the NNW–SSE direction in the eastern part of the embayment, and the lowest point (–55 m elevation) is located in the northernmost part of this trough.

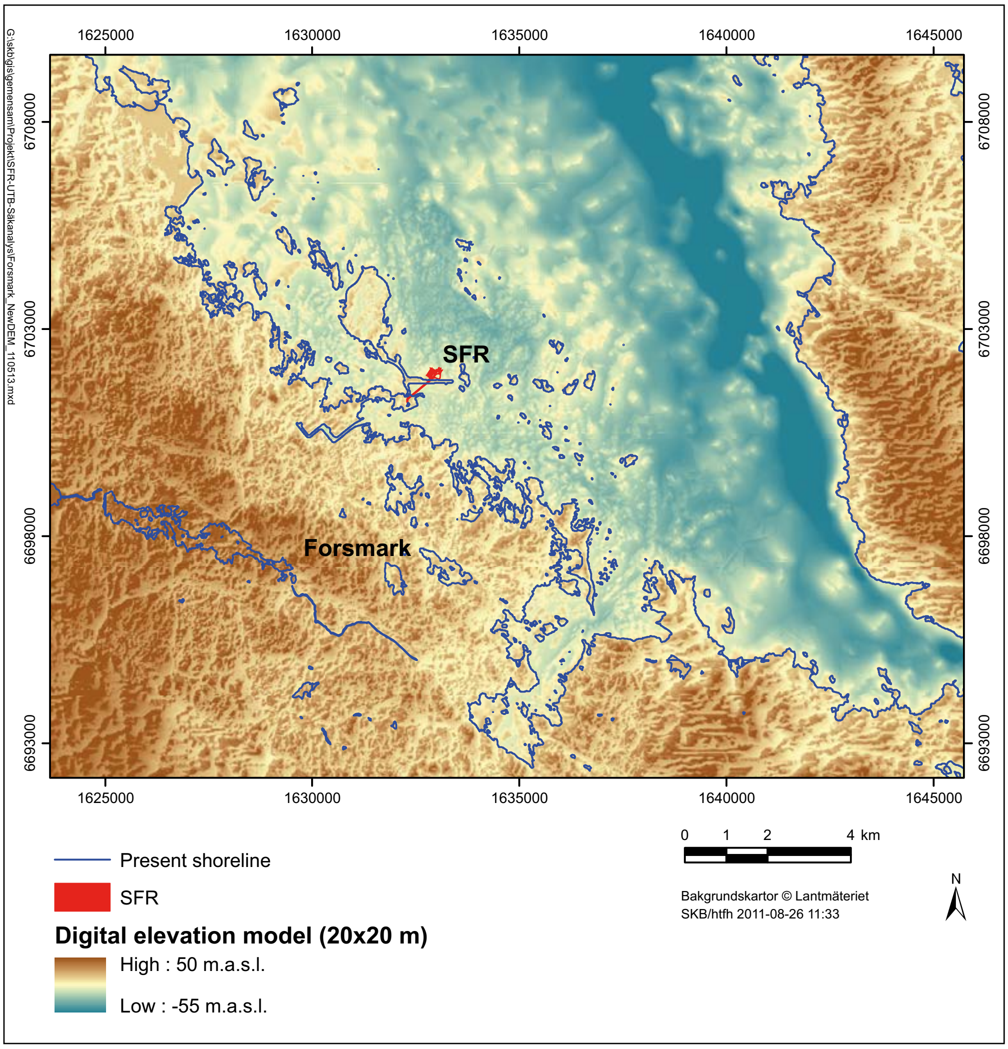


Figure 3-2. *DEM (digital elevation model) of the Forsmark area, including the bathymetry of the lakes and the sea (Strömgren and Brydsten 2013). The DEM has a horizontal resolution of 20 m. The map shows present shorelines and the location of the existing SFR facility.*

In the Forsmark area, as in other parts of Sweden, most regolith (unconsolidated deposits above the bedrock) was formed during or after the final phase of the latest glaciation, which in Forsmark occurred at around 8800 BC. Since it was formed during the Quaternary period, regolith is commonly denoted Quaternary deposits. Soils, i.e. the upper part of the regolith in terrestrial systems, and the uppermost sediments in aquatic systems, are affected by a number of processes, e.g. deposition, decomposition of organic material, bioturbation, erosion, and in terrestrial areas also frost action and weathering. Data describing regolith properties are an important input when modelling the hydrology and transport of elements and various compounds within the biosphere and between the geosphere and the biosphere. Soil properties are also strongly associated with vegetation types and land use in terrestrial ecosystems.

The descriptions of the spatial distribution of regolith and its properties are based on the public, large-scale regolith map and primary data obtained from extensive field mapping, investigations in the form of drilling, excavations and geophysics, and physical and chemical laboratory tests. For further details on the availability of primary data associated with regolith and soil and evaluations of such data, see Hedenström and Sohlenius (2008), Lundin et al. (2004), Nyberg et al. (2011), and Sohlenius et al. (2013a). The distribution of regolith in Forsmark (Figure 3-3) is typical for areas located below the highest coastline. Till is the dominant type of regolith in the highest topographical areas and occupies some 65% of the surface in terrestrial areas and 30% of the sea floor outside Forsmark.

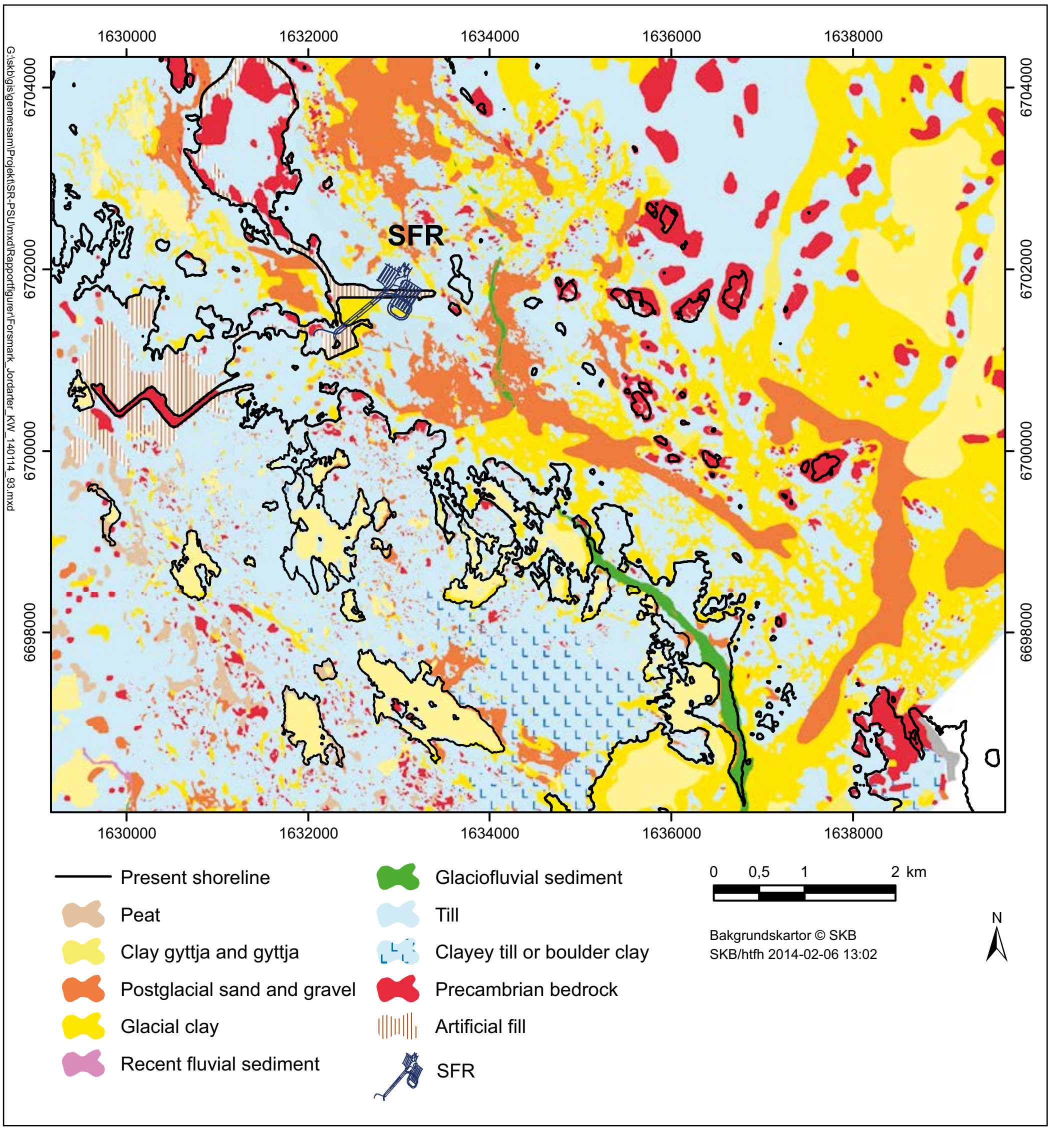


Figure 3-3. Surface distribution (at a depth of 0.5 m) of regolith and areas with exposed bedrock in the Forsmark area. Note that lakes and the sea are shown without surface water.

A glaciofluvial deposit, Börstilåsen, has N–S and NW–SE directions along the coast of the mainland, and a continuation at the sea floor east of SFR. Glacial clay occurs primarily in depressions on the sea floor and below present lakes. Postglacial sand often covers the glacial clay. Postglacial clay gyttja, rich in organic material, is predominantly found and is presently deposited in shallow bays and in the deepest parts of the sea floor. Gyttja mainly consists of organic material and is currently deposited in the lakes. Peat accumulates in fens and along the shores of the lakes. The sea floor in the SFR area (i.e. above the existing repository) is dominated by till and, in the lower topographical areas, by glacial clay covered with sand. The shallowest areas and islands have a high proportion of exposed bedrock.

The description of the surface distribution of different soil types was obtained using the regolith map (Figure 3-3), and background maps of vegetation type, land use and wetness index (a function of local contributing upslope area and slope). Soil-type classifications were conducted in pits dug in each land use type. Compared with most other parts of Sweden, regolith in the Forsmark area has been subjected to soil-forming processes only for a relatively short time and most of the soils are therefore immature and lack distinct soil horizons (Lundin et al. 2004). Till and glacial clay in Forsmark have high contents of calcium carbonate ($CaCO_3$), and originate from Palaeozoic limestone that outcrops on the sea floor north of the Forsmark area. The high content of $CaCO_3$ in the soils strongly affects their chemical properties.

A regolith depth and stratigraphy model (RDM), which is an update of a previous model (Hedenström et al. 2008), has been developed to provide a geometric model of the thickness and surface distribution of regolith layers at a landscape level (Figure 3-4). The RDM is based on the general

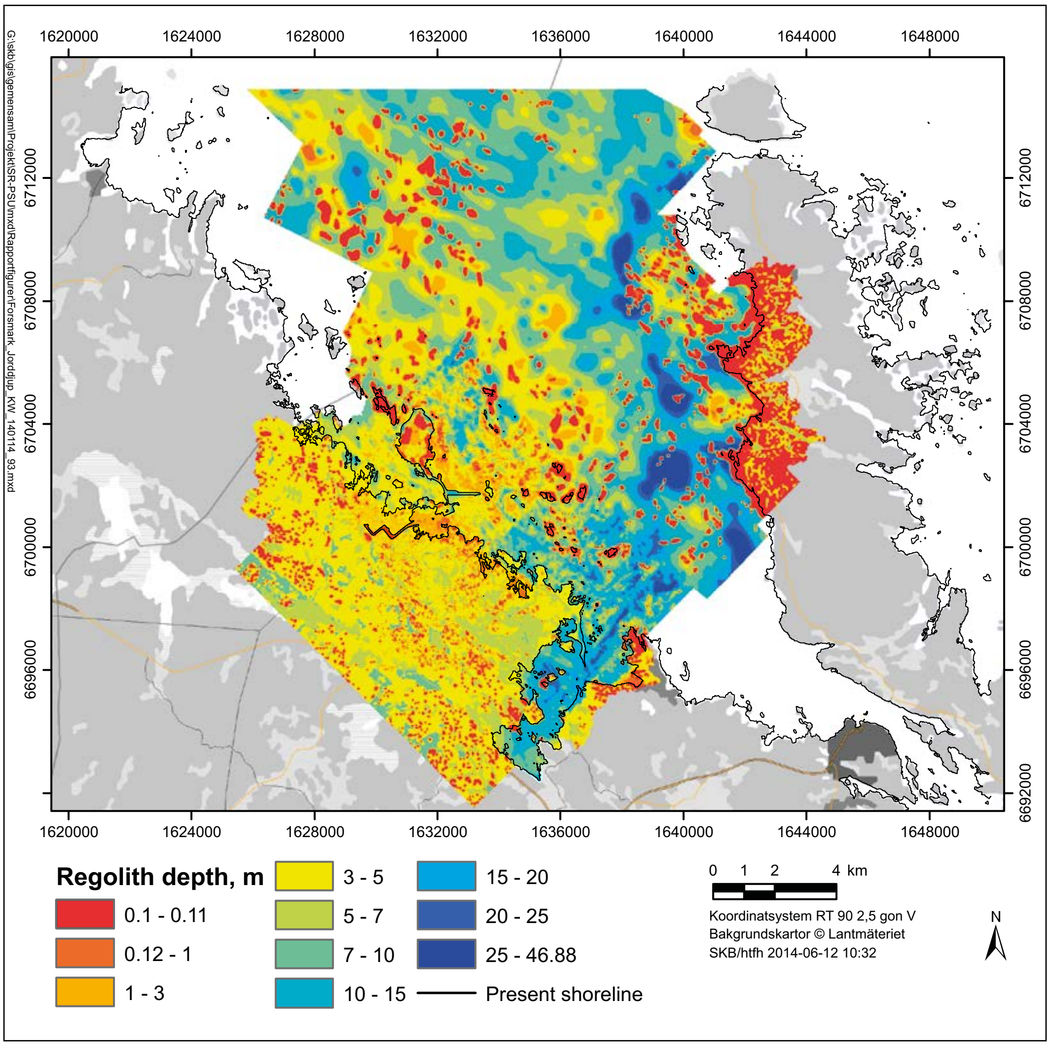


Figure 3-4. *Modelled total regolith depth at Forsmark (Sohlenius et al. 2013a). Bedrock outcrops are shown as areas with regolith depth 0.1–0.11 m.*

top-down stratigraphy for the Forsmark area, consisting of peat, gyttja and clay gyttja, postglacial sand/gravel, glacial clay, glaciofluvial sediments, and till. A detailed description of the RDM is provided in Sohlenius et al. (2013a).

The total regolith depth in the RDM area varies between 0.1 m (modelled as a thin surface layer on bedrock outcrops) and 47 m. The coastal zone and the islands (including the coastal zone of the island of Gräsö) are characterised by thin regolith and frequent bedrock outcrops (Figure 3-4). Generally, the regolith is deeper in the marine area, with an average thickness of c. 8 m, whereas the average thickness in the terrestrial area is c. 4 m. The regolith thickness is 1–4 m on the sea floor above the SFR repository.

3.2 Hydrology and chemistry

At the SMHI (Swedish Meteorological and Hydrological Institute) station Örskär, located c. 17 km northeast of Forsmark, the mean annual air temperature is c. +5.5°C for the current reference normal period 1961–1990 (Johansson et al. 2005), whereas the mean annual air temperature at Forsmark was approximately +7°C during the period 2004–2010 (Werner et al. 2013a, b). The vegetation period (mean air temperature above +5°C) lasts approximately from May to September (Johansson et al. 2005). The prevailing wind direction is from the southwest. For the seven-year period of January 2004–December 2010, the locally measured (and corrected for wind losses etc) mean annual precipitation was 589 mm, which is slightly above the calculated 1961–1990 annual mean of 559 mm (Johansson et al. 2005).

The calculated mean annual potential evapotranspiration was 509 mm during the period 2004–2010 (Werner et al. 2013a). Some 25–30% of the annual precipitation falls in the form of snow, whereas there are large variations of the period of snow cover (1–4 months) across winter seasons. Based on the meteorological and hydrological monitoring programme (also including data from surrounding stations operated by SMHI), the long-term water balance of the Forsmark area can be estimated as precipitation 560 mm y^{-1}, actual evapotranspiration 400–410 mm y^{-1}, and runoff 150–160 mm y^{-1} (Johansson et al. 2005, Werner et al. 2013a).

Figure 3-5 shows an overview map of lakes, streams and discharge-gauging stations in the Forsmark area. In total, 25 lake catchments and sub-catchment areas (sizes 0.03–8.67 km^2) have been delineated within the Forsmark area (Brunberg et al. 2004, Andersson 2010). Wetlands are common and cover 10–20% of the Forsmark area (Löfgren 2010). Many wetlands contain ecologically important ponds, whose depths and extents vary across wet and dry periods. The largest lakes are Lake Fiskarfjärden, Lake Bolundsfjärden, Lake Eckarfjärden (Figure 3-6) and Lake Gällsboträsket. Even the largest lakes are smaller than 1 km^2 in size and they are also quite shallow (average depth is less than one metre). Seawater intrusion occasionally (e.g. January, 2005 and January, 2007) takes place into the lakes located close to the sea, e.g. Lake Norra Bassängen and Lake Puttan (north of Lake Bolundsfjärden) and Lake Bolundsfjärden, during periods when the sea level is above lake thresholds and lake levels. The streams in Forsmark are small and many stream stretches are dry during summer (Figure 3-7).

The infiltration capacity of the regolith generally exceeds rainfall and snowmelt intensities, and groundwater recharge is dominated by precipitation and snowmelt (Johansson 2008). Generally, the lakes are locations for groundwater discharge for most of the year. However, intense evapotranspiration during summer lowers groundwater levels, and some lakes may periodically switch to being recharge areas. Due to the low hydraulic conductivity of the bottom sediments, the resulting water fluxes can be assumed to be relatively small.

The horizontal hydraulic conductivity of till that dominates the area decreases from c. 10^{-5} m s^{-1} near the ground surface to c. 10^{-6} and 10^{-7} m s^{-1} below c. 0.5–0.6 m depth for coarse and fine-grained till, respectively (Johansson 2008). Moreover, there are indications that the hydraulic conductivity is higher at the bedrock-regolith interface compared with the till itself. The till is anisotropic, with the horizontal hydraulic conductivity on the order of 30 times larger than the vertical conductivity.

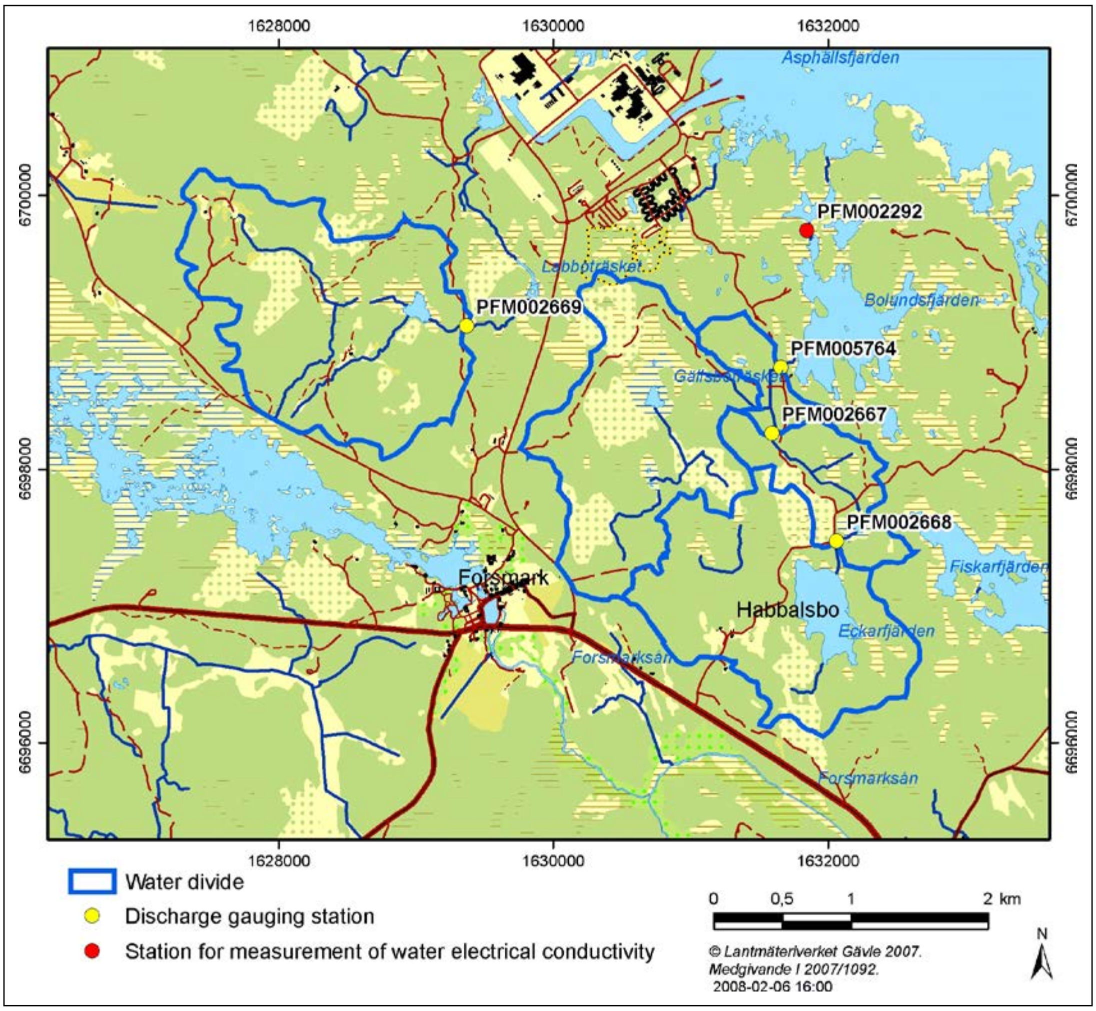


__Figure 3-5.__ Overview map of lakes, streams (thin blue lines) and discharge-gauging stations. SKB's meteorological station Högmasten is located near the shoreline, south of the cooling-water canal for the Forsmark nuclear power plant (the buildings in the northernmost part of the map). In 2012, a new meteorological station (Labbomasten) was established at Drill site 1, southwest of PFM002292.

__Figure 3-6.__ Lake Eckarfjärden (see also Figure 3-5), one of the larger lakes in the Forsmark area. As with other lakes in the area, Lake Eckarfjärden is a shallow oligotrophic hardwater lake surrounded by reed beds.

Figure 3-7. Photos showing (left) the largest stream in Forsmark, near the inlet to Lake Bolundsfjärden (see Figure 3-5) and (right) a stream section that is dry in the summer, a common sight in the Forsmark area.

The groundwater table in the regolith is generally shallow (within one metre of the ground surface) and follows the ground-surface topography (upper plot of Figure 3-8). Hence, surface-water divides and groundwater divides in the regolith can be assumed to coincide. The small-scale topography results in shallow, local groundwater flow systems in the regolith that overlie larger-scale flow systems in the bedrock.

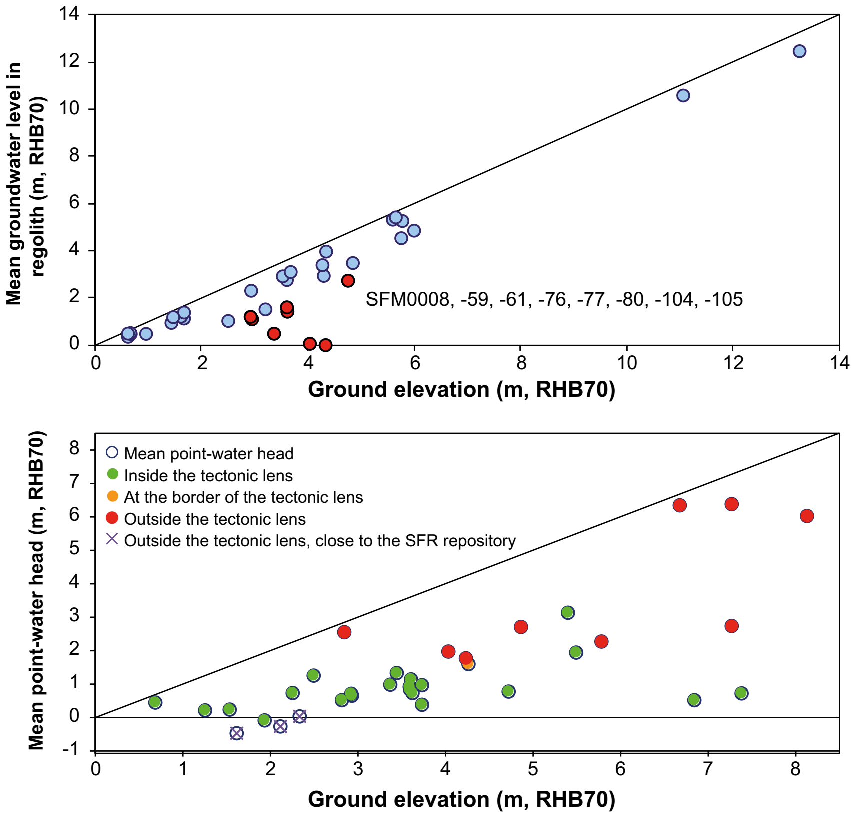


Figure 3-8. Cross plots and 1:1 lines of average groundwater levels measured up to December 31, 2010 in regolith (upper plot; red dots represent outliers) and bedrock (lower plot; percussion boreholes) versus ground-surface elevations. Groundwater levels in the bedrock are denoted "point water heads" due to differences in salinity (and thereby density) with depth (see e.g. Johansson 2008).

The so-called tectonic lens (e.g. Follin 2008) is a hydrogeologically important feature within model areas of the numerical flow models established in the SR-PSU project. In this lens, the upper c. 150 m of the bedrock contains sub-horizontal, transmissive structures recognised as sheet joints, where measured point-water heads in the bedrock are slightly above the current sea level and considerably lower than those in the regolith (lower plot of Figure 3-8). There is a weak coupling between groundwater levels in the upper part of the bedrock and the ground-surface elevation, in particular inside the tectonic lens. As shown in the lower plot of Figure 3-8, point-water heads measured in the bedrock close to the SFR facility (outside the lens) are at or below the current sea level.

Numerical water-flow models of present and future conditions were established within the SR-PSU project using the MIKE SHE modelling tool (Werner et al. 2013a). These models are updates of the SDM-Site and SR-Site flow models (Bosson et al. 2008, 2010). Regarding present conditions, updates include, for example, topography, surface distribution of regolith, and regolith depth and stratigraphy (cf. Section 3.1). Figure 3-9 below shows an example of MIKE SHE modelling results for present conditions, in terms of average depth to the groundwater table (phreatic surface) for the period October 2003–September 2006. Overall, the MIKE SHE modelling results show good agreements with the time series of measured stream discharges, surface-water levels and groundwater levels in regolith and bedrock. For further details regarding the SR-PSU flow model setup, model calibration and modelling results for present and future conditions, see Werner et al. (2013a).

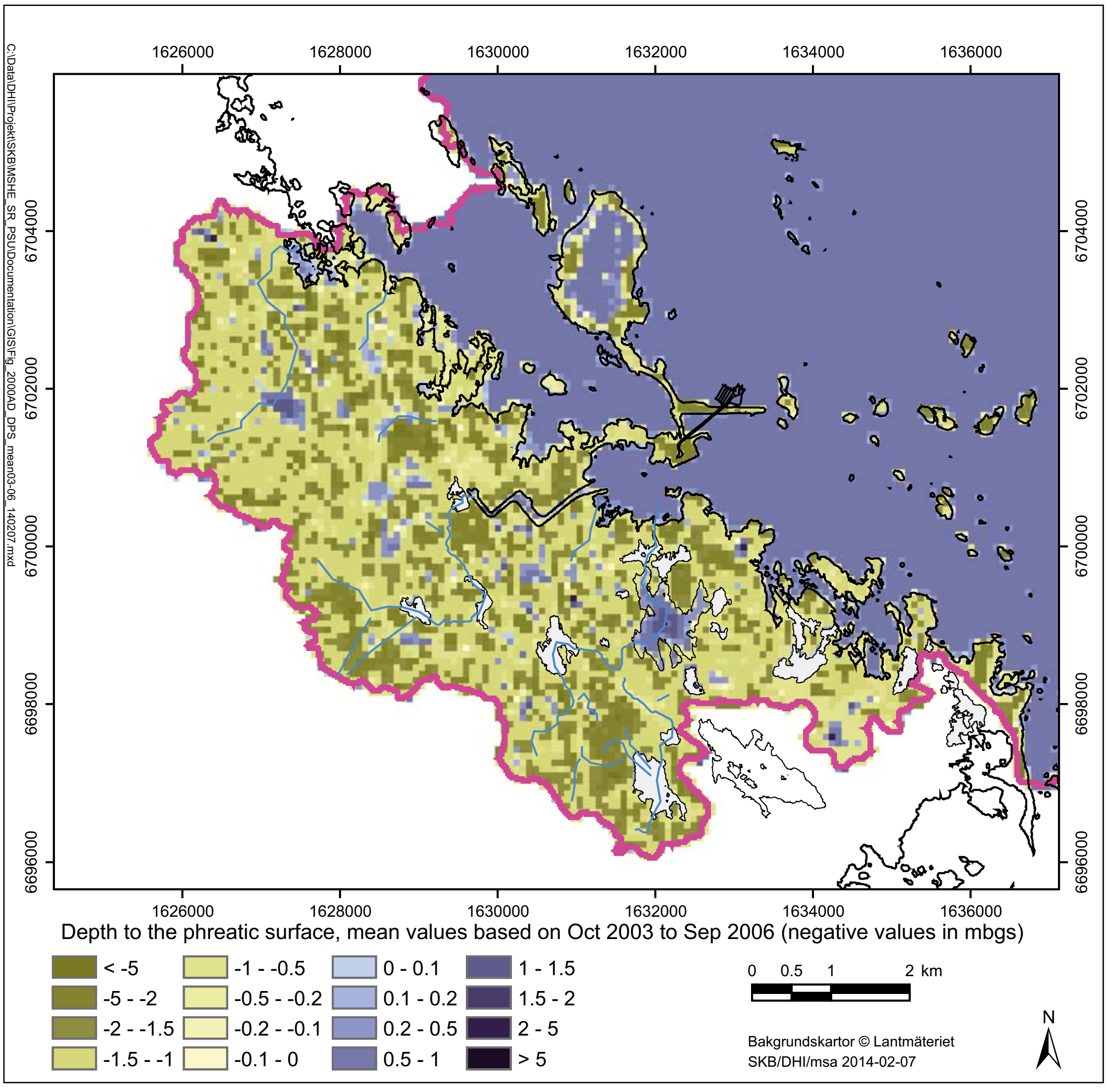


Figure 3-9. *MIKE SHE flow modelling results in terms of average depth to the groundwater table (phreatic surface) during the period October, 2003–September, 2006. Negative values denote below ground, and positive values are above lake/sea bottom.*

The marine area at Forsmark consists of the open-ended embayment Öregrundsgrepen, with a wide and deep boundary towards north and a narrow and shallower strait towards south. Based on the sea bathymetry according to the DEM (Strömgren and Brydsten 2013), the present-day marine area outside Forsmark was divided into 38 basins (Figure 3-10). Most of this coastal area is shallow (sea depth less than 10 m), except for Gräsörännan with sea depths exceeding 50 m. The salinity stratification in Öregrundsgrepen is generally weak. Local freshwater runoff produces slightly lower salinity compared with the Gulf of Bothnia (Aquilonius 2010). The direction of the flow through Öregrundsgrepen varies with time, but on an annual basis there is a net flow directed from north to south (Karlsson et al. 2010).

The water retention time (average age in the 38 basins) was calculated to vary between 13 and 29 days (19 on average) (Werner et al. 2013a). Water turnover is more rapid in the deeper areas close to the open Bothnian Sea, whereas turnover is slower in the partly isolated shallow coastal basins 117 and 118 (Figure 3-10). Most of the sea bottom consists of shallow and exposed hard bottoms (boulders or bedrock, cf. Figure 3-3 and for an example see Figure 3-11), interspersed by deeper valleys with soft bottoms.

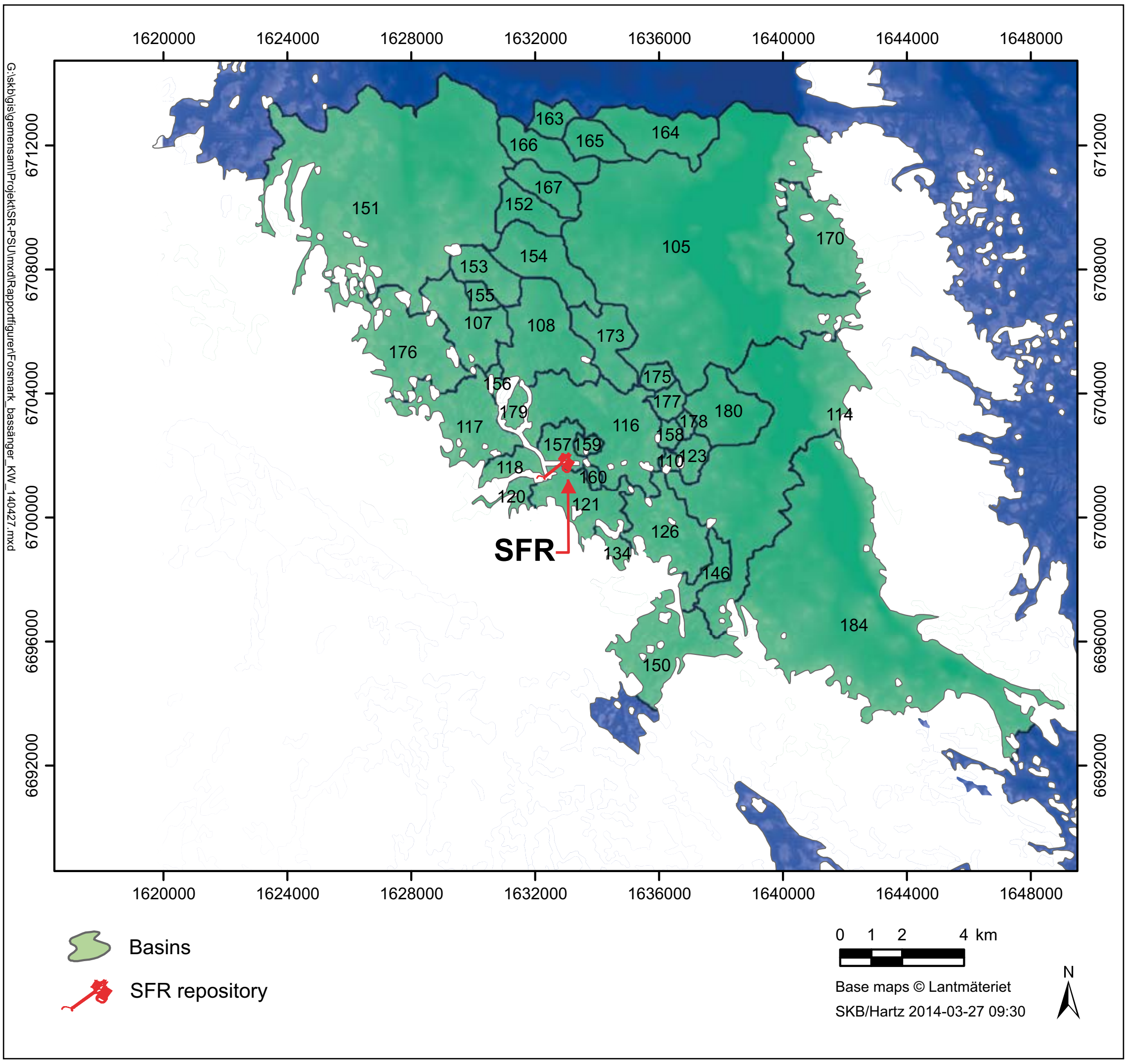


Figure 3-10. *Coastal basins (delineated based on the DEM) outside Forsmark. The inlet to the cooling-water canal for the Forsmark nuclear power plant is visible in basin 120, and the location of the SFR facility is indicated on the map.*

The hydrogeochemistry (chemistry of surface water, groundwater, regolith, soils and sediments) of the surface system at Forsmark has been the subject of various site investigation and modelling activities, including studies of the hydrochemistry (water chemistry) of limnic and marine systems (e.g. Sonesten 2005, Tröjbom and Söderbäck 2006, Tröjbom et al. 2007, Andersson 2010, Aquilonius 2010, Qvarfordt et al. 2010), the chemistry of terrestrial systems including geochemistry of regolith and sediments (Hedenström and Sohlenius 2008, Löfgren 2010, Sheppard et al. 2009, 2011), and synthesis reports concerning the chemistry of the surface system (Tröjbom and Grolander 2010, Tröjbom and Nordén 2010). A recent study was also conducted to increase the knowledge of dissolved carbon pools in mires of Forsmark (Löfgren 2011). There is an ongoing long-term hydrochemical monitoring programme at the site, including surface waters and groundwater from regolith and bedrock (SKB 2007).

The high content of calcium carbonate in the regolith and the recent emergence of the area above sea level affect the chemistry of surface waters and shallow groundwater. Specifically, surface water and shallow groundwater in Forsmark are generally slightly alkaline (pH 7–8) and have high concentrations of major constituents, caused by marine and glacial remnants deposited during the latest glaciation. Calcite has had a strong effect on the development of terrestrial and limnic ecosystems at the site. For instance, secondary calcite precipitation and co-precipitation of phosphate contribute to the development of the nutrient-poor oligotrophic hardwater lakes that are characteristic of the Forsmark area (Andersson 2010). 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 into and out of these pools, an overall picture of major sources and sinks of elements in the landscape (Tröjbom and Grolander 2010). The results show that the completely dominant fraction of the total content of most elements in both terrestrial and limnic ecosystems is found 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. This pattern is due to the large biomass in terrestrial ecosystems compared with limnic ecosystems.

The transport and retention of radionuclides in the regolith can be modelled by the use of distribution coefficients (K_d), whereas the uptake of radionuclides in biota can be described by concentration ratios (CR). Since the analysis by Tröjbom and Grolander (2010), supplementary sampling and analyses of regolith and biota have been performed in order to improve the site-specific K_d and CR database (Sheppard et al. 2011). Mobility of elements in relation to chemistry in agricultural soils and wetlands has been investigated based on site data (Sohlenius et al. 2013b). Moreover, transport and uptake of radionuclides in coastal ecosystems have been modelled with different models to illustrate concentration ratios for biota at ambient water chemistry (Erichsen et al. 2013).

3.3 Marine ecosystems

Brackish conditions, shallow waters, subdued bathymetry, restricted light penetration and upwelling along the coast characterise the marine ecosystems at Forsmark. Together, these factors result in a high primary production in the near-shore zone, in a region of otherwise fairly low production (Aquilonius 2010). The primary production is lower in deeper areas and is there restricted to the pelagic zone due to limitation of light in the benthic habitats. The salinity of the seawater is low due to a large freshwater supply from terrestrial areas and very limited mixing with the North Sea, resulting in low diversity of fauna as few organisms are adapted to such brackish conditions. The primary producers are dominated by benthic organisms such as microalgae, vascular plants and benthic macroalgae. The fauna are dominated by detritivores (i.e. snails and mussels feeding on dead organic material) on both hard bottom (Figure 3-11) and soft bottom substrates. The fish community is dominated by the marine species herring (*Clupea harengus membras*) in the pelagic zone, whereas limnic species (especially Eurasian perch, *Perca fluviatilis*) dominate in near-coastal areas and in secluded bays.

Figure 3-11. *Hard bottom with red algae and bladder wrack at Forsmark.*

Comparison between results from sampling of marine vegetation and the GIS model used to model biomasses of marine basins (Aquilonius 2010) indicates that the GIS model predicts total biomass fairly well, with 1.4 times higher biomass in a field investigation compared to modelled (Aquilonius et al. 2011). Data from the mapping of reed beds in shallow bays in the Forsmark area (Strömgren and Lindgren 2011) have been used to improve the understanding of terrestrialisation, i.e. infill of ecosystems transforming from marine basins to lakes to wetlands.

As for limnic ecosystems, both abiotic and biotic processes influence transport and accumulation of elements in marine ecosystems (Figure 3-12). However, modelling of carbon budgets (Aquilonius 2010) shows that in marine ecosystems advective flux (water turnover) is often the dominating factor for transport and accumulation of elements (in particular in open and more offshore basins), and in comparison, biotic fluxes (e.g. primary production within the basins) are less important.

The modelling of delineated marine basins shows that the whole marine area as an average has positive NEP (net ecosystem production) with higher primary production than decomposition. Specifically, shallow areas near the coastline have positive NEP, whereas more offshore areas have negative NEP, mainly due to the large contribution from benthic macroalgae in shallow areas. Further details on the availability of primary data associated with marine ecosystems and evaluations of such data are provided in Aquilonius (2010).

3.4 Limnic ecosystems

Present-day lakes in the Forsmark area are small and shallow (mean depth typically below 1 m, Figure 3-6). They are characterised as oligotrophic hardwater lakes, with high levels of calcium and low nutrient levels (Andersson 2010). This lake type is common along the coast of northern Uppland region where Forsmark is situated, but rare in the rest of Sweden (Brunberg et al. 2002, Hamrén and Collinder 2010).

Shallow depths and moderate water colour permit photosynthesis in the entire benthic habitat, and the lake bottoms are covered by dense stands of macroalgae and a thick layer of microphytobenthos (microscopic algae and cyanobacteria). These two types of primary producers dominate the biomass and primary production, making phytoplankton biomass and production less important.

All lakes are surrounded by reed belts, which are extensive especially around the smaller lakes. The fish community in the lakes of Forsmark is dominated by perch (*Perca fluviatilis*), roach (*Rutilus rutilus*), tench (*Tinca tinca*) and crucian carp (*Carassius carassius*), of which the latter two species are resistant to low oxygen concentrations during winter.

The streams in the Forsmark area are small and many stream stretches are dry during summer (Figure 3-7). However, some streams close to the coast carry water for most of the year and function as passages for migrating spawning fish, and extensive spawning migration has been observed between the sea and Lake Norra Bassängen (Loreth 2005). The two large streams Olandsån and Forsmarksån, located outside of the Forsmark area, carry water during the whole year and discharge into the sea bay Kallrigafjärden. The vegetation abundance in the streams is heterogeneously distributed, varying between 0 and 100% coverage of the streambed, but with some longer parts with intense growth (75–100% coverage) (Andersson et al. 2011).

Both abiotic and biotic processes influence transport and accumulation of elements in limnic ecosystems (Figure 3-12). Modelling of carbon dynamics in limnic ecosystems shows that, contrary to typical Swedish lakes, primary production exceeds respiration in many lakes in the Forsmark area (Andersson 2010). In some of the larger lakes in the area (e.g. Lake Bolundsfjärden and Lake Eckarfjärden), the primary production involves large fluxes of carbon compared with the amounts that are transported from the surrounding catchment area. Consequently, there is a large potential for carbon entering the lakes to be incorporated into the lake food web via primary producers. However, much of the primary produced carbon is circulated within the microbial food web and transferred back to abiotic pools or sequestered in sediments.

In the larger lakes, there is a relatively large deposition in sediments, which can be a permanent sink for radionuclides and other pollutants. In smaller lakes and ponds, the amounts of carbon involved in the primary production and deposited in sediments are small compared with the amounts of carbon transported from the surrounding catchment area. According to the ecosystems modelling, these lakes hence function more as through-flow systems (Andersson 2010). The chemical properties of the elements, the size of the lake and its location in the catchment area determine the fate of elements entering lake systems. Further details on the availability of primary data associated with limnic ecosystems and evaluations of such data are provided in Andersson (2010).

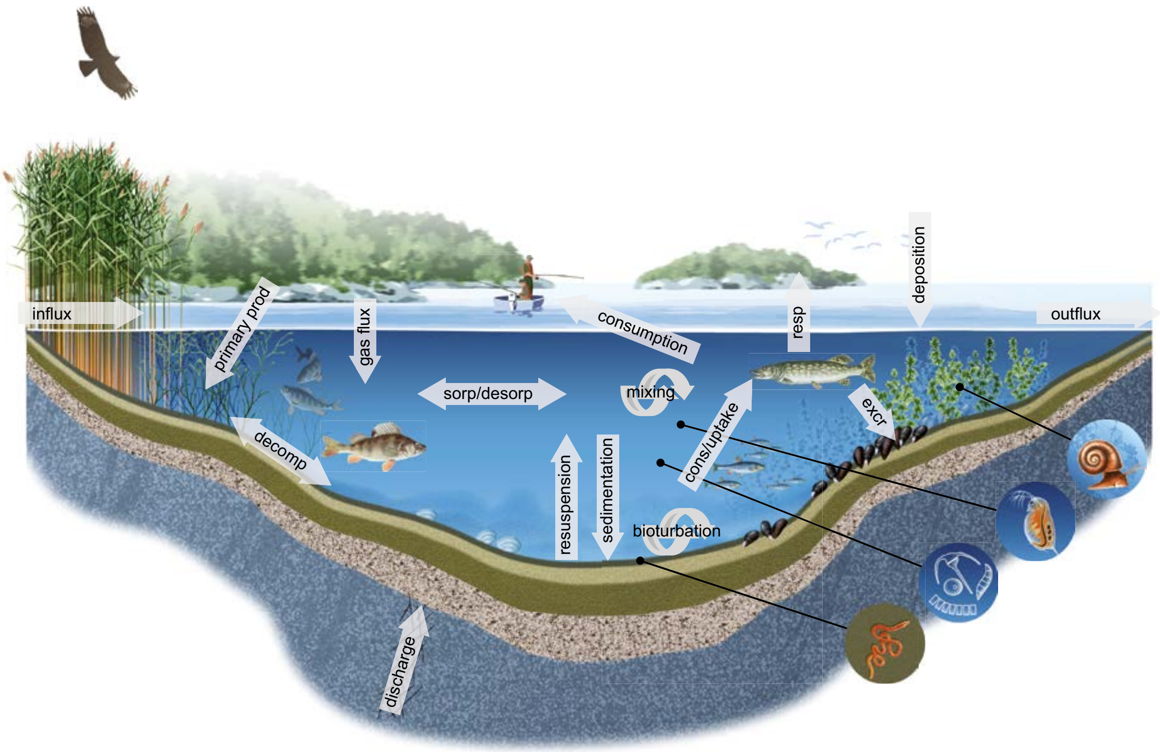


Figure 3-12. Conceptual model of functional groups and important fluxes affecting transport and accumulation of elements in aquatic (i.e. limnic and marine) ecosystems. "Influx" and "Outflux" represent fluxes from/to adjacent limnic or terrestrial systems (for limnic systems) and adjacent marine basins (for marine systems). The symbols to the right are examples of flora and fauna in aquatic ecosystems.

3.5 Terrestrial ecosystems

The terrestrial vegetation is strongly affected by topography, regolith characteristics and human land use. Some three quarters of the land area in Forsmark is covered by forests, dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) (Löfgren 2010). Due to the calcareous regolith, the field layer is characterised by herbs, broad-leaved grasses and many orchid species. The area has a long history of forestry, with a large percentage of younger and older clear-cuts in different succession stages. Most of the frequent wetlands are coniferous forest swamps or open mires (Figure 3-13). Less mature wetlands consist of rich fens due to the high calcareous content of the regolith. Agricultural land (arable land and grassland) only covers a minor part of the land area of Forsmark.

The most common large mammal species in the Forsmark area are roe deer (*Capreolus capreolus*) and moose (*Alces alces*). In total, 96 bird species have been found in the Forsmark area. The most common species in Forsmark are, as in the rest of Sweden, chaffinch (*Fringilla coelebs*) and willow warbler (*Phylloscopus trochilus*) (Löfgren 2010). Forsmark is an interesting area from a nature conservation point of view, where the highest nature values are associated with wetlands and forests containing red listed and/or legally protected species (Hamrén and Collinder 2010). Two such rare species are the wetland species fen orchid (*Liparis loeselii*) and the pool frog (*Rana lessonae*), which both have a restricted national distribution range within the north of Uppland and are found in this area.

Modelling of carbon dynamics for two conifer forest stands (i.e. the dominant vegetation type in Forsmark) and one forested wetland shows that the largest carbon flux in terrestrial ecosystems is the uptake of carbon by primary producers, and that the vegetation at all the investigated localities acts as a carbon sink today (Löfgren 2010). The net primary production sets the upper limit for the potential uptake of different elements into biomass, which in turn limits the extent of further propagation up the food web. Eventually, biomass reaches the soil compartment as litter and is mineralised. The balance between litter production and heterotrophic respiration determines to what extent organic material (and incorporated elements) can be accumulated in the soil.

Dynamic vegetation modelling based on site data shows that other vegetation types (e.g. deciduous trees, meadows and arable land) also are carbon sinks, with the exception of clear-cut forests that act as carbon sources (Löfgren 2010). Figure 3-14 illustrates a compilation of important processes for a mire ecosystem. Further details on the availability of primary data associated with terrestrial ecosystems and evaluations of such data are provided in Löfgren (2010).

Figure 3-13. *A wetland in Forsmark dominated by reed (Phragmites australis).*

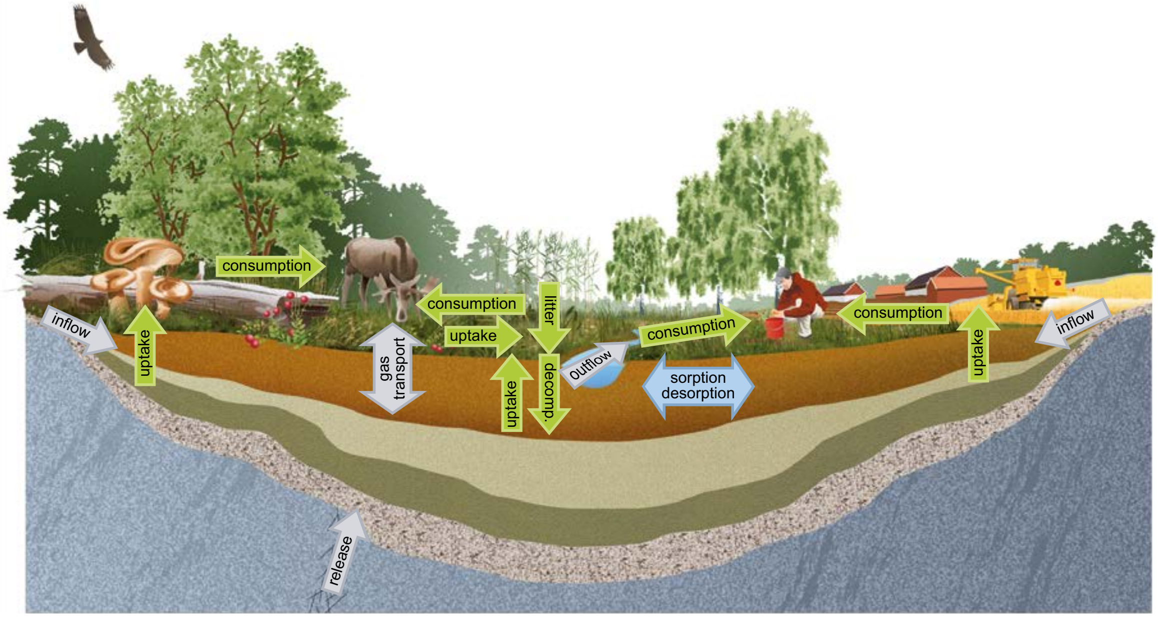


__Figure 3-14.__ Conceptual model of important fluxes affecting transport and accumulation of elements in a wetland ecosystem and arable land on a drained part of a mire (Löfgren 2010). Green arrows are fluxes mediated by biota (including water for drinking), grey arrows are water and gas fluxes, and the blue arrow represents sorption/desorption processes. "Release" indicates a hypothetical release of radionuclide-contaminated groundwater from the bedrock. The mire was preceded by a lake stage and a marine stage, in which gyttja/clay and postglacial clay (shown as the greenish regolith layers) were deposited prior to the peat (uppermost, brown layer).

3.6 Wells and water-resources management

All public water supplies in the Municipality of Östhammar are based on groundwater (Werner et al. 2010). The closest public water supply is located at the esker Börstilåsen, some kilometres southeast of SFR. According to the municipal comprehensive plan, there are no future needs for public water supplies in areas close to SFR.

At present, c. 30% of the inhabitants in Östhammar obtain their drinking water from private wells. The owner of the Forsmark nuclear power plant has previously drilled a number of boreholes in bedrock to prospect for water, but these boreholes are now abandoned. Today, there are some private wells (dug in regolith or drilled in bedrock) in land areas along the coast. Analyses of the well water show that the water quality varies, such that some wells contain potable water and others non-potable water. Consequently, some wells are not used as drinking-water supplies but instead for other purposes, e.g. irrigation of garden plots.

According to a regional analysis of well density (both dug and drilled wells), the current well density varies between c. 0.2 and 2 wells per km^2 depending on size and location of the analysed area (Kautsky 2001). The current well density is 0.2–0.9 wells per km^2 in different sub-areas within an area close to SFR (size 400 km^2) and 0.5–2 wells per km^2 in different sub-areas within northern Uppland (size 3,300 km^2).

According to an analysis of updated data from the SGU Well Archive (© Geological Survey of Sweden, SGU) on more than 5,000 private wells drilled in bedrock in northern Uppland (cf. Gentzschein et al. (2007)), a typical well depth in bedrock is c. 60 m. Based on hydraulic tests in core boreholes at the SFR facility, the median hydraulic conductivity in the depth interval 0–100 m is estimated to c. $1.5 \cdot 10^{-7}$ m s^{-1}. For a well depth in bedrock of 60 m, the equivalent maximum well capacity is c. 1,900 L h^{-1} (more than 46,000 L d^{-1}). For further descriptions of dug and drilled wells, see Werner et al. (2013a).

Current water handling in Forsmark includes groundwater diversion from SFR, a cooling-water canal from the sea to the Forsmark nuclear power plant, the use of Lake Bruksdammen (c. 4 km southwest from Forsmark) as a water supply for the power plant, and a groundwater-drainage system at the power plant (Werner et al. 2013a). There are no land improvements or drainage activities registered in public records. However, there are shallow ditches in the forests (the ditches are constructed for drainage purposes) and the lake outlet from Lake Eckarfjärden has previously been lowered in order to lower the level of the lake. Some minor natural springs have been observed in the area (see, for example, Nilsson and Borgiel 2005). None of these springs are registered in public records, and they have not been used according to available information.

3.7 Human population and land use

There are holiday houses but no permanent residents in a 20 km^2 area around SFR (Miliander et al. 2004). The land use has previously been dominated by commercial forestry, and wood extraction has been the only significant man-made outflow of biomass from the area. The only agricultural activity at present is situated at Storskäret (Figure 3-1). It is focused on meat production and the cattle graze outdoors during the vegetation period.

The Forsmark nuclear power plant is a large industrial activity in an otherwise relatively undisturbed area. The dominant leisure activity in the area is hunting. Forsmark is only occasionally used for leisure due to the small local population, the relative inaccessibility of the area and the distance from major urban areas.

4 Site development – future conditions and systems

This chapter gives a short description of the natural processes driving the development of the Forsmark site and their effects on future site conditions and ecosystems. The main processes are identified and described, and their implications for topography, geology, hydrology and chemistry are outlined. Finally, the main effects on aquatic and terrestrial ecosystems are described. The contents of this chapter are, to a large extent, based on analyses performed in connection with the SR-Site safety assessment, as summarised in Lindborg (2010). The landscape succession resulting from the combined effects of natural processes and human land use is analysed in Chapter 5, whereas the application of the landscape development model in the context of radionuclide transport and dose modelling is described in Chapter 6.

4.1 Main processes driving site development

The long-term development of the Forsmark area is dependent on two main and partly interdependent factors: climate variations and shoreline displacement. These two factors in combination strongly affect a number of processes, which in turn determine the development of ecosystems and future conditions of importance for radionuclide transport, exposure and resulting doses and risks. Examples of such processes are erosion and sedimentation, groundwater recharge and discharge, soil formation, primary production, and decomposition of organic matter.

In the past, shoreline displacement has strongly affected the Forsmark area, both before and after the latest deglaciation. At the end of the latest deglaciation around 8,800 BC, the area was covered by approximately 150 m of glacio-lacustrine water and the nearest shoreline was situated some 100 km west of Forsmark, see Chapter 3 in Söderbäck (2008). Thereafter, the isostatic rebound has been continuous and slowly declining in rate. 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 (cf. below).

The present regressive shoreline displacement will continuously bring new areas of the sea floor above the wave base. This will expose sediments to wave erosion and resuspended fine-grained particles will be transported out of the area into the Bothnian Sea, or re-settle on deeper bottoms within the study area (Brydsten and Strömgren 2010, 2013). Accordingly, the relocation of sediments may have important implications for transport and accumulation of radionuclides potentially originating from a future repository.

When new areas of the present seafloor are raised above the sea level, weathering of the calcium-rich regolith is initiated. 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 of the coastal area in Forsmark will likely be transformed to more nutrient rich or dystrophic (low pH, brown-water) conditions within some thousands of years after isolation from the sea (see Andersson 2010).

The shoreline displacement will also cause a continuing and predictable change in the abiotic environment, e.g. in water depth and nutrient availability. It is therefore appropriate to describe the origin and succession of major ecosystem types in relation to shoreline displacement. One example of this is the isolation of a sea bay into a lake, followed by the succession of the lake (lake ontogeny) and its development into a wetland. As the lake ages, sediment and organic matter accumulate due to sedimentation and vegetation growth, and eventually all lakes will transform to wetlands. The rate of lake infilling is mainly dependent on lake depth, area and volume (Brydsten and Strömgren 2010, 2013).

Mires may also develop on newly emerged land without a preceding lake stage (Kellner 2003), or with a lake stage that is short relative to the temporal resolution of the models describing site development in the biosphere assessment. As discussed further below, this is actually the case for some of the biosphere objects of largest importance in the SR-PSU safety assessment (Chapter 6).

4.2 Climate and climate-related processes

In the **Climate report**, the current scientific knowledge on the influence of enhanced atmospheric greenhouse gas concentrations and low-amplitude insolation variability in the next tens of thousands of years was used as a basis for defining the climate cases considered in SR-PSU. Specifically, a review of current knowledge on past and future projected climate evolution is given in Chapter 3 of the **Climate report**. In Chapter 4 of the **Climate report**, the four climate cases considered in the SR-PSU safety assessment are defined and described. These climate cases are:

- the global warming climate case (included in main safety assessment scenario),
- the early periglacial climate case (included in main safety assessment scenario),
- the extended global warming climate case,
- the Weichselian glacial cycle climate case.

Essentially, the first three cases are defined to span the range in future climate evolution associated with low, medium and high human carbon emissions. The *early periglacial climate case* represents low human carbon emissions and a relatively fast decrease in atmospheric CO_2 concentration. The *global warming climate case* represents medium human carbon emissions and the *extended global warming climate case* represents a development with high human carbon emissions. A generalised time evolution for the next 10,000 years of the near-surface temperature in Forsmark in these first three climate cases is shown in Figure 4-1b–d. Peak temperatures in Forsmark occur around 2500 AD to 3000 AD followed by a slow decrease in temperature. In all three cases, peak precipitation is estimated to be c. 20–30% higher than at present and to occur at the same time as peak temperatures.

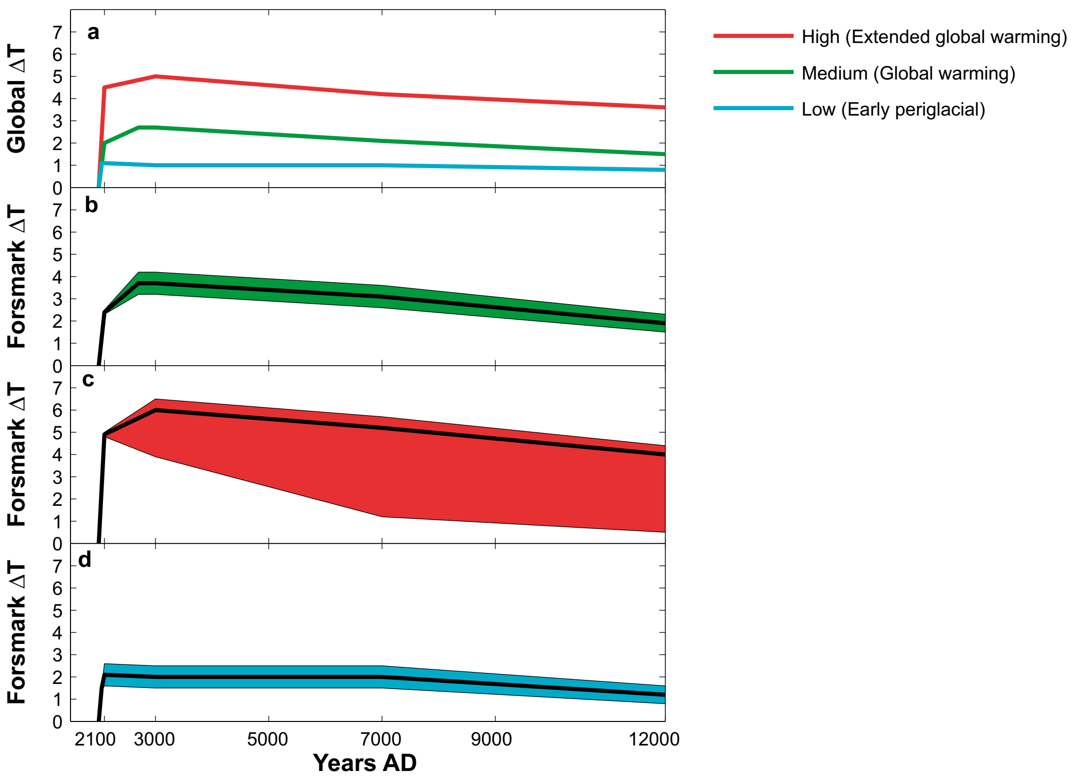


Figure 4-1. *Plate (a) shows projected future global annual average near-surface air temperature (°C) evolution for low (blue), medium (green) and high (red) cumulative carbon emissions (figure from the* ***Climate report****). The low, medium and high scenarios correspond to the early periglacial, global warming and extended global warming climate cases, respectively. Plate (b) shows the corresponding estimated temperature evolution for the Forsmark region for the global warming climate case (medium emission case), whereas plates (c) and (d) show the corresponding estimated Forsmark temperature evolutions for the extended global warming (high emission) and early periglacial (low emission) climate cases, respectively. The temperature is expressed as an increase from the present annual air temperature. The figure also includes the uncertainty interval estimated for each case (see the* ***Climate report*** *for details).*

The *Weichselian glacial cycle climate case* represents a repetition of conditions reconstructed for the last glacial cycle. This climate case is included to span the uncertainty in the onset of ice sheet growth in the Northern Hemisphere under fully natural climate variability, and for comparison with earlier safety assessments for the SFR repository. Current scientific knowledge on future climate evolution, reviewed in Section 3.3 in the **Climate report**, suggests that the combination of human intervention and relatively small-amplitude variations in insolation will lead to a global climate evolution in the next 100,000 years which is significantly different from previous glacial cycles. Therefore, the Weichselian cycle case is not considered in the SR-PSU landscape development modelling. However, a detailed description of how this climate case was handled in the previous SR-Site assessment is presented in Lindborg (2010).

The four SR-PSU climate cases are summarised in Table 4-1, which shows the sequence and duration of different climate domains for the climate cases; for reasons mentioned above, the *Weichselian glacial cycle climate case* is not described in detail. The three cases involving global warming are illustrated in Figure 4-2 (*global warming climate case*), Figure 4-3 (*early periglacial climate case*) and Figure 4-4 (*extended global warming climate case*). In addition to the sequence of climate domains, Figure 4-2 shows modelled permafrost depth and shore level during the 100,000-year assessment period. The shore level change considered in the other climate cases is discussed below.

Note that the periods with submerged (sea-covered) conditions are not defined as a separate climate domain. They are typically part of the temperate climate domain but still often handled and described separately in the **Climate report** and safety assessment modelling due to their large effects on flow, transport and exposure conditions. For the purposes of the present discussion, it is sufficient to say that submerged conditions prevail during only a short initial part of the assessment period in the *global warming* and *early periglacial climate cases* (< 1% of the period) and in the *extended global warming climate case* (c. 2%, cf. below). For comparison, the corresponding proportion is 16% in the *Weichselian glacial cycle climate case* (which is defined for a period of 120,000 years).

The temperate climate domain dominates in the *global warming climate case* (Table 4-1). It covers some 69% of the assessment period in this case, with the remaining 31% characterised by the periglacial domain. As shown in Figure 4-2, the temperate and periglacial domains alternate during the second half of the assessment period, whereas the first half has temperate conditions continuously.

The *early periglacial climate case* (Figure 4-3) differs from the *global warming climate case* in that it includes a 3,000-year period of periglacial domain that begins c. 15,500 after present (AP), i.e. at c. 17,500 AD. This implies that the proportions of temperate and periglacial domains during the assessment period decrease and increase by 3%, respectively. In the *extended global warming climate case* (Figure 4-4) the onset of periglacial climate domains is delayed such that temperate conditions prevail during the whole assessment period. Table 4-1 also shows that the *Weichselian glacial cycle climate case* has a larger total proportion of cold climates, including the glacial climate domain when the site is covered by ice.

Table 4-1. Summary of the climate cases considered in the SR-PSU safety assessment (ka is short for kilo annum, i.e. thousands of years, AP stands for after present). Note that periods of submerged conditions are included in the temperate domain and not reported separately. The Weichselian glacial cycle climate case is defined for a period of 120 ka, rather than for 100 ka as the other climate cases.

Climate case	Description	Climate domains
Global warming	Temperate conditions until 50 ka AP followed by natural variability and cooling of climate until 100 ka	Temperate: 69% Periglacial: 31%
Early periglacial	Same as the global warming case except for a 3 ka period of periglacial conditions centred at 17 ka AP	Temperate: 66% Periglacial: 34%
Extended global warming	Temperate conditions until 100 ka AP	Temperate: 100%
Weichselian glacial cycle	Repetition of reconstructed last glacial cycle conditions	Temperate: 42% Periglacial: 34% Glacial: 24%

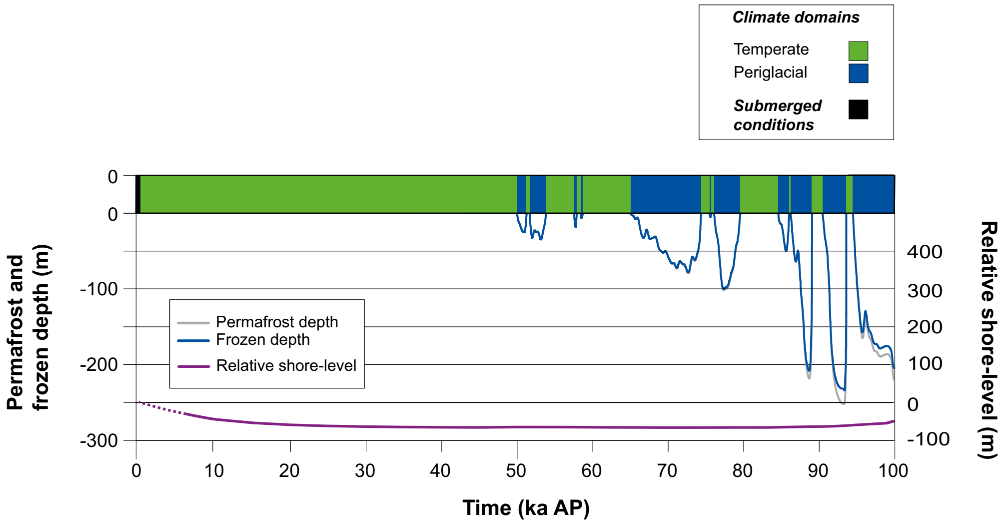


Figure 4-2. Description of climate-related conditions at Forsmark as a time series of climate domains and submerged periods for the global warming climate case. Figure from the ***Climate report****.*

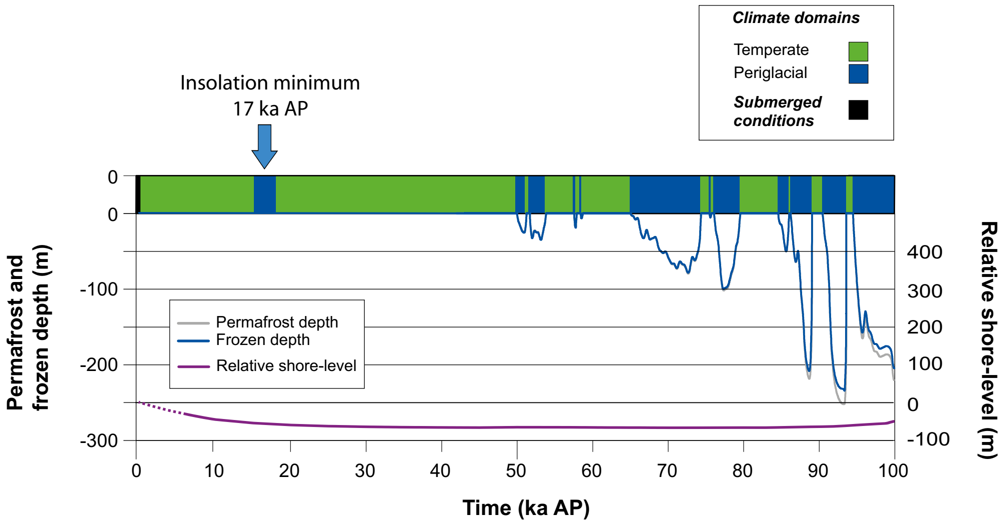


Figure 4-3. Description of climate-related conditions at Forsmark as a time series of climate domains and submerged periods for the early periglacial climate case. Figure from the ***Climate report****.*

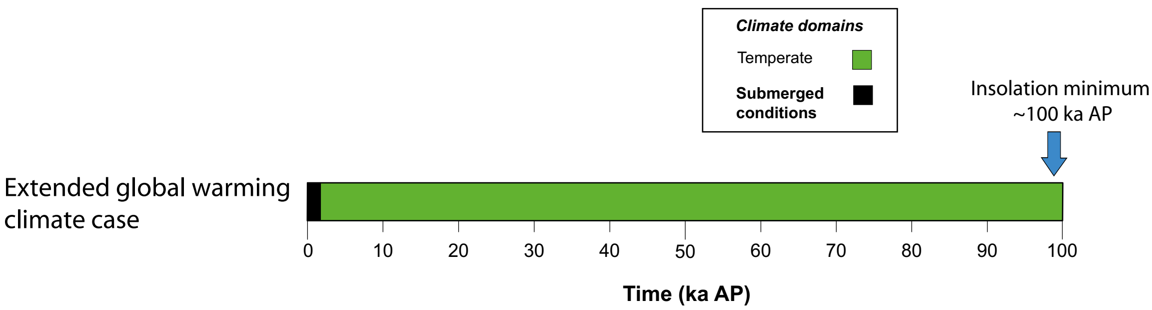


Figure 4-4. Description of climate-related conditions at Forsmark as a time series of climate domains and submerged periods for the extended global warming climate case. Figure from the ***Climate report****.*

The vertical shoreline displacement in Forsmark is determined by the net effect of eustatic changes (e.g. sea level rise associated with changes in the volume and spatial distribution of ocean water) and isostatic changes (at the Forsmark site manifested mainly through glacial isostatic rebound). The present-day net effect of the two processes at the Forsmark site is a slow sea level regression. Global sea level is expected to increase in the next centuries to millennia as a result of global warming causing thermal expansion of ocean water, melting of glaciers and melting of ice sheets (see the **Climate report)**. Depending on the future sea level rise, the shoreline change at Forsmark will slow down and may even result in a transgression in the next century. The shore level evolution used in SR-PSU is illustrated in Figure 4-5.

Based on present scientific literature, a maximum possible sea level change until 2100 AD at Forsmark is determined in the **Climate report**. Further, sea level change at Forsmark until 12,000 AD is assessed in the **Climate report** based on the scientific literature. As described in the **Climate report**, the uncertainty in future sea level response to global warming until 2100 AD is very large. Sea level change beyond 2100 AD is naturally associated with even larger uncertainties. To account for these uncertainties, a maximum sea level rise at Forsmark until 12,000 AD was calculated based on published estimates of the maximum contributions from ocean steric expansion, a complete melting of the Greenland and West Antarctic ice sheets and a complete melting of all glaciers and ice caps.

In order to estimate the maximum possible sea level rise at Forsmark, the maximum contributions are all pessimistically assumed to occur within the next few centuries to the next millennium. When all contributions to sea level rise are summed, the maximum total mean sea level rise in the Baltic is ~ 10 m during the coming 10,000 years. The uncertainty range associated with future sea level rise is taken into account in the SR-PSU safety assessment in the *global warming climate case* and the *extended global warming climate case* (**Climate report**). The *global warming climate case* represents the lower end of the uncertainty range, with negligible effects of global sea level rise, whereas the *extended global warming climate case* represents the upper end of the uncertainty range.

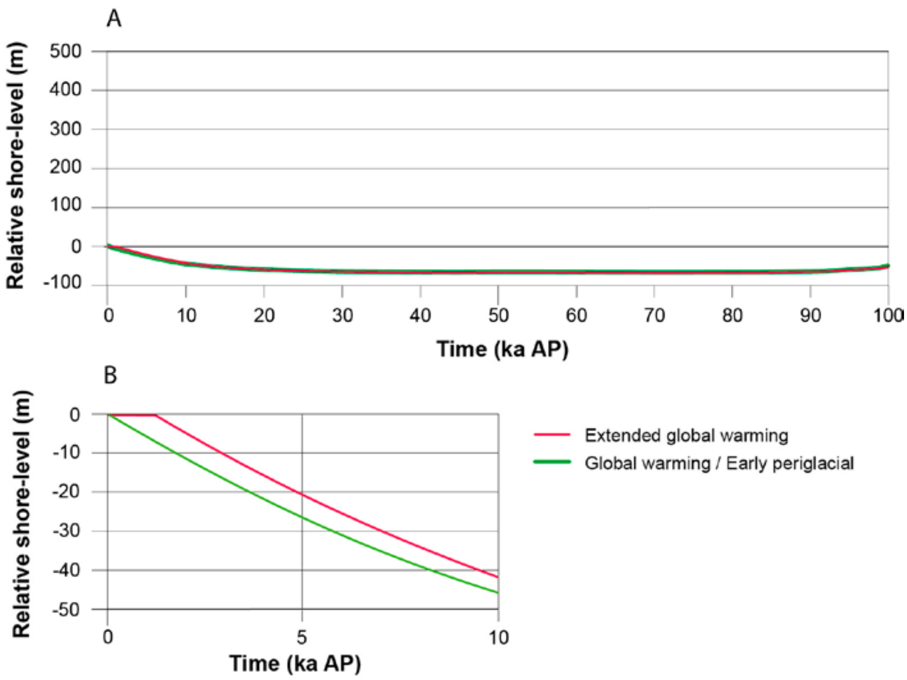


Figure 4-5. *Shore level evolution data from the present to (A) 100,000 years after present (i.e. 100 ka AP) and (B) 10,000 years after present (10 ka AP) for the global warming and early periglacial climate cases (green line) and the extended global warming climate case (red line). Negative numbers indicate that the area is situated above the contemporary sea level. The curves were constructed by modelling combined with results from observations of present-day uplift rates (Påsse 2001,* ***Climate report****). Figure from the* ***Climate report****.*

The two cases thus represent a minimum length period of submerged conditions above SFR in the *global warming climate case* and a maximum length period of submerged conditions above SFR in the *extended global warming climate case*.

The SFR repository is today covered by the Baltic Sea, with a maximum water depth of 7.2 m over SFR 1 and 5.3 m over the planned SFR 3 (layout L2). With the relative shore level change curve for the *global warming climate case* (**Climate report**), the time for a complete transformation to terrestrial conditions above the repository (SFR 1 and SFR 3) is c. 1,200 years.

In the *extended global warming climate case*, the maximum contributions to sea level rise in the Forsmark region from various processes are added, pessimistically and unrealistically assuming that they all occur within the next millennium. It would take c. 1,200 years for the isostatic uplift in Forsmark, which is 8.4 mm y^{-1} for the present and near future (the isostatic rebound not compensated for sea level change, Lidberg et al. 2010), to compensate for this maximum sea level rise of c. 10 m. In the *extended global warming climate case*, the shore level at Forsmark is therefore assumed to be the same at present as in 3200 AD (Figure 4-5). After that, the situation is assumed to be similar to today, with the isostatic uplift slowly raising the repository site over the level of the Baltic Sea. Based on this simplistic approach, the *extended global warming climate case* is defined with an initial submerged period of the repository of c. 2,400 years.

The climate will constrain the human utilisation of the landscape, where, for example, the agricultural practices will be severely restricted, or non-existent, under permafrost conditions. A warmer climate may affect the agricultural practices in different ways, e.g. the growing season may be extended, opening up the possibility for intensified cultivation. Studies suggest that the increasing annual precipitation will fall outside the growing season (e.g. BACC 2008, IPCC 2013), which in turn suggests that an increased production would demand additional water, e.g. from irrigation (or genetically adapted/modified crops). However, large-scale irrigation is considered unlikely in relation to the location of potential agricultural areas in the landscape (drained mires) and the present and future climate (SKB 2014), but scoping calculations have been done in order to evaluate the outcome of irrigation on small-scale production of potatoes and vegetables under temperate conditions in a garden plot.

The same type of regolith would potentially be used for agricultural practices regardless of the climate. A warmer and moister climate will also have effects on the formation and development of mires in the landscape, both in terms of terrestrialisation of lakes and the peat accumulation over time that may increase or decrease. Moreover, the expansion of peat would be climate dependent and would potentially cover larger areas in a moister future climate (e.g. Franzén et al. 2012).

4.3 Topography and regolith

The present summary of regolith development in Forsmark in based on Lindborg (2010) and the references therein; the reader is referred to these sources for more details on the processes and how they were modelled. The accumulation of sediment and peat as well as the erosion of sediment on the sea floor will continue in the future. The distribution of regolith in the Forsmark area will consequently change throughout the time period considered in the safety assessment. The proportional distribution of different deposits in the terrestrial part of the Forsmark area will change as new land is uplifted. Obviously, the future distribution of regolith cannot be predicted in detail. However, it can be expected that the proportion of terrestrial areas with clay will increase as the broad valley of "Öregrundsgrepen" is uplifted.

In the present terrestrial area, the proportion of peat-covered areas will increase significantly as the shallow lakes are infilled, and the low-lying wetlands are covered by a layer of peat. New lakes will form when the present sea floor is uplifted. These lakes will successively be filled with gyttja and peat. As indicated by the results of the landscape development modelling presented in Chapter 5, the proportion of land suitable for agriculture will increase significantly in the future as the areas with clay sediments at the floor of "Öregrundsgrepen" are uplifted.

A colder climate may cause an increased proportion of areas to be covered by peat. The mires formed in a colder climate, as in northern Sweden, are often a mixture of fen and bog areas. If the climate in Forsmark becomes more similar to the climate in northern Sweden, it is consequently likely that a large portion of the landscape will be covered by peat. A warmer and drier future climate may also affect the properties of peat-covered areas. Bogs are formed in areas with a high precipitation, and a warmer climate with higher evapotranspiration may prevent the development of fens into bogs.

During the forthcoming thousands of years, the present soils will successively develop into more mature soil types. At present, the most commonly occurring soils have developed on till and are often rich in calcite and consequently have high pH. In the future, the soil pH will decrease as the calcite is leached out. Podsol will thereafter probably be the most common future soil type in the area. Also the areal proportion of histosol will successively increase when the lakes are infilled with peat and when a peat layer has accumulated in the wetlands.

A coupled regolith-lake development model (RLDM) has been constructed and is applied to the Forsmark area. The model and its application in the SR-PSU assessment are reported in Brydsten and Strömgren (2013). The SR-PSU RLDM is based on an earlier model developed for SR-Site (Brydsten and Strömgren 2010). The SR-PSU modelling methodology is summarised in Section 5.4 of the present report (see also Lindborg et al. 2013), where the differences from the previous modelling are also listed. Below, some general features of the RLDM development are outlined, and some example results are also given.

Specifically, the Brydsten and Strömgren (2013) study presents a model that can predict the surface geology, stratigraphy, and thickness of different strata at any time during the period considered in a safety assessment, and applies this model to the Forsmark site. The RLDM is divided into two modules: a marine module that predicts the sediment dynamics caused by wind waves and a lake module that predicts the lake infill processes. The RLDM marine module starts at the time when the area has recently been deglaciated and all regolith materials are of glacial origin. These conditions are generated using the regolith depth and stratigraphy model (RDM), which also has been updated as a part of the SR-PSU work (Sohlenius et al. 2013a).

In the marine sediment modelling, postglacial clay/silt is added or removed in each raster cell based on the sediment dynamic environment for that time. This sediment dynamic data is output from the sediment dynamic model as presented by Brydsten (2009). In a cell where erosion is the predominant process, all postglacial accumulation is resuspended and transported out of the cell. For each time step, the RLDM marine module outputs are raster maps of Quaternary surface geology, thickness of postglacial clay, and sea-bottom elevation (given by the DEM).

The lakes are modelled with a module within the RLDM based on an equation for net sedimentation rate and an equation for vegetation colonisation (Brydsten and Strömgren 2013). Each lake is modelled separately. The DEM and the thickness of the marine postglacial clay from the time step before lake isolation is used as the only input to the module. The lake module runs in 100-year time steps until the lake is completely infilled. Raster maps of Quaternary surface geology, DEM, thickness of the marine and limnic postglacial clay (gyttja clay and clay gyttja), and thickness of the peat are outputs from the lake module for each time step. In a post-processing routine, the outputs from the marine and lake modules are merged into single raster maps for Quaternary surface geology, DEM, and RDM.

As an example of results from modelling with the RLDM, Figure 4-6 shows surface distributions of Quaternary deposits at two different times in the future, 3000 AD and 11,000 AD. By comparing the two maps it is clear that relatively large changes take place as a result of the above-mentioned processes. The perhaps most obvious development is the increase in peat-covered areas, which for obvious reasons are primarily observed in new land areas outside the present shoreline (e.g. Figure 3-3). The formation of a set of large lakes in the present sea in the eastern part of the area is also indicated by changes in the regolith. In particular, the sedimentation forming post-glacial clay in these lakes and the peat development around them are clearly reflected in the regolith distributions. The areas indicated by thick lines in Figure 4-6 are the regional and local model areas considered in the hydrological modelling with MIKE SHE, see Section 4.4.1.

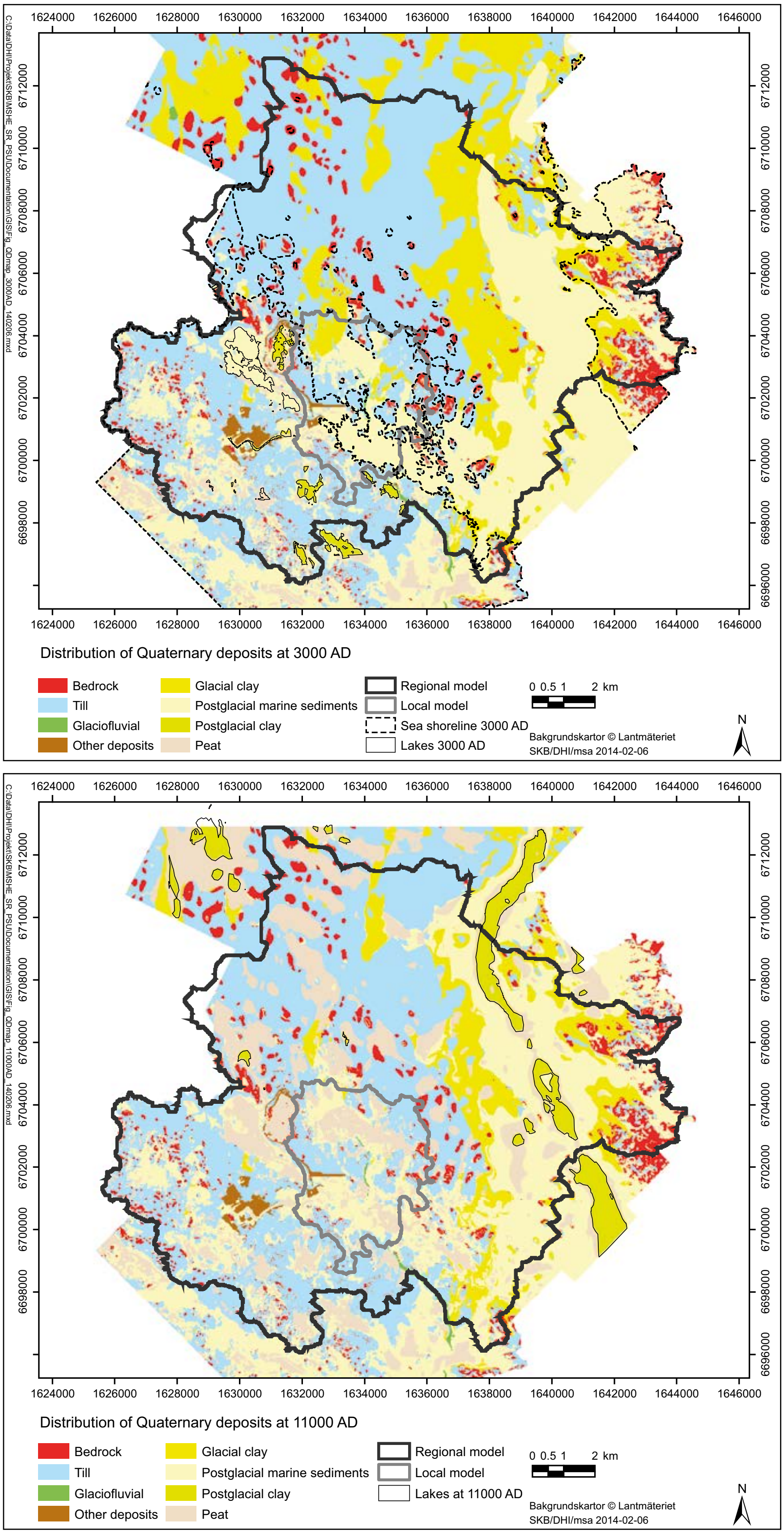


Figure 4-6. *Surface distributions of regolith at 3000 AD (top) and 11,000 AD (bottom), according to the modelling with the regolith-lake development model, RLDM (Brydsten and Strömgren 2013). The areas indicated on the map are the regional (thick black line) and local (grey line) model areas used in the hydrological modelling (Section 4.4.1). The brown areas mark man-made deposits within industrial areas, i.e. the nuclear power plant to the west and the Forsmark harbour with the SFR facility.*

4.4 Hydrology and chemistry

4.4.1 Hydrological development

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 dissolved substances and particles. Conceptual and numerical models describing present (cf. Chapter 3) and future hydrology were developed, based on SDM-Site (Bosson et al. 2008) and SR-Site (Bosson et al. 2010).

Modelling of future hydrology was conducted on a local spatial scale, supported by regional-scale boundary conditions (the model areas are shown in Figure 4-6). MIKE SHE water-flow models were developed for the times 2000 AD (present conditions), 3000, 5000 and 11,000 AD, using locally measured meteorological data for a selected one-year period referred to as the normal year (Werner et al. 2013a). This year has an accumulated precipitation that is close to the estimated annual average for the so-called reference normal period (1961–1990), and is also close to the locally measured annual average for the period 2004–2010.

Moreover, the influence on surface hydrology of a wet and warm climate, representing a significantly changed future climate, was investigated using the 5000 AD model. Meteorological data for the wet and warm climate were obtained from Kjellström et al. (2009). The four time slices differ due to shoreline displacement and landscape development, in terms of, for example, topography, vegetation, shoreline position, and distribution and depth of regolith (Brydsten and Strömgren 2013). Werner et al. (2013a) also discuss the influence of periglacial conditions with permafrost on water flow in the surface system and interactions with groundwater flow in the underlying bedrock.

For the normal-year meteorological data (see definition above), with an annually accumulated precipitation of less than 600 mm, the overall water balance does not change dramatically due to landscape development, according to the MIKE SHE modelling. The modelled wet and warm climate is characterised by significantly more precipitation (c. 1,500 mm y^{-1}), a higher potential evapotranspiration, and more runoff compared to the normal year. In particular, the influence of the climate is large in terms of surface and near-surface water flows, whereas the influence of the climate decreases with depth in the rock.

Figure 4-7 shows average vertical head differences in the regolith (which indicate whether the groundwater flow has an upward or downward direction) in the local MIKE SHE model area at 5000 AD, using normal-year meteorological data. In future land areas formed as a result of shoreline displacement, the modelled pattern of groundwater recharge and discharge areas in the regolith is similar to that observed in present land areas. This indicates that near-surface hydraulic gradients and flow directions are more dependent on topography than on the detailed distribution of regolith or the distance to the shoreline. However, the results show that the stratigraphy and depth of regolith may influence local recharge and discharge patterns in the regolith. Discharge areas for deep groundwater are concentrated to low-elevation areas, and regolith stratigraphy and depth in these areas (see Section 4.3) are therefore important for near-surface transport of dissolved substances and particles.

Werner et al. (2013a) present MIKE SHE water-balance calculations of a number of groundwater discharge areas in the future landscape, delineated as biosphere objects (see Chapter 6 for description of biosphere objects). According to these calculations, groundwater discharge from the rock to the regolith increases with time, especially during the initial period after shoreline passage (3000 to 5000 AD) when the relatively low flow rates associated with the sea period increase to those prevailing in the coastal terrestrial landscape. At 11,000 AD, all lakes within the local model area have been transformed to terrestrial areas, resulting in less evapotranspiration and higher annual average stream discharges compared with 5000 AD.

As illustrated in Figure 4-8, the hydrology of periglacial environments is influenced by ice, snow and frozen ground. In particular, frozen ground in the form of permafrost is a typical feature of periglacial systems that controls the distribution and routing of water across the landscape. Permafrost reduces groundwater recharge and discharge relative to unfrozen conditions, and the exchange of deep and shallow groundwater occurs via taliks, i.e. unfrozen pockets of water located above, below or within frozen ground. In particular, through taliks, which are unfrozen ground exposed at the ground surface and to a larger mass of unfrozen ground below, connect the unfrozen groundwater flow system at depth to the active layer on the ground surface. The active layer is an upper layer that is subject to cyclic freeze and thaw and hence frozen or unfrozen depending on weather conditions.

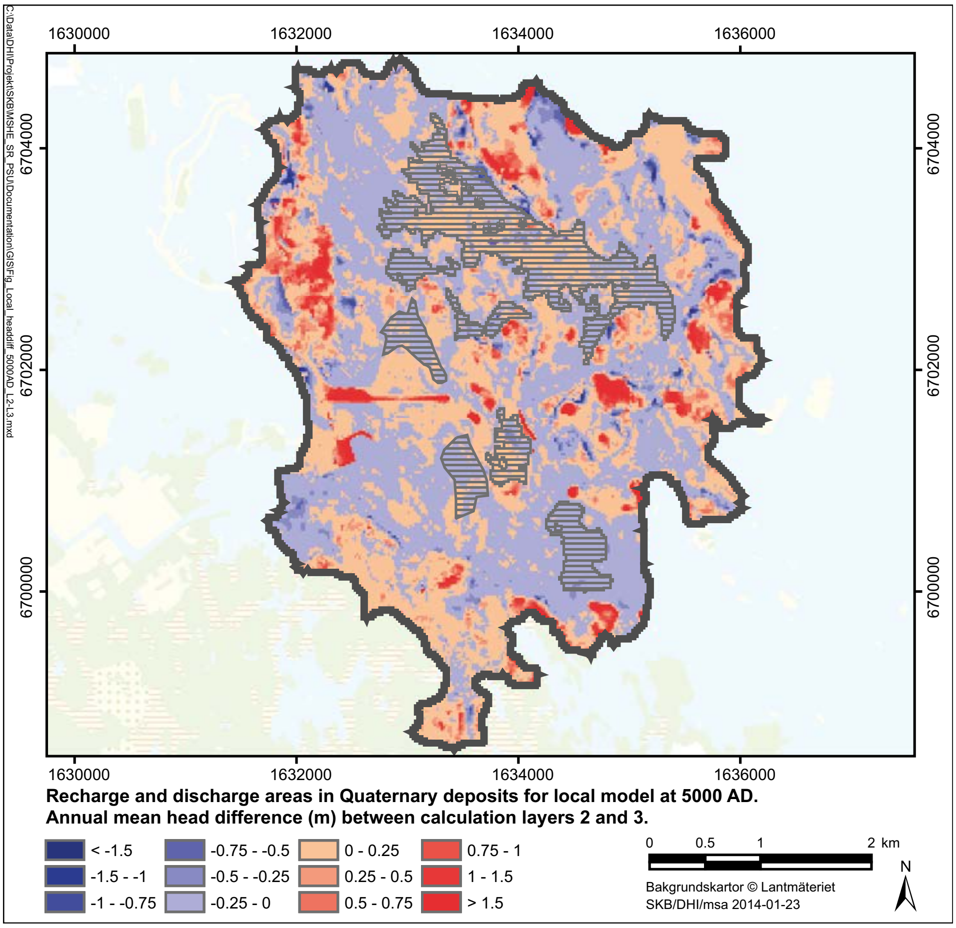


Figure 4-7. *MIKE SHE-calculated annual average vertical hydraulic-head differences in the regolith at 5000 AD. Blue colours represent areas with upward flow (discharge) and red colours areas with downward flow (recharge). Dashed areas indicate the delineated biosphere objects (see Chapter 6).*

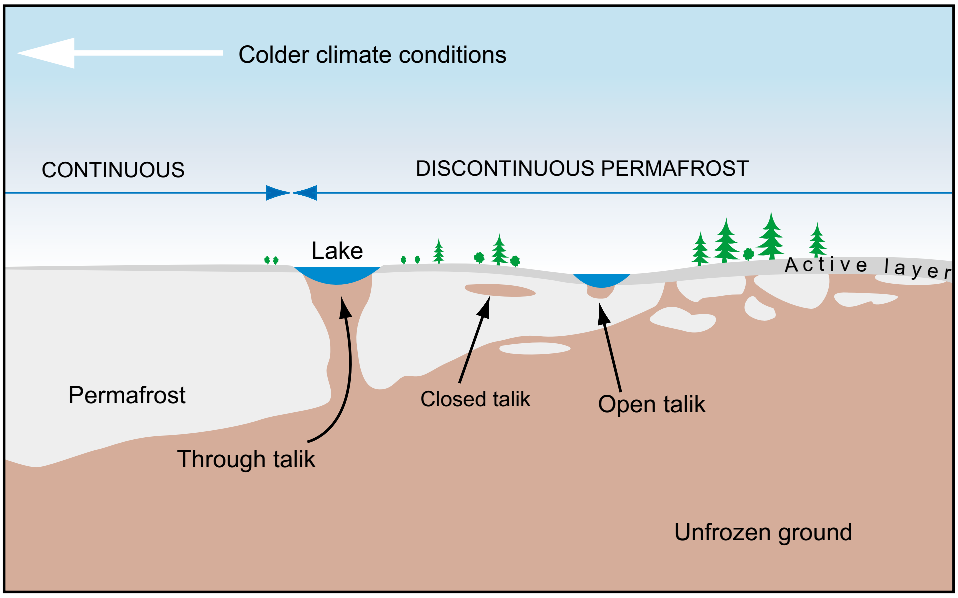


Figure 4-8. *A schematic profile through a permafrost area with an active layer and different types of taliks (Bosson et al. 2010).*

Periglacial environments are characterised by a relatively short hydrologically active snowmelt period, during which water is redistributed on the ground surface and in the active layer. A large part of the snowmelt occurs when the active layer is still frozen, hence preventing infiltration. Moreover, once the active layer is thawed it is quickly saturated, which promotes ground-surface storage, ponding and surface-water runoff. In a periglacial environment without permafrost, groundwater flow in the uppermost regolith is the largest part of the runoff, whereas surface water has the largest contribution to runoff with permafrost. Permafrost also delays groundwater discharge to streams, because the active layer has to thaw before near-surface groundwater flow can take place. The handling of permafrost and other features of the periglacial landscape in the hydrological modelling is described in Werner et al. (2013a).

4.4.2 Hydrogeochemical development

The chemical conditions observed in the Forsmark area today are a consequence of past landscape development, past and present 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 development. The present chemical conditions found in the modelled area in Forsmark therefore represent a time span of about 10,000 years since the last deglaciation. This means that the spatial gradient of today may be extrapolated and translated into a succession of landscape development for the future. Several factors will influence the development of the chemical environment of the Forsmark landscape in the future. External abiotic factors, such as land uplift, climate and atmospheric deposition, set the limits, whereas internal factors, such as primary production and land use, may have a profound influence via feedback mechanisms.

The typical ontogeny of the lakes in this area is a short oligotrophic hardwater stage (that may or may not occur) lasting about 1,000 years followed by the development of brown-water lakes and finally wetland formation (Andersson 2010). The deeper parts of Öregrundsgrepen will in the future possibly develop into a number of relatively large and deep eutrophic lakes with a hydrochemistry more resembling larger lakes further south along the coast. Some future lakes in Forsmark will receive water from larger catchments (e.g. the Forsmarksån and Olandsån catchments), compared with the small drainage areas of present Forsmark lakes. This might have great effects on the ontogeny of these lakes, e.g. the existence of an oligotrophic hardwater stage, but since they will form at some distance from SFR they need not be considered in the SR-PSU modelling.

Similarly, the first stage in the wetland ontogeny of the Forsmark area is today characterised by rich fens dominated by *Bryales*. These are replaced by poor fen communities dominated by *Sphagnum* as the mire development proceeds and the influence of mineral-enriched groundwater diminishes over time (e.g. Löfgren 2011). This development can be seen already after 2,000 years for catchments located high in the landscape (e.g. Rönningarna). The transition may take longer time if a larger amount of groundwater is directed into the mire (i.e. if the catchment is larger).

Calcite-bearing till deposited during the last glaciation has had profound effects on the hydrochemistry in the Forsmark area. Weathering of calcite releases Ca^{2+} ions and increases alkalinity in the shallow groundwater and in fresh surface water. The ample supply of Ca^{2+} ions and the high alkalinity give conditions conducive to precipitation of calcite in wetlands and lakes forming calcareous sediments (Hedenström and Sohlenius 2008). Estimates based on pool quantities and present weathering rates suggest that the calcite in the regolith layers might be consumed by weathering reactions in a relatively near future, perhaps within a time span of some 1,000 years depending on the assumptions (Tröjbom and Grolander 2010).

Studies reported in Ingmar and Moreborg (1976) showed that the calcite in the soil horizon has been consumed down to considerable depths further inland from Forsmark and that there is a clear gradient of this depth towards the coast. The observation that the oligotrophic hardwater stage usually persists a few thousand years perhaps supports the diminishing calcite influence, although other factors in the catchment could have influence on the presence of this lake type (Andersson 2010). These estimates imply that the calcite influence will diminish in a relatively near future, at least in a 10,000 year perspective. The present deviating conditions of the Forsmark area will therefore change towards the hydrochemical environment seen in most other parts of Sweden.

The quantitative effects of calcite leaching on the chemistry of surface water and sediments, and on agricultural soil are hard to predict. However, by contrasting the water and soil chemistry of Forsmark with that of a similar coastal site lacking influence from calcite (i.e. Laxemar), an upper limit of the effects of calcite outwash can be estimated. Such a comparison suggests that the pH of lake water may decrease by no more than one unit (Andersson 2010). Similarly, the pH of surface peat in mires and cultivated clays and organic soils may decrease by no more than 1.3 units (Sheppard 2011, Lundin et al. 2004, Löfgren 2011).

In the long term, this has implications on the magnitude of processes such as co-precipitation and primary production in limnic and mire ecosystems. Dissolved Ca and P, as well as pH and alkalinity will drop. The surface water quality in the Forsmark area will approach the conditions found in the brown-water lakes and streams further inland today. This probably means higher concentrations of total organic carbon (TOC) as well as increased concentrations of total P. As explained in Lindborg (2010), it could also be presumed that weathering rates of less readily weathered minerals such as silicates will increase in the future when the calcite in the regolith is depleted. Also the release of other major constituents originating from weathering of these types of minerals, e.g. Al and Na, Mg, Ca, are assumed to be enhanced in the future chemical environment, as well as release of trace elements incorporated in the bulk minerals, e.g. U, Th, Zr and rare earth elements.

4.5 Marine ecosystems

4.5.1 Development under temperate conditions

Future temperate marine ecosystems are assumed be similar to those at present (Aquilonius 2010, Lindborg 2010). Nevertheless, the predicted abiotic changes will alter the size of functional groups and the magnitude of the fluxes within the ecosystems. The major change will be when an ecosystem, in a deeper offshore area, shifts from being dominated by pelagic primary producers to benthic primary producers, along with the uplifting of the sea-floor. However, the primary production in these shifting habitats will most probably still be of similar magnitude to that in the presently existing shallower coastal areas. At present, the whole marine area in Forsmark is net autotrophic, due to the high primary production in the shallow areas and in the long-term future it is likely that the marine ecosystem will continue to be net autotrophic.

The influence of less saline discharge water from land will lower the salinity and the organisms will shift from being a broad mix of freshwater and marine species in the Baltic Sea, towards a dominance of more freshwater species. According to modelling, the marine area in Forsmark is almost completely gone from the model area at 11,000 AD, and the salinity in the remaining basins will have decreased to between 2 to 3 ppm, which is consistent with present Bothnian Bay conditions (Gustafsson 2004, Janssen et al. 1999). The Bothnian Sea will be isolated from the Baltic Proper around 25,000 AD and become a large freshwater lake (Påsse 2001).

4.5.2 Effects of global warming

Under global warming conditions, increases in precipitation and thereby runoff associated with increased temperature may affect the load of nutrients and particulate matter in the marine area. Decreased duration and extent of sea ice, increased water temperature, increased freshwater input, and changes in wind stress will affect the rate of nutrient supply through their effect on vertical mixing and upwelling. Changes in vertical mixing and upwelling will affect the timing, location, and species composition of phytoplankton blooms, which will in turn affect the zooplankton community and the productivity of fish. Since bacterial respiration is temperature-dependent, the increased temperature will most likely be associated with increased bacterial respiration in the pelagic and benthic marine ecosystem (BACC 2008).

In addition, a higher respiration rate at the bottoms induced by increased primary production and temperature may lead to an increase in anoxic bottoms, which in turn will affect the reproduction of many fish species that are dependent on oxygen-rich bottoms for reproduction. Another negative effect for fish dependent on the spring bloom for successful reproduction is that the earlier start of the season might shift the start of the spring bloom, causing a mismatch between primary producers and consumers, which will have effects along the food chain that reduce fish productivity. For other fish species, the higher temperature will mean a higher growth rate and a longer growth season, and for these species production is expected to be higher (BACC 2008).

It is likely that the thermocline in most coastal areas will establish at greater depth during the summer. As a result, the warm-water species will extend their habitats at the expense of the cold-water species. A similar spread of freshwater species at the expense of species with higher salinity optima is also likely to occur due to the decrease in salinity. The range and biomass of marine species may decrease, at the same time as the range and biomass of freshwater species will increase. In the case of marine mammals, a reduction in the extent of ice cover during the winter will lead to reduced reproduction of seals (*Phoca hispida botnica)*, since they need ice to breed their pups (BACC 2008).

4.5.3 Periglacial conditions

In a future periglacial climate, the primary production could, due to the nutrient conditions, be higher, lower or similar to present conditions. Nevertheless, it is likely that it will be within the range of estimates for today. In addition, a likely development is that rates of respiration will decrease along with temperature. As the environment becomes colder, some temperate species presently at the site, may be limited by their cold-tolerance and will become rarer or absent at the site, whereas polar (Arctic) species may extend into the area with present polar species becoming more abundant and new species entering the site. However, for marine areas, the same types of higher organisms are expected at Forsmark, although species abundance and composition may be altered. For example, marine mammals are already present in the Baltic, but the growing season will be shorter and the ice will provide an increased habitat for breeding of marine mammals, which therefore may increase in abundance.

The bird fauna population has been very stable in the Baltic during the recent interglacial (BACC 2008) and will probably be similar in the future. The sea-bound flora and fauna will probably be dominated by freshwater species and show a higher degree of species able to adapt to colder climates. The colonisation of new marine species will probably be very limited due to the semi-enclosed character of the Baltic Sea, although new freshwater species may colonise.

4.6 Limnic ecosystems

4.6.1 Development under temperate conditions

Sea bays may either be isolated from the sea at an early stage and thereafter gradually turn into a lake (Figure 4-9), or may remain as a bay until shoreline displacement turns it into a wetland. After isolation from the sea, the lake ecosystem gradually matures in an ontogenetic process that includes subsequent sedimentation and deposition of substances originating from the surrounding catchment or being produced within the lake. Hence, the long-term ultimate fate for most lakes is an inevitable fill-up and conversion to a wetland, as further discussed in Chapter 8 in Andersson (2010) and in the summary description in Lindborg (2010).

In Forsmark, all present-day lakes have developed into shallow oligotrophic hardwater lakes that are characteristic of the area. In the future, shoreline dispacement will isolate both shallow and deeper marine basins and turn them into freshwater bodies. Most lakes that form in the area close to SFR will be shallow, but three lakes further away from the repository will have depths of more than 10 metres and are therefore considered to represent deep lakes. The remaining lakes that form in the model area will have depths around 2 metres or less and are considered shallow.

Many of the shallow lakes that will emerge due to land-rise are assumed to closely resemble the present-day oligotrophic hardwater lakes in Forsmark with high primary production on the lake floor. However, it is also possible that they, due to inflow of matter from the catchment, will become dystrophic, i.e. with brown water and dominated by respiration of allochthonous material produced in the surrounding terrestrial catchment. The deep lakes that will emerge in the Forsmark area differ from the shallow ones in a number of respects and are assumed to more closely resemble other deep lakes in surrounding areas.

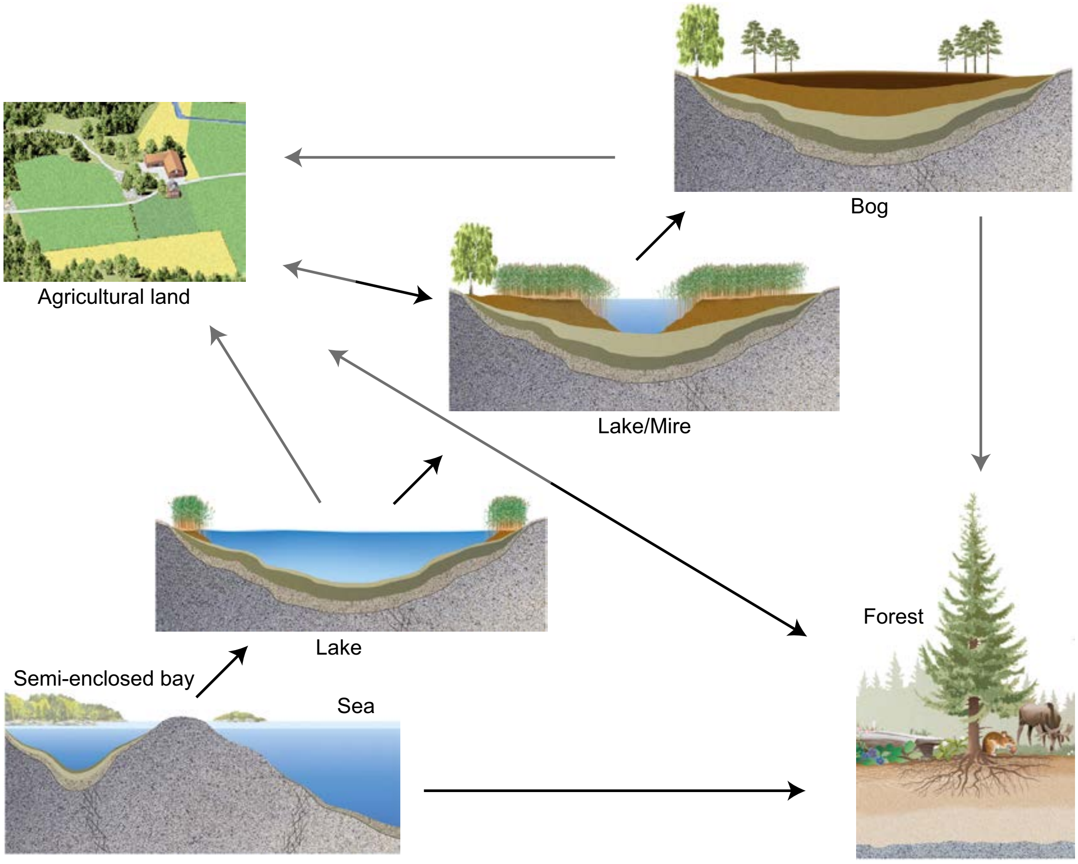


Figure 4-9. *A schematic illustration of the major ecosystems that may be found at certain points during a temporal sequence, where the original sea bottom slowly becomes land due to shoreline displacement. Black arrows indicate natural succession, while grey arrows indicate human-induced changes to provide new agricultural land or improved forestry. Agricultural land may be abandoned and will then develop into forest or, if the hydrological conditions are suitable, into a fen. A forest may be "slashed and burned" and used as agricultural land.*

The lakes will be deep enough to allow for thermal stratification during both summer and winter. In the future deep lakes, a large part of the pelagic production may be utilised directly in the pelagic habitat by zooplankton, but the losses through the outlet will probably be large due to large catchment areas and thereby short retention times. In addition to lakes, ephemeral pools like the small ponds found in Forsmark today, will most likely be formed also in the future. However, due to the size of the ponds, they will be transformed into wetlands relatively quickly.

In the future, small streams closely resembling the streams in the Forsmark area today (cf. Chapter 3) will form in the area close to SFR. Further away in the model area, larger streams than those currently present will be formed, and are assumed to more closely resemble the relatively large River Forsmarksån. These deeper streams are assumed to not host benthic primary producers, but on the other hand they may contain larger amounts of pelagic producers. The retention time in future streams will be shorter than at present, due to larger water flows induced by larger catchment areas.

4.6.2 Effects of global warming

Lakes are affected by global warming and lakes have been proposed to serve as sentinels of climate change due to their rapid and observable responses (Adrian et al. 2009). However, the response of lakes to global warming is individual and affected by catchment characteristics, lake morphometry and food web interactions, and the response of lakes to global warming is less clear than effects on terrestrial ecosystems (see Andersson (2010) for a discussion). Generally, the effect on abiotic parameters is relatively easily foreseen, whereas effects on biotic parameters are difficult to determine.

An increased air temperature will lead to a longer stratification period in summer and shorter periods with ice coverage. Since the temperature in winter in the global warming scenario will range between 0 and 6°C, there will likely be at most short periods of ice coverage interrupted by open water periods. This also has implications for other abiotic and biotic parameters in the lakes, such as mixing, light conditions, biomass and production. Runoff is modelled to increase, which will influence nutrient concentrations by altered input, but also by altered retention time in lakes. Processes within the lake, such as mixing and anoxia, may influence the future nutrient concentrations in the water column. In most lakes, dissolved organic carbon (DOC) is expected to increase due to global warming.

There may be a shift in occurrence of anoxia from winter to summer. At present, anoxia occurs in the shallow lakes in Forsmark during winter. A shortened period with ice coverage reduces the risk of anoxia in winter. On the other hand, increased production in summer can lead to increased amounts of degradable matter, resulting in increased respiration (eutrophication) and increased anoxia during summer stratification. The effects on biotic components in lakes are difficult to foresee and there may, for example, be an increase or decrease in phytoplankton biomass. For a more comprehensive discussion on possible effects of global warming on the Forsmark lakes, readers are referred to Andersson (2010).

4.6.3 Periglacial conditions

As the environment becomes colder, some temperate species occurring at the site today may be limited by their cold-tolerance and will become rarer or absent at the site, whereas polar (Arctic) species may increase in the area, with present polar species becoming more abundant and new species entering the site. A large difference between present lakes in Forsmark and future periglacial lakes is that there will be no reed surrounding the periglacial lakes (Andersson 2010). The reed belts surrounding present-day lakes may be important for the functioning of the lakes by influencing the composition of water entering the lake from the sub-catchment. Moreover, the reed belts may function as sheltered breeding areas for aquatic organisms. In periglacial regions, lakes may instead be surrounded by bryophytes or other vascular plants than reed.

A useful approach to describe the potential species present in the Forsmark area under different climate conditions is to gather information on the biota composition in areas with the relevant climate today. For the periglacial climate domain this has been done using the information gained in the SKB assessment for the Greenland Analogue Surface Project (GRASP, see SKB 2013a). No amphibian or mammal species were identified in the limnic reference ecosystems at the Greenland site, and these organism types are also expected to be absent at the Forsmark site under periglacial conditions. Otherwise, organism types are expected to be similar to those at present at Forsmark although the abundance and composition of species may be altered.

In addition to existing lakes defined by bedrock depressions, there will be thermokarst lakes (thaw lakes) in a periglacial system. Thermokarst lakes develop in a cyclic pattern where permafrost freezes and thaws, forming temporary water-filled depressions with a life span of a couple of hundred years. Thermokarst lakes are usually small and shallow. From an ecological point of view they may be important for the landscape, as they may be hotspots of biological activity in tundra regions with abundant microbial activity, primary production, benthic communities and birds. However, thermokarst lakes do not have connection to deep groundwater flow and are therefore not important in the context of radionuclide transport from a geological repository.

In colder climates, lake ice coverage will be thicker and persist longer during the winter. This leads to less light penetration, affecting the primary producers beneath the ice as well as the mixing and transport of nutrients. Nutrient concentrations may be lower due to a shorter runoff season, altered weathering, production and retention in the ground surrounding the lake, as well as altered internal circulation of nutrients. There is an increased risk of oxygen depletion during the winter due to longer periods with ice cover.

Despite a shorter growing season, biomass of primary producers is not necessarily lower under periglacial conditions than in temperate regions. Species composition may change, but biomass and production of benthic primary producers under periglacial conditions are assumed to closely resemble the biomass and production under temperate conditions. Phytoplankton biomass is relatively low in present-day Forsmark lakes and it is likely that the biomasses will be similar in a periglacial climate. Even if primary production remains similar between periglacial and temperate climate domains, biomass and production of fish will probably decrease under periglacial conditions (for further details see Andersson (2010)).

4.7 Terrestrial ecosystems

4.7.1 Development under temperate conditions

A number of different terrestrial ecosystem types are found in the Forsmark region and further inland, which differ in properties, such as dominating functional groups, biomass, net primary production (NPP) and groundwater availability. Based on hydrological modelling, the mire has been identified as the terrestrial ecosystem type that most likely could be affected by an inflow of radionuclide-containing groundwater from the repository, due to its location in the low-lying parts of the landscape (see Chapter 6). More specifically, this is valid for the different fen stages, whereas the bog surface constitutes an independent hydrological unit completely dependent upon precipitation (Löfgren 2010). Consequently, the focus here is on the mire ecosystems and their potential use as agricultural land after drainage.

Mires are formed basically through three different processes: terrestrialisation, paludification and primary mire formation (Löfgren 2010). Terrestrialisation is the filling-in of shallow lakes by sedimentation and establishment of vegetation. Paludification, which is the dominant process of mire formation in Sweden, is peat formation on more or less water-permeable soils, mainly by changed hydrological conditions or expanding mires. Primary mire formation is when peat is developed directly on fresh soils after emergence from water or ice. All three processes are likely to occur in the Forsmark area, but terrestrialisation probably represents the largest areas of peatland development in the investigation area today.

This pattern, where reed is the dominating pioneer during terrestrialisation, is also seen in the peat archives of bogs further inland (Fredriksson 2004, Bergström 2001), although the extent of the historical importance of reed during terrestrialisation is uncertain. The typical mire of the Forsmark area is characterised by high pH and will undergo a natural long-term acidification when turning into a more bog-like mire (Figure 4-10). Most wetlands are discharge areas; however, the raised bog, with rain-fed production on the bog plane has a restricted or non-existent connection to the groundwater table, and is of less interest in a safety assessment where the radionuclides enter the ecosystem from below.

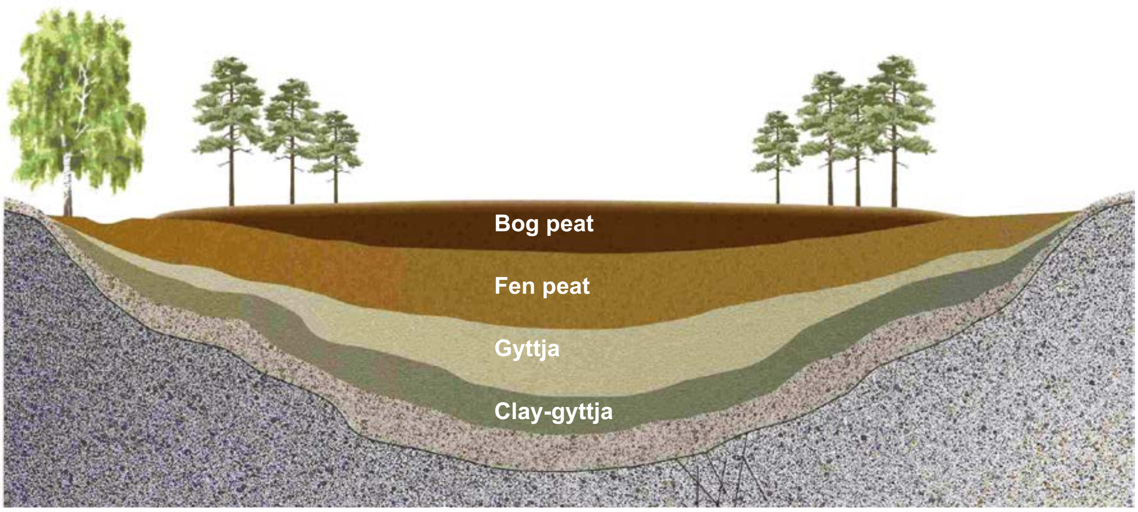


Figure 4-10. *A schematic bog where the stratigraphy illustrates the different successional stages from the isolated sea bay to the bog.*

Most of the ecosystems have their different characteristic land uses, which are presented and discussed in Chapter 5. One of the largest impacts on ecosystems is drainage activity, which historically has been pursued to create arable land or to improve the forestry yield (Löfgren 2010). Land suitable for cultivation is often situated in the low-lying parts of the terrain and often occurs in small irregular pockets in the surrounding boulder-rich terrain. In the middle of the 19th century, larger wetland areas in the woodlands were drained and cultivated as arable land (Figure 4-9). In the future, large areas of glacial clay will be exposed, which has to be considered as a more preferable substrate for cultivation (Chapter 5).

The largest part of the land area is not defined by the stages described above and is dominated by till and outcrops. Wave-exposed Baltic Sea shores will undergo a relocation of previously accumulated sediments, and these shores will emerge as wave-washed till, where the grain size of the remaining sediments is a function of the fetch at the specific shore. Shores with wave-washed till are the most common kinds in the Forsmark area, but rocky shores and shores with fine sediments can also be found. The emerging rocky and till shores have a seashore vegetation zonation that is defined by their tolerance to water inundation and salt sprays. Flora and vegetation will change steadily following the shoreline regression, with a relatively high degree of determinism in the successional pattern (see Löfgren (2010) and references therein).

4.7.2 Effects of global warming

A warmer climate usually means potentially increased biomass and NPP, as well as reduced carbon storage in the short term, depending on the magnitude of the climate change (Chapin et al. 2002, BACC 2008). Modelling of the vegetation with the dynamic vegetation model LPJ-GUESS (Sitch et al. 2003) generated data to describe the vegetation under the modelled global warming climate conditions. The modelling result suggests that Forsmark would be dominated by broad-leaved trees, with larger biomass but with NPP similar to that of today.

Other modelling approaches, e.g. BACC (2008), suggest a climate response where forest productivity and biomass increase. They also highlight the uncertainties concerning the carbon dynamics in wetlands. An increased temperature, with an increased evapotranspiration, will likely lower the groundwater table and increase heterotrophic respiration. This can initially be balanced by an increased plant production in the mire, which is enhanced by drying. Strack et al. (2008) suggested that dry peatland areas such as bog hummocks and ridges will act as smaller sinks or sources of CO_2, whereas wet zones will likely become greater sinks.

4.7.3 Periglacial conditions

As the environment becomes colder, the geographical range of organisms will move south. Some temperate species presently at the site may be limited by their cold-tolerance and will become rarer or absent at the site, whereas polar (Arctic) species may extend into the area with present polar species becoming more abundant and new species entering the site. The species potentially present in the Forsmark area under different climate conditions could be described using information on the biota composition in areas with the relevant climate today. For the periglacial climate domain this has been done using the information gained in the SKB assessment for the Greenland Analogue Surface Project (GRASP, see SKB 2013a). There, large trees, gastropods, amphibians and reptiles are absent, and these organism types are also expected to be absent at the Forsmark site under periglacial conditions. Otherwise, organism types are expected to be similar to those occurring presently at Forsmark, although abundance and composition of species may be altered.

The biome representing tundra has vegetation characteristics that are dominated by the field and bottom layer. Under periglacial conditions in Forsmark, the same regolith may be assumed to be present as under temperate conditions, and potential functional vegetation types characteristic for this biome can be suggested and associated with these regolith types. A shrub layer may be dominant in a transition zone between the tree line and the tundra, and also be present in the tundra environment under more wet/moist conditions, e.g. on minerogenic soils close to mires or along rivers. Similarly, sheltered low points (which in most cases also have a deeper soil layer) would be colonised early during an advancing tree-line or will contain the last fragments of trees when the tree-line is regressing. These sheltered areas are less exposed to wind and have a warmer and moister microclimate.

The same areas that have been classified as wetlands during periods of temperate conditions will also be wetlands in a periglacial landscape, and will be dominated by sedges and bryophytes. This general vegetation description should be regarded as a rough suggestion and a number of factors such as slope aspect or prevailing wind direction are important structuring components in regard to where these or similar vegetation types are found in a subarctic or arctic landscape (see Löfgren 2010). Moreover, a prevailing permafrost regime, together with lower evapotranspiration, would suggest larger areas being partially or periodically water-inundated than expected from the patterns of the current landscape.

A sufficiently reduced temperature will eventually change a temperate or boreal environment to a more tundra-like environment. This will lead to lower biomasses and NPPs in both forested taiga and tundra peatlands. Such a change might also increase relative carbon storage in relation to NPP, whereas the actual amount that is stored, e.g. as peat, will be lower than under present conditions. A lower mean annual temperature will reduce the yield of crop production, and the specific conditions found in a permafrost landscape will dramatically change the potential for cultivation. For a detailed discussion on terrestrial ecosystems and how they are expected to change under different climate conditions, the reader is referred to Löfgren (2010); a summary is provided in Lindborg (2010).

5 Modelling landscape development and land use

5.1 Introduction

The safety assessment spans a large time scale and it is necessary to investigate potential effects of the factors known to be of importance for the properties of the landscape. First of all the present landscape and its constituents are briefly described. Subsequently, different factors of importance for the landscape configuration are described, such as human utilisation of the landscape, the shoreline displacement and the climate. These are then elaborated to sketch the potential configuration of future landscapes in a landscape development model (LDM). The examples of potential future landscapes are based on knowledge from the present landscape, historical land use, historical data and geological evidence on shoreline displacement, and climate modelling.

In SR-PSU the assessment time frame is 100,000 years, but the largest changes in the landscape will take place before 20,000 AD. During this time the coastal location is changed into an inland locality, where most of the lakes have developed into mires. Consequently, the modelling time frame for the LDM is from today to 20,000 AD. This period has been modelled using different assumptions of land use to illustrate the potential impact on the landscape based on the *global warming climate case* implying moderate changes relative to the present climate. Furthermore, among the SR-PSU climate cases (Chapter 4) there are two other cases that are illustrated using the LDM, a periglacial climate occurring from around 17,500 AD and prevailing for c. 3,000 years, and an extended global warming climate that may reach its temperature maximum around 3000 AD (**Climate report**). Accordingly, the LDM was used to illustrate the landscape development in five variants: 1) land use similar as the present, 2) intensive land use, 3) no land use, 4) a periglacial climate with no land use, and 5) an extended global warming with similar land use as the present.

5.2 The landscape of Forsmark

In this section, the historical and present landscapes of Forsmark are discussed. Certain processes important for landscape development, such as lake and wetland succession, are discussed in Chapter 4. During some periods, human utilisation has been a major component affecting the composition of the landscape. The agricultural land is the most intensively managed land in the landscape and is a major provider of food for human consumption, either directly as crop production or as production of fodder and other types of feed for animals. For a number of radionuclides, cultivation is the land use that generates the highest doses to human. Cultivation of organic soil situated in discharge areas for groundwater where radionuclides have accumulated for a long period is likely to be a major exposure pathway for human inhabitants (SKB 2010, Saetre et al. 2013b).

Crops grown on peat in former wetlands, which are/have been exposed to discharge of deep groundwater, may take up radionuclides mainly from two sources. Firstly, the peat-forming plant material may contain radionuclides incorporated during the wetland stage and/or adsorbed later, which are released during mineralisation and, secondly, the drained wetland may still potentially act as a discharge area for contaminated deep groundwater. Special effort has therefore been put on estimating characteristics of cultivated peat deposits and when they can be cultivated. The knowledge of the present and historical land use and climate are used to sketch future landscapes. One of the most important tasks for the LDM is consequently to identify sub-areas within future discharge areas that may be used for cultivation. To fulfil such a task it is important to be able to define robust criteria for the identification of such sub-areas. For a more comprehensive description of the present/past land use and historical development of the Forsmark region the reader is referred to Lindborg (2010) and Söderbäck (2008).

5.2.1 Ecosystems and the present landscape

The site descriptions have provided large amounts of information describing the ecosystems of today, and this information is presented separately for marine systems (Aquilonius 2010), limnic systems (Andersson 2010) and terrestrial systems (Löfgren 2010). Six different ecosystems have been used to characterise the landscape, emphasising differences in transport and accumulation of matter, land use and the ability to identify these vegetation types by remote sensing. These ecosystems are: sea, lake, stream, wetland, agricultural land and forest (Figure 5-1). The characteristics and present distribution of these ecosystems, and how they are interconnected over time by successional and developmental processes, are described in detail in Lindborg (2010) and in Chapter 3 and Chapter 4 of the present report. The present conditions are assumed to represent ecosystem characteristics in the base case. However, in addition to possible effects of a changing climate, future ecosystems may differ from the present ones due to landscape development. Differences in expected ecosystem characteristics under future temperate conditions compared with present conditions are discussed in the section covering landscape development in Lindborg (2010).

5.2.2 Present land use in the Forsmark region

In the County of Uppsala, arable land is mostly situated on clays and other fine-grained deposits, which were deposited in the lowest topographical areas when the area was covered by the Baltic Sea. These deposits are, however, almost lacking in the terrestrial part of the present Forsmark area and the proportion of arable land is therefore low. Due to the ongoing shoreline displacement, new land areas suitable for agriculture will continuously be exposed.

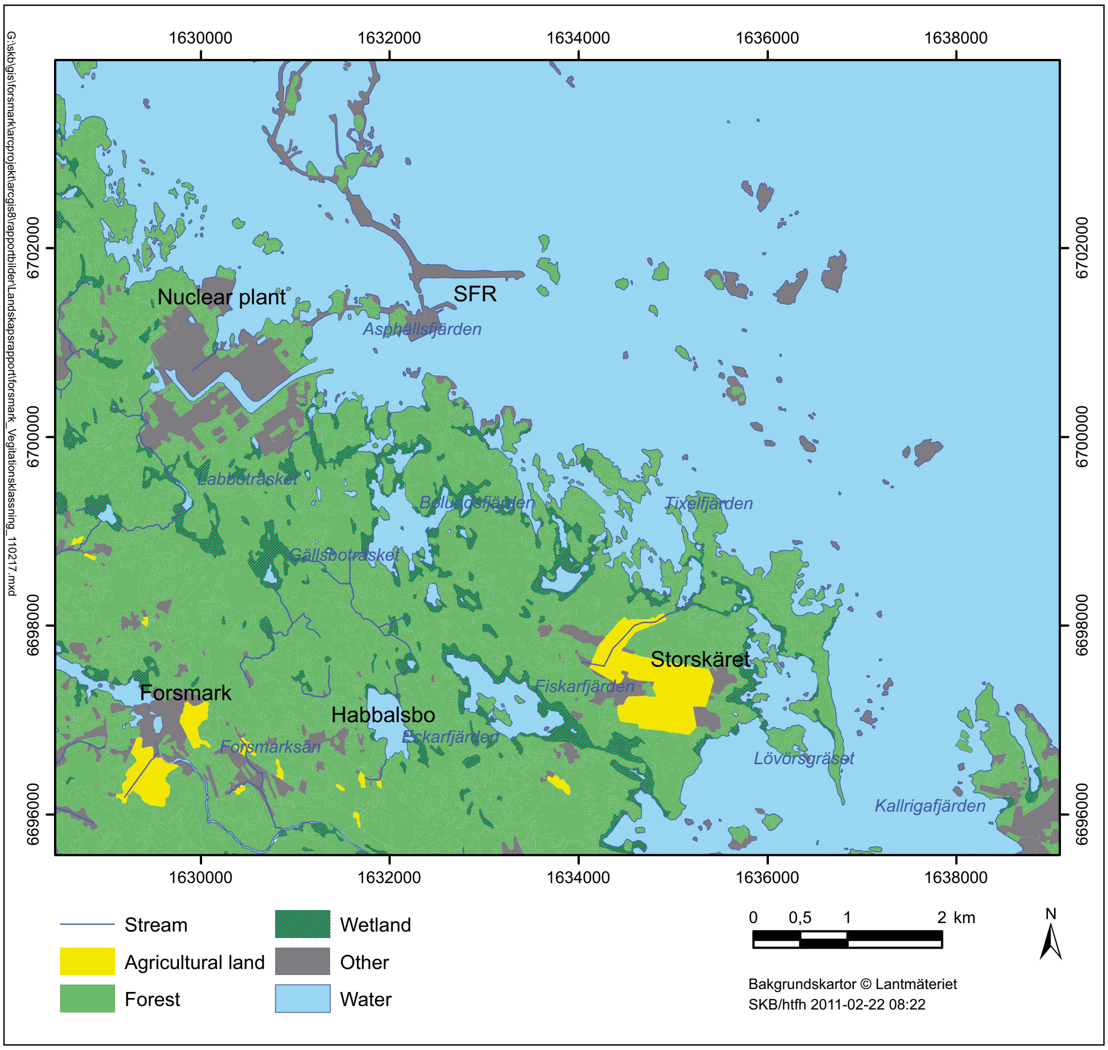


Figure 5-1. *Distribution of ecosystems at Forsmark. The surface systems are divided into six ecosystem types, three terrestrial (agricultural land, wetland and forest) and three aquatic (lakes, streams and marine ecosystems). The areas marked as "other" include buildings, hard surfaces, and other open land not associated with the six ecosystem types mentioned above. Figure from Lindborg (2010).*

According to the land use data, the agricultural land in the Forsmark model area comprises 84 ha, of which 34 ha is arable area and 50 ha is classified as semi-natural grasslands or pastures (Löfgren 2010). Only around 10% of the total agricultural area earlier used (arable area and pasture) is today used for production of grain and vegetables. In Sweden, the dominant crop type is fodder crop for animal production, which is grown on 74% of the agricultural area. This means that 26% of the agricultural area in Sweden is used for production of grain and vegetables for human consumption. Accordingly, the current land use situation in the Forsmark area is more concentrated on production of fodder and grass for domestic animals than the agricultural land area in Sweden in general (Löfgren 2010).

Lindborg (2010) used GIS to compare arable land shown on the topographic map (Lantmäteriet, www.lantmateriet.se, accessed 2009-12-01) with the distribution of regolith (unconsolidated deposits) shown on SGU's maps (SGU's database for Quaternary deposits, www.sgu.se, accessed 2009-12-01). The results show that most arable land in the region around Forsmark is situated in areas with water-deposited clays (glacial and postglacial) and sand. Only a small fraction of the arable land is situated in areas with peat and till. The till in most areas has a high content of boulders and stones and is therefore not suitable for cultivation. However, areas with fine-grained till with a low content of stones and boulders can be cultivated relatively easily. One such area is the cultivated clayey till around Storskäret, which is situated 4 km southeast of SFR (Figure 5-1). Lindborg (2010) also studied the proportions of the different regolith types that are used for cultivation. It is clear that a high proportion of the glacial and postglacial clays are used for cultivation, whereas only a small proportion of the peat-covered areas are cultivated. Since water-laid clay is almost lacking in the terrestrial areas close to SFR the proportion of arable land is low. That can, however, change in the future when the fine-grained deposits situated at shallow water depths around SFR are uplifted.

The areas used as arable land in the eastern County of Uppsala where Forsmark is situated have decreased since 1950 (cf. Berg et al. 2006). Also, the proportion of small areas used for cultivation has decreased since 1950. A qualitative comparison between the present and 1950 distributions of arable land shows that the types of regolith that are used for cultivation have not changed significantly (cf. Lindborg 2010). However, the use of areas to provide summer fodder for animal husbandry has changed over time. The use of wood pastures once was common when most of the suitable land areas were cultivated, but decreased and disappeared during the first part of 20th century. Today, a large part of livestock grazing and haymaking takes place in former arable fields with richer soils and higher nutrient content due to fertilisation.

The proportion of organic deposits used for cultivation in the whole of Sweden has decreased significantly during the last 60 years (cf. Lindborg 2010). The present proportion of cultivated peat deposits in the County of Uppsala (5%) is close to the Swedish average (Berglund et al. 2009). One reason for the decreased proportion of cultivated peat areas during the last 60 years may be that the peat layers have oxidised and many present areas with arable land are situated on deposits, such as postglacial clay and clay gyttja, underlying former peat layers. It is, however, clear that large peat areas formerly used for cultivation have been abandoned. Today it is generally not allowed to make new ditches in areas unaffected by ditches, and peat-covered wetlands are at present not converted to arable land in Sweden. Further south in Europe, much larger proportions of the peatlands are currently used for agriculture, the great majority being used as meadows and pastures (Strack et al. 2008), which indicates that a larger proportion of the Swedish peatland could potentially be used for cultivation in the future.

Even though a relatively small proportion of the wetlands has been drained for agricultural purposes, many of the wetland areas in the County of Uppsala have been drained for improving forest growth. This has caused subsidence and oxidation of peat in large areas. These processes are, however, much slower in forested areas than in areas used as arable land (Maljanen et al. 2010). Additionally, some wetlands have been drained for exploration of fuel peat or of peat used for cultivation. Peat is a national energy resource although at present it is only used to a small extent. The peat in the Forsmark regional model areas is at present not suitable for use as fuel, due to high sulphur and ash contents and to relatively small and shallow peat deposits (Lindborg 2010, Fredriksson 2004).

5.2.3 The historical landscape

A major part of the Forsmark model area was completely covered by water until c. 1500 BC. The known development of human land use is therefore based on information from other areas of Sweden. Before the Younger Stone Age (4000–1800 BC), the impact of human activities on the natural landscape was small and almost all terrestrial areas in South- and Mid-Sweden were consequently covered by forest. In southern Sweden, the dense forests were cleared during the first phase of the Younger Stone Age (Hyenstrand 1994), often by the use of fire, and the open areas created were first cultivated for some years and then used as grazing land.

During the Bronze Age (1800–300 BC) and the Iron Age (300 BC–1100 AD), the areas with cultivated soils gradually increased. Iron mining has had an important role in the Forsmark region since the Iron Age. As the iron industry became more organised in the 16th century, forests were cut down to feed furnaces and mines with wood and charcoal. The region around Lake Mälaren in south-central Sweden was almost depleted of trees at the end of this period (Welinder et al. 1998).

Before the modernisation of agriculture, only fairly dry soils could be cultivated. Heavy clays and wetlands were used for haymaking, and stone-ridden tills and bedrock with surficial soil were grazed. The modernisation of agriculture made it possible to drain areas with peat and heavy clays for cultivation. The usage of peat as arable land is a rather recent phenomenon. Extensive draining of wetlands started a bit more than one hundred years ago and peaked in the 1930s in Sweden (Eliasson 1992). This was done by lowering the groundwater table in mires and lakes by ditching. During the 18th to 20th centuries there was a demand for increased food production since the population was growing. This resulted in extensive ditching of wetlands and lowering of lakes, which considerably changed the landscape.

Many mires in Sweden have been partly or completely drained and in some areas in the south of Sweden with intensive cultivation as much as 90% of the wetlands have been drained (Svanberg and Vilborg 2001). The proportion of open landscape was largest in the late 19th century. However, this trend came to an end as management was rationalised by the use of fertilisers and better equipment in the early 20th century. Sweden has subsequently experienced a nationwide regression in agricultural activities.

5.2.4 Cultivation of peat – patterns and boundaries

The thickness and properties of peat are of importance for the possibility to drain a wetland and use it for agricultural purposes. Peat may accumulate in either fens or bogs. Fens are usually discharge areas for groundwater. As peat continues to accumulate, the fen can at a certain point develop into a bog where the surface of the mire becomes hydrologically independent of the landscape. At that point, the wetland has reached an ombrotrophic stage where the production of vegetation is all rain-fed. The peat developed during ombrotrophic conditions has low nutritious value (i.e. the C:N-ratio is high, Osvald 1937) and low pH, and this peat can therefore be regarded as less suitable for agricultural purposes (Berglund 1996a). Moreover, the potential accumulation in vegetation of radionuclides entering from below will level off as the bog plane rises.

The proportional distribution of different peat types which were used for cultivation during the mid-20th century was studied by Hjertstedt (1946). At that time the most commonly cultivated peat types in the County of Uppsala were *Carex* peat and *Bryales* peat, which are both formed in fens. Compared with other parts of Sweden, a relatively large proportion of *Bryales* peat was cultivated in the County of Uppsala. Hjertstedt (1946) also showed that a low proportion of nutrient-poor peat that has been formed in bog environments (*Sphagnum* peat and forest bog peat) was cultivated. As mentioned above, bog peat is generally low in nutrients and pH compared with fen peat. However, bog peat can be cultivated after remediation. Regardless of peat type, it is not possible to cultivate wetlands with thin peat layers if the peat is underlain by deposits that are not suitable for cultivation (e.g. certain types of till).

According to studies in Finland by Valmari (1977), groundwater depths of 50–60 cm below the surface are suitable water table depths for many crops. The groundwater depth in cultivated organic soils is however often deeper, and Berglund (1996b) reports depths between 50 and 100 cm in six cultivated organic soils from Sweden. Due to oxidation and compaction, peat subsides considerably when the groundwater is lowered, and the original peat layer must therefore be considerably thicker than 50–60 cm to make cultivation possible. Subsidence of peat due to cultivation is thoroughly discussed in Lindborg (2010) and Sohlenius et al. (2013c). Peat subsidence depends mainly on compaction and oxidation. The first years after draining are dominated by a relatively fast subsidence, which is caused by consolidation of the peat (Figure 5-2). After some years the thickness of the peat layer decreases more slowly and oxidation is the main process involved in that decrease.

Data presented in Kasimir-Klemedtsson et al. (1997) show that the total subsidence in cultivated peat areas can vary between 5 and 30 mm y^{-1} depending on the intensity of the management. Accordingly, high management intensity may cause a subsidence as large as 1.5 m during a 50-year period. Since subsidence of peat is a fast process, one reason for the decreasing proportion of cultivated peat areas is most probably that it is difficult to maintain the drainage due to subsidence of the peat. Another reason may be that the peat is underlain by deposits less suitable for cultivation. It may, however, be possible to continue cultivation after the oxidation of the peat if the properties of underlying deposits are suitable for cultivation and the maintenance of drainage is possible.

Sohlenius et al. (2013c) used peat data from a survey carried out 90 years ago (von Post and Granlund 1926) to determine the succession of peat-covered wetlands in the County of Uppsala. The study by Sohlenius et al. (2013c) showed that half of the cultivated peatlands (in total, 45 peatlands were studied) had gone through a lake stage, whereas the other half consisted of peat that had started to form in fens situated in discharge areas for groundwater. The peatlands that are used for cultivation and where the peatland stage has been preceded by a lake stage generally have larger peat depths. These peatlands are also characterised by more stages in their development compared with peatlands formed directly from a fen. Notable is that none of the studied cultivated peatlands are directly underlain by till; they are all underlain by more fine-grained minerogenic material.

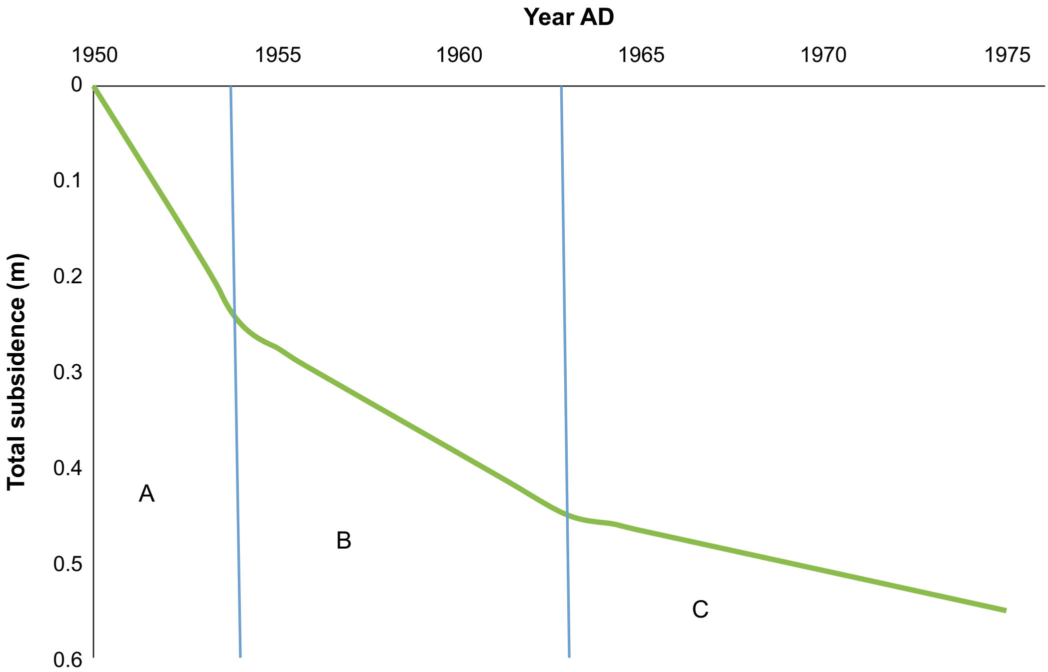


Figure 5-2. *Schematic description of the subsidence of peat after draining a wetland for cultivation (modified from Berglund 1989). The initial period (A) after the peatland was drained is characterised by a fast subsidence where compaction is the main contributor to the subsidence. The compaction continues after the initial period but at a slower rate (B). After 10–15 years oxidation is the main contributor to subsidence (C). Oxidation occurs throughout the illustrated period and is not expected to decrease with time. Over a longer period of time, the rate of oxidation is, however, expected to decrease, since the amount of organic material that is easy to oxidise will decrease.*

5.3 Future landscape at Forsmark

The future climate at Forsmark will be crucial for landscape development. Historical land use can be used to evaluate the future land use as described above. Below follows a discussion on types of agricultural land and wetlands that may be used for agriculture, the development of agricultural land and how different climatic scenarios may determine the landscape development.

5.3.1 Future distribution of arable land

Today, the regolith type most frequently used as arable land in the region is water-deposited clays. In the Forsmark model area, a relatively low proportion of the mainland is covered by such deposits. However, the floor of Öregrundsgrepen between the island of Gräsö and the mainland comprises a large proportion of water-deposited clay and sand, which is likely to become cultivated in the future when the present sea floor has been uplifted. Parts of the clay- and sand-dominated areas will, however, become covered by shallow lakes and wetlands, which successively will be covered by a layer of fen peat. Parts of the shallow wetlands can probably be relatively easily drained and cultivated. Such land use is analogous with the present land use on the mainland in the County of Uppsala. There are also forested areas with sand and clay on the present mainland that probably could be cultivated.

Almost all agricultural land in Forsmark is today situated on clayey till, and discharge of groundwater occurs only in parts of these areas (Werner et al. 2007). Till is often situated in the topographical high areas whereas the more commonly cultivated water-deposited clays are situated in the lowest areas, which may be discharge areas for groundwater. There are no observations showing the occurrence of clayey till on the present sea floor, which may be an effect of the difficulty to detect such deposits with the marine geological survey methods. However, clayey till occurs both on the island of Gräsö and on the mainland, and it is therefore likely that clayey till also occurs on the present sea floor.

A large proportion of the present mainland is covered by till with a normal frequency of surficial boulders (5–30 boulders/100 m^2). These areas are today covered by forest, although it cannot be ruled out that a certain part of that till area may be used as arable land in the future. It is, however, unlikely that there will be any extensive cultivation of these areas. Outcrops, glaciofluvial deposits, and till with a high frequency of boulders are practically impossible to cultivate and will probably remain forested.

Even though the demand for arable land has decreased during the last decades, the need for arable land may increase in the future, e.g. due to increasing global demand for food. This would probably cause an increase in small areas used as arable land and many of the areas cultivated 60 years ago may be cultivated again. Furthermore, an increasing demand for food would probably also increase the areal use of peat as arable land.

In contrast to peat, areas with minerogenic deposits can probably be cultivated for many thousands of years. Most of the regolith used as arable land today is dominated by minerogenic material. Erosion and weathering are slowly affecting these deposits. Erosion may be a fast process, but most likely not on the generally flat landscape discussed here (Cerdan et al. 2010). Chemical weathering is a slow process releasing nutrients needed for primary production. As long as the soils contain significant amounts of calcite, the elevated pH means highly fertile soils, but the calcite dissolution will in the long run lead to a lowered pH and a decreased productivity.

5.3.2 Future wetlands and land use

Future areas suitable for cultivation will, as mentioned above, mainly consist of clay and sand, which today are situated at the floor of Öregrundsgrepen. Many of the wetlands that will form directly upon the clay or sand can probably relatively easily be drained and used as arable land. The wetlands that will form after a lake stage can in many cases also be used as arable land. Some of the lakes will not be suitable for cultivation in the future, since the peat layers will be too thin and rest directly upon deposits that are difficult to cultivate (cf. Osvald 1937, Fredriksson 2004), e.g. till with large boulders. In the present LDM, all present and future wetlands that have a peat layer thicker than 1.5 metres are assumed to be used for cultivation. That assumption probably overestimates the future areas used as arable land, but should be seen as an attempt to estimate the maximum distribution of future arable land.

Even though many lake and wetland deposits are underlain by minerogenic deposits suitable for cultivation, it may be difficult to maintain the drainage of these areas for a long time due to subsidence of the organic deposits; especially fens developed in former lakes are often underlain by thick layers of gyttja sediments, which are sensitive to compaction. Such areas are consequently difficult to use as arable land for a long period (> 100 years). Future locations with relatively thin peat layers that will form in the clay- and sand-dominated areas can, however, be suitable for cultivation for a longer period of time. This is because these areas are underlain by deposits that are not sensitive to compaction and are suitable for cultivation when the peat has disappeared. The accumulation rate of fen peat is often below 1 mm y^{-1} (Sohlenius et al. 2013c) and peat suitable for cultivation is consequently not available in recently uplifted areas.

As mentioned above, bog peat is low in nutrients and it is therefore not likely that bogs will be drained for agricultural purposes. Moreover, the raised bog, with rain-fed production on the bog plane, is of limited interest in a safety assessment where the radionuclides enter the ecosystem from below. Consequently, a higher degree of *Sphagnum* bog peat will both make the mire less suitable for cultivation and also dilute the content of radionuclides originating from the deep groundwater. At a point when the bog peat has reached a certain depth, mixing of the surface layer, e.g. by ploughing, will not reach the more nutrient-rich fen peat below the bog peat.

Based on this argument, a sufficiently deep layer of bog peat would both restrict the potential contamination from deep ground water and the use as arable land. There seems to be a broad range of estimates of how fast mires turn into bogs, and how fast bog peat accumulates. Mäkilä and Goslar (2008) presented data on bog peat accumulation where the mean accumulation on raised bogs during the last 500 years was 0.64 mm y^{-1} suggesting that it takes approximately 1,500 years to develop 1 m depth. Sohlenius et al. (2013c) found that the accumulation rate of *Sphagnum* peat in the northern County of Uppsala is slightly higher than 1 mm y^{-1}. Somewhat higher accumulation rates are implied by radiocarbon dates from Rönningarna in Forsmark, showing that 1.5 m of peat was developed during 850 years (1.8 mm y^{-1}, Sternbeck et al. 2006).

The onset of bog peat accumulation varies due to local conditions and, in many fens, bog peat starts to form after a fen stage of several thousand years (Lundqvist 1963). Consequently, it seems that the window of opportunity for agriculture on mires may be variable depending on size, age, local hydrological conditions and climate. Although it is likely that the peat in the area generally does not fulfil the demands of the present peat industry, this may change in the future. The demands of the industry might change, and it is also possible that the properties of the peat might change in the future. It is therefore possible that some peat in the future will be used as fuel peat.

By using data describing bulk densities of cultivated and wetland peat it was possible to calculate a subsidence factor as the ratio between the cultivated and uncultivated peat. This gave an estimated ratio of 0.34 (Grolander 2013), which does not include oxidation. The subsidence of peat soils will therefore increase with time, since these soils also subside due to oxidation (Figure 5-2). The subsidence of gyttja sediments was calculated in a similar way as for peat, which gave a ratio of 0.25. The large subsidence of the gyttja sediments is an effect of the organic material, which causes a high porosity and thereby low stability of soils developed on these sediments. The glacial clays will also subside when the groundwater table is lowered. Since the glacial clay lacks significant amounts of organic matter, that subsidence will be much less than for the organic deposits described above. No attempt was therefore made to quantify the subsidence of glacial clay.

To estimate potential doses to humans it is assumed that peat-covered wetlands can be used as arable land for a period of 50 years (approximating a human lifetime in the assessment). The utilisation is assumed to be possible as soon as mire vegetation is formed and the criteria of a regolith depth of at least 0.5 m after compaction and a location at least 1 m above sea level are fulfilled. As a consequence of drainage and lowering of the water table, crops can be grown on the peat and take up radionuclides from the surficial drained layer. The necessary peat depth set as a prerequisite for a potential use of peatlands for a longer period of time (approximately 50 years) is set to 0.5 m of consolidated peat and/or gyttja clay and/or glacial clay. A factor/function for each regolith type is used to describe the subsidence (Grolander 2013). The total subsidence during a 50-year period was calculated for each layer.

5.3.3 Climate change

Climate has been relatively constant in the time perspective discussed for agricultural use above, but has been more varied in terms of temperature and precipitation during the development of peatlands during the Holocene in the northern part of the County of Uppsala. The choice of possible future climate developments ("climate cases") analysed in the SR-PSU safety assessment is based on current knowledge of the past and potential future evolution of climate and climate-related processes.

The present landscape modelling considers the three SR-PSU climate cases that involve various degrees of global warming, namely the *global warming*, *extended global warming*, and *early periglacial climate cases*. The climate cases are described in the **Climate report**, and a summary is provided in Section 4.2. The climate will constrain the future human utilisation of the landscape, where the agricultural practices will be severely restricted or non-existent under a periglacial climate. In contrast, an extended global warming climate could imply an intensified agricultural use of the present agricultural land, due to the higher temperature and a prolonged growing season. Accordingly, no agricultural land is present in the landscape variant that has a periglacial climate, whereas the present use of agricultural land is assumed valid also in the *extended global warming climate case*.

As described in Section 4.2, different shoreline displacement models are used in the different climate cases, which must be taken into account in the landscape development modelling. Specifically, the *extended global warming climate case* differs from the other cases in this respect. Whereas the *global warming* and *early periglacial climate cases* involve a continuous shoreline displacement from today extending several thousand years into the future, the *extended global warming climate case* first has a period of raising sea level and then a shoreline returning to its present location in about 1,200 years. After that, the situation is assumed to develop as is happening today, with the isostatic uplift slowly raising the site over the level of the Baltic Sea.

The ecosystem characteristics in the *global warming climate case*, such as vegetation, are represented by the present conditions (Chapter 3). The ecosystem characteristics during periods of colder or warmer climate conditions, i.e. under periglacial climate and under extended global warming climate, are predicted by substituting "time for space" using knowledge of ecosystem characteristics in regions with colder or warmer climate today (Grolander 2013).

5.4 The landscape development model

A landscape development model (LDM) was used to illustrate the future landscape development based on the description above. Five different variants were identified in order to describe changes in land use and climate. The aim was to describe and characterise the landscape with regard to parameters underpinning the dose calculations. Another aim was to be able to set areas typically hosting biosphere objects into a larger landscape context, which would be important for discussions on human use of resources in the landscape.

5.4.1 Methodology

Based on the knowledge of present and historical ecosystems at the Forsmark site, as well as the knowledge of ecosystems in other climatic conditions, rules were constructed and applied in GIS software to describe a number of potential landscapes at Forsmark covering different assumptions of land use and climate conditions. Below, the rules, assumptions, methodology and the resulting landscape development maps presented. The methodology presented here follows Brydsten and Strömgren (2010), with a few modifications in the regolith-lake development model (RLDM) that is used in the LDM (see Figure 5-3).

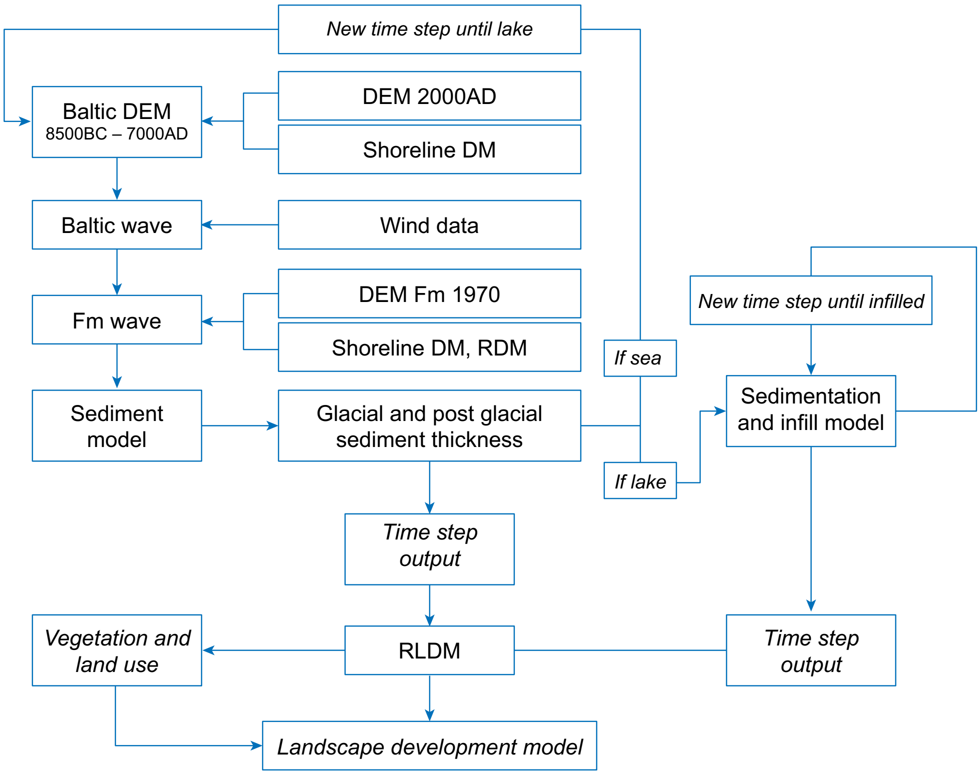


Figure 5-3. *A conceptual flow chart of the coupled regolith-lake(-biota) development model (RLDM). The flow chart describes the work process and the linkage between the underlying models used for each time step to build the landscape development model (LDM) for Forsmark ("Fm" in the figure). The marine module runs independently from the lake module and the lakes are modelled separately depending on their appearance in time.*

The main modifications of the RLDM since Brydsten and Strömgren (2010) are:

- The wave model uses a 20 m s^{-1} wind only, since a sensitivity analysis showed this to be adequate.
- The resolution of the Forsmark wave model results (20 m) was the same as for all other model input.
- The new DEM reported in Strömgren and Brydsten (2013) was used as input.
- Two metres of glacial clay were added to parts of the model area at the initial time step and erosion of glacial clay was added in the following time steps (see below).
- A new infill model of vegetation in shallow bays was used.
- Consequences of erodible material at the lake threshold were taken into account by lowering the threshold accordingly.

A detailed description of the SR-PSU RLDM and the above changes relative to the corresponding SR-Site modelling is given in Brydsten and Strömgren (2013).

5.4.2 Sources of data describing landscape development

Different sources of information were used to describe the development of the landscape. A large proportion of the data comes from the RLDM. The RLDM shows how the distribution and stratigraphy of regolith, lakes, wetlands and the relationship between land and sea change over time. Furthermore, it includes a dynamic elevation model demonstrating how the elevation of the landscape changes as a consequence of accumulation and erosion of regolith. The data describing different aspects of the landscape that are used as input to the LDM are briefly described below.

- **Shoreline displacement** – The shoreline displacement model shows how the shoreline moves, and hence the changing subdivision of the model area into terrestrial and marine components through time. The SR-PSU shoreline displacement models are presented in the **Climate report** (see also Section 4.2 of the present report). The larger-scale shoreline displacement modelling performed in connection with the RLDM used additional input from Brydsten (2009).
- **Lakes** – The present and future distribution of lakes was originally modelled by Brydsten and Strömgren (2013). Lakes are formed in topographical depressions that, in the modelling, were identified by using the digital elevation model, DEM (Strömgren and Brydsten 2013). The level of a lake may, however, be lower than indicated by the DEM due to the occurrence of easily eroded regolith at the lake threshold. The future depth of a lake will be less than that obtained from the present-day DEM, due to the occurrence of sediment layers generated by the sedimentation model (Brydsten and Strömgren 2013). The lakes are successively filled with clay gyttja and peat and are consequently slowly transformed into wetlands. In the LDM, small lakes and ponds are assumed to be instantaneously filled with peat and are consequently not illustrated.
- **Wetlands** – Wetlands are formed when lakes are filled with peat and clay gyttja. This process was modelled by Brydsten and Strömgren (2013). Wetlands not preceded by a lake stage were modelled by the use of a topographical wetness index (TWI), which is described in Brydsten and Strömgren (2013). Moreover, the peat distribution from the Quaternary geology map was also used to identify wetlands on land above the sea level, because peat infilling would lower the predictions based on TWI. In variants 1, 2 and 5 of the LDM, the wetlands are partly drained and used for agriculture and forestry (see Table 5-1 and text below).
- **Streams –** The locations of streams were modelled by using the present-day DEM and do not change in time (see Brydsten and Strömgren (2013) for further explanation). No erosion adjustment between time steps was taken into account. Using the GIS-program ArcView Hydrology extension, the DEM was "filled", which means that all negative features were filled up to their threshold levels before the actual modelling started. For each time step, the original stream network (covering the whole model area) was clipped at the shoreline of that time step. Streams passing through lake areas were adjusted by connecting the small ponds that exist in the later stages of the lake infilling process. Upstream of the highest situated lakes, the streams were removed when they became too small to have flow all year around (based on the Hydrology extension flow accumulation value being < 7,000, which corresponds to a mean runoff 0.02 $m^3 s^{-1}$). However, none of the seven basins that were studied in detail in SR-PSU were affected by this rule.
- **Bedrock outcrops** – The distribution of outcrops originates from the maps of regolith, which demonstrate the present distribution of regolith in the modelled area (Sohlenius et al. 2013a, see also Chapter 3). However, in the sedimentation model some of the outcrops recorded during the mapping of regolith become covered with regolith (Brydsten and Strömgren 2013), and some of the present outcrops, shown on the regolith map, are consequently not shown in the LDM.
- **Till** – The distribution of till, including the distribution of clayey till with a low frequency of boulders, originates from the maps of regolith (Sohlenius et al. 2013a). The artificial fill was taken from the map of regolith and is used as till in the LDM.
- **Glaciofluvial deposits** – The distribution of glaciofluvial deposits was taken from the maps of regolith (Sohlenius et al. 2013a).
- **Glacial clay** – The distribution of glacial clay was modelled by Brydsten and Strömgren (2013). The result is based on the present distribution of glacial clay, as obtained from the regolith map in Sohlenius et al. (2013a), on which a layer of clay was superimposed to represent the situation after the latest deglaciation. It is likely that the whole model area was covered by glacial clay as the sea water depth at maximum was more than 200 m. The variation in glacial clay thickness on the sea floor at that time is unknown; the mean value of the thickness was assumed to be 2 m in areas not affected by erosion. This means that the modelled thickness in early time steps could have large errors, but already at approximately 3000 BC the glacial clay thickness reaches steady state based on the wave power. The remaining clay at each time step was used as input to the LDM.
- **Marine and lacustrine sediments (clay gyttja)** – These fine-grained sediments are rich in organic material and are denoted clay gyttja in this report. The distribution of clay gyttja was taken from the model by Brydsten and Strömgren (2013), where these sediments start to accumulate directly after the latest deglaciation and thereafter have been affected by both sedimentation and erosion. The distribution of clay gyttja changes consequently through time. In the model by Brydsten and Strömgren (2013), clay gyttja accumulates in lakes, in shallow bays and in the deepest parts of the sea.

- **Peat** – The distribution and thickness of peat through time has been modelled by Brydsten and Strömgren (2013). In their model, peat is formed in shallow water-covered areas. Specifically, lakes with water depths less than two metres and shallow parts of bays with 1.3 metres water depth or less are successively filled with vegetation. The final peat depth corresponds to the water depth before the onset of peat accumulation. In deeper lakes, peat can start to form when accumulating clay gyttja has decreased the water depth to less than two metres. Peat is also formed in numerous shallow ponds and lakes with lifetimes too short for them to be included in the LDM. Present and future wetlands and future areas with TWI values higher than 13.2 are covered by peat in the LDM. The peat ingrowth rate is based on estimates from present Forsmark. The rate was further adopted to simulate a periglacial climate based on literature data (Brydsten and Strömgren 2013).
- **Cultivated clay gyttja** – In the LDM the thickness of cultivated clay gyttja has to be equal to or more than 0.5 metres that correspond to at least two metres of undrained clay gyttja. The original thickness of undrained clay gyttja is multiplied by 0.25, which represents the compaction that occurs when converting water-saturated clay gyttja to arable land. The factor 0.25 is based on the density difference between drained cultivated clay gyttja and undrained clay gyttja (Grolander 2013).
- **Cultivated peat** – In the LDM the thickness of cultivated peat is equal to or greater than 0.5 metres, which corresponds to at least 1.5 metres of undrained peat. The original thickness of undrained peat is multiplied by 0.34, which illustrates the subsidence that occurs when converting water-saturated peat to arable land. The factor 0.34 is based on the density difference between drained cultivated peat and undrained peat (Grolander 2013).

Table 5-1 shows how the regolith is used to model different types of ecosystems in the variants of the LDM.

Table 5-1. The relations between regolith types and dominating terrestrial vegetation types in the five LDM variants modelled. The following vegetation types were used: A = arable land, CF = mixed coniferous forest, W = wetland, PF = pine forest on bedrock. For LDM variant 4, B = barren outcrops, TH = tundra heath. For LDM variant 5, OF = oak forest, DF = mixed deciduous forest (mostly beech). The criterion for arable land is that the total depth of the cultivable regolith layers must sum up to at least 0.5 m of compacted material before it is considered cultivable and that the area must be at least 1 m above sea level. Different compaction factors are assumed for peat and clay gyttja, whereas glacial clay is assumed to have no compaction (Grolander 2013). The total area of cultivable regolith types must exceed a certain size limit, depending on the variant, or the area will be forest or, if wetness index is high (TWI > 13.2), wetland. All types of regolith can be wetlands in areas with a high TWI, if not fitting the criteria for ditching. See Appendix 3 for a detailed description.

Type of regolith	Variant 1 Global warming with land use similar to the present	Variant 2 Global warming with intensive land use	Variant 3 Global warming with no land use	Variant 4 Periglacial conditions	Variant 5 Extended global warming with land use similar to the present
Peat	W if > 0.24 ha, else CF	A if cultivable areas > 0.24 ha and layers > 0.5 m, else CF if bordering areas with A, else W	W if > 0.24 ha, else CF	W if > 0.24 ha, else TH	W if > 0.24 ha, else DF
Clay gyttja	A if > 1 ha and cultivable layers > 0.5 m, else CF	A if area > 0.24 ha and cultivable layers > 0.5 m, else CF	CF	TH	A if > 1 ha and cultivable layers > 0.5 m, else DF
Glacial clay	A if > 1 ha and cultivable layers > 0.5 m, else CF	A if > 0.24 ha and cultivable layers > 0.5 m, else CF	CF	TH	A if > 1 ha and cultivable layers > 0.5 m, else DF
Glaciofluvial deposits	CF	CF	CF	TH	DF
Clayey till with a low frequency of superficial boulders	A if > 1 ha	A if > 0.24 ha	CF	TH	A if > 1 ha
Till with normal or high frequency of superficial boulders	CF	CF	CF	TH	DF
Outcrops	PF	PF	PF	B	OF

5.4.3 Description of the variants of the landscape development model

Five variants of landscape development have been produced. Site data and modelling results describing the conditions during the modelled part of the present interglacial, from 1500 BC to 40,000 AD, are used as a basis for these variants. These conditions include properties such as rate of shoreline displacement and regolith distribution (see Section 5.3). In the following, the variants and the criteria used when defining and developing them are described.

The modelled five LDM variants are:

1) Global warming with a land use similar to that at present, where only the most suitable land areas are cultivated.
2) Global warming with an extensive land use corresponding to the pattern found during the areal maxima of historical land use. This is also the landscape development that is assumed in the radionuclide modelling of the biosphere in SR-PSU (see Chapters 7–10).
3) Global warming with a land use development unaffected by humans (no cultivation).
4) Periglacial conditions unaffected by human land use (no cultivation).
5) Extended global warming with a land use similar as the present, where only the most suitable land areas are cultivated.

The first three variants assume a climate affected by global warming, where the temperature may increase and reach a mean annual temperature of +8.4°C (see Section 4.2), which is an approximate increase of 3°C compared with the mean temperature of today. However, these three LDM variants are based on knowledge obtained for a climate similar to today in terms of temperature and precipitation. Variant 4 demonstrates the possible development of landscape in a considerably colder climate, where permafrost is assumed to hinder agricultural cultivation of crops and slow down the ingrowth of lakes. Variant 5 demonstrates landscape development under considerably warmer conditions, in a climate more strongly affected by global warming with a maximum increase of 6°C up to a mean annual temperature of +10.7°C. For the terrestrial areas, most priority has been put on estimating the distribution of wetlands and areas used as arable land. Most other areas are shown as a forest type that would dominate under the specified climate. However, forest on outcrops is shown as a separate type of forest in all variants except in variant 4, where forest is completely lacking due to the periglacial climate conditions.

In variants 1, 2 and 5, certain regolith is used for cultivation if situated more than 1 metre above sea level. Areas at lower altitudes than that are assumed to be too difficult to drain for cultivation. This limit was based on studies of maps from the coast of Uppland. Lindborg (2010) used 2 metres above sea level as the lower limit for possible cultivation. However, data from the Board of Agriculture (www.jordbruksverket.se, accessed 2013-12-01), showing the distribution of arable land, illustrate that arable land commonly occurs at lower levels (sometimes even below one metre above sea level). At present, open wetlands occur at low altitudes along the coast, where the wetlands are covered by reed, and at high altitudes where many of the wetlands have developed into raised open bogs due to nutrient-poor conditions. There are, however, too many parameters involved to separate open from forested wetlands in the LDM. In all variants, 0.24 ha has been defined as the smallest illustrated area, which represents six 20-metre cells in the model and corresponds roughly to the smallest area represented on the SGU maps of regolith; areas smaller than 0.24 ha are modelled as forest, in all variants.

Variant 2 represents the most intensive land use and is used as a basis for the radionuclide modelling in SR-PSU. Therefore, this variant is modelled in more detail than the other four variants. At 8500 BC the last ice sheet retreated and the area was completely covered by the Baltic Sea; the first land areas appear at 1500 BC, and by 40,000 AD no sea exists in the model area and all lakes are filled with sediment and peat.

Variant 1 – Global warming with land use similar to the present

The vegetation corresponds to the dominant vegetation types found in the area today, where pine-dominated forest on outcrops are separated from mainly needle-leaved forest (both Scots pine and Norway spruce) on deeper regolith layers. Forests and wetlands are situated in areas that are not suitable for cultivation. All former lakes will remain wetlands in this variant. Wetlands not preceded by a lake stage and bordering arable land are taken to have been drained for forestry.

The regolith types most frequently used for cultivation today are also used as arable land in this variant. Cultivation is considered possible in areas situated at least one metre above sea level. Peat is not commonly cultivated today and is correspondingly illustrated as wetlands (e. g. former lakes). However, wetlands in areas with clay and sand are taken to be arable land.

All areas with suitable deposits larger than 1 ha (10,000 m^2) are used as arable land. There are, however, many areas with suitable deposits larger than 1 ha that presently are covered by forest. This variant will therefore give a somewhat more extensive distribution of arable land than at the present. There are, on the other hand, also some areas smaller than 1 ha, which today are used as arable land.

There are several types of regolith that to a minor extent are used for cultivation at present, e.g. sandy till and peat. These deposits are not cultivated in variant 1, which locally may cause a small underestimation of the cultivated areas. However, all areas with regolith used as arable land in variant 1 are not completely cultivated at present, e.g. only around half of the areas with glacial clay are cultivated.

Postglacial sand is to a large extent used for agriculture today, but this regolith type is not shown in the RLDM that was used as input to the LDM. However, field observations show that the postglacial sand is often underlain by glacial clay (cf. Sohlenius et al. 2013a), and most areas with postglacial sand will accordingly be used for cultivation in the model.

Variant 2 – Global warming with intensive land use

This variant illustrates a landscape succession when almost all areas that can be cultivated are used as arable land, which corresponds to the areal maxima of land use found during the mid-20th century. In this variant, all areas larger than 0.24 ha with deposits suitable for cultivation and which can be drained are used as arable land.

Former lakes are used as arable land as soon as they are covered by peat layers thick enough for cultivation and when the area is situated at least one metre above sea level. All wetlands with deposits not suitable for cultivation but bordering arable land are drained for forestry. The vegetation follows the criteria used in variant 1. In reality, it will be difficult to lower the groundwater table in some of the present and future wetlands due to the flatness of the landscape.

It is possible that some of the areas with sandy/silty till that are covered by forest in variant 2 could be cultivated. However, a large proportion of the till has a relatively high proportion of superficial stones and boulders. It is therefore unlikely that significant areas with sandy/silty till can be cultivated. Most of the areas with sandy/silty till are shown as forest in this model. Some areas with this till type are, however, modelled as wetlands due to a high wetness index.

Variant 3 – Global warming with land use unaffected by human activities.

In this variant the terrestrial part of the area is almost completely covered with forest following the criteria used for vegetation in variant 1 and 2. All former lakes and areas with high wetness index are wetlands in this variant. Also in a landscape unaffected by humans, open areas can be expected, e.g. due to a change in fire frequency or a high abundance of large herbivores. The areas with open land are difficult to estimate and may vary through time due to different natural processes. They are therefore not included in the present landscape development modelling.

Variant 4 – Periglacial conditions with no influence of human activities.

The vegetation pattern for periglacial conditions was generalised from a tundra biome (Breckle 2002, Peel et al. 2007) dominated by field and ground layers. Areas with outcrops or thin regolith layers were assumed to be barrens. Heathland was assumed to be present on more coarse-grained regolith on slopes and other more or less well-drained localities. The succession of lakes to peat-covered wetlands is slower than in the other variants, due to the cold climate. This was, however, not implemented due to the fact that all lakes had been terrestrialised at the time when periglacial conditions occurred in the modelling.

The permafrost will cause lower permeability of the regolith, which in turn will cause changes of the groundwater flow patterns (Chapter 4). The distribution of wetlands may consequently be different from that shown by the resulting model. In reality, permafrost occurs in a wide range of climate conditions, represented both by high and extremely low precipitation. Periglacial landscapes with high precipitation will naturally have a much larger proportion of wetlands compared to regions with dry conditions. The regional climate model simulations from SR-Site (Kjellström et al. 2009) suggest that the precipitation would be low (170 mm y^{-1}) and consequently no large changes in the distribution of wetlands are suggested.

Variant 5 – Extended global warming with a land use similar to today

This variant describes a warmer climate where the annual temperature may reach +10.7°C compared to approximately +5°C today (see Section 4.2). This is similar to an annual mean temperature that is found in southern Europe. Norway spruce has its southern limit in central Europe and is replaced by deciduous trees further south. A modelling approach, using the dynamic vegetation model LPJ-GUESS (Smith et al. 2001) for the coming 100 years with a projected temperature increase in Sweden, suggests that Norway spruce will shift northwards and deciduous trees will advance from the south (Ministry of the Environment 2007).

Results of a similar modelling activity, where the model was run for a longer time period and with a greater temperature increase, suggested that deciduous forest would be the dominating vegetation in the landscape of central Sweden (Kjellström et al. 2009), which also would be the case in Forsmark. Today, deciduous tree species like beech, elm and lime have somewhat different habitats in the south of Sweden. Beech is normally found on soils with a lower pH but may also occur on more mull-rich soils with higher pH and compete with Norway spruce in similar habitats. The higher pH tolerant species like elm, lime and ash are also shade tolerant species, whereas oak is more tolerant to dry conditions.

However, the general pattern is that human land use is the overall most important explanation of local distribution patterns today. It may therefore be difficult to predict the exact abundance or dominance of different species. However, it is suggested that oak will be the dominant tree species in drier locations now dominated by Scots pine, and beech will be the dominant deciduous species with the higher pH tolerant species like elm, lime and maybe ash as more or less prevalent constituents in the landscape.

5.4.4 Modelling and presentation of future landscapes

As explained above, variant 2 represents a development in which all areas that can be cultivated are used as arable land (see Section 5.4.3 for details), and is the landscape development applied to the radionuclide model for the biosphere in the SR-PSU base case (BCC1, see Chapter 7). Variant 2 was therefore modelled with a more detailed temporal resolution than the other four variants and shows the potential landscape during altogether 41 snapshots between 8500 BC and 40,000 AD. The Forsmark area was completely covered by the Baltic Sea from 8500 BC to 2000 BC and this period is only shown for two time steps in the resulting animation described later.

For the following period, the landscape development for variant 2 was produced in 500-year time steps from 1500 BC to 15,000 AD and in 5,000-year time steps from 15,000 AD to 40,000 AD. The landscape development for variants 1 and 3 was produced for four time steps: 2000, 3000, 5000 and 20,000 AD. Variant 4 was illustrated with one snapshot at 20,000 AD, which was in accordance with the expected timing of a potential periglacial period (Section 4.2). Landscape development for the extended global warming (variant 5) was illustrated by the time steps 3000, 5000 and 20,000 AD (Section 4.2). The landscape development for variants 1, 2, 3 and 5 was produced using data from the RLDM for the *global warming climate case* and for variant 4 using data from the RLDM for the *early periglacial climate case* (Brydsten and Strömgren 2013).

ArcGIS 9.3 was used for all GIS-calculations. Most of the data were produced in ESRI raster format using a 20-metre cell size. The geographical properties necessary for the modelling of the landscape development variants are described earlier in this chapter. The classification of ecosystems is shown in Table 5-2. Data from the RLDM were used to produce raster layers representing the landscape from 1500 BC to 10,500 AD for the *global warming climate case* (Brydsten and Strömgren 2013). All regolith for each time step were added on the bedrock surface and a DEM was calculated for each time step. A detailed description of the landscape development modelling is given in Appendix 3.

Table 5-2. Classification of the ecosystems represented in variants 1–5 of the LDM. "X" refers to the classification used for each variant.

Ecosystem classification	Global warming with present land use (Variant 1)	Global warming with intensive land use (Variant 2)	Global warming with no land use (Variant 3)	Periglacial conditions (Variant 4)	Extended global warming with present land use (Variant 5)
Mixed coniferous forest	X	X	X		
Pine forest on bedrock	X	X	X		
Oak forest on bedrock					X
Mixed deciduous forest					X
Arable land	X	X			X
Wetland	X	X	X	X	X
Lake/Sea	X	X	X	X	X
Tundra heath				X	
Barren outcrop				X	

5.5 Resulting spatiotemporal development

Below is a description of the landscape development in a climate characterised by global warming (variants 1–3), periglacial conditions (variant 4) and extensive global warming (variant 5). The results presented describe the calculation cases adopted in SR-PSU (Chapter 7). In the *early periglacial climae case* periglacial conditions occur around 17,500 AD and persist for 3,000 years, and therefore a periglacial landscape is presented for 20,000 AD. Moreover, the *extended global warming climate case* will reach its temperature maximum around 3000 AD not decreasing to present-day temperatures again until c. 50,000 years after present, and therefore this variant is presented at 3000 AD and beyond.

Additionally, there are descriptions of the impact of different land uses on the landscape. These are all presented from today and onwards. Focus is on variant 2, which is used in the radionuclide model for the biosphere in SR-PSU. Landscape development for variant 2 (all areas that can be cultivated are used as arable land) for the time steps 2000, 3000, 5000, and 20,000 AD are shown in Figure 5-4. This variant was modelled from 8500 BC, when the area was deglaciated and thereafter covered by the Baltic, until 40,000 AD when the last lakes have been filled with peat and sediments. The early time steps can be assumed to illustrate the situation in Forsmark after a glaciation, which is considered in, for example, biosphere calculation case 4 described in Chapter 7.

In Figure 5-5, the relative distributions of ecosystems are shown for the period between –1500 AD (1500 BC) and 40,000 AD. It is obvious that the shoreline displacement will cause a fast future increase of the terrestrial share of the modelled area. This, in turn, will cause an increase in areas that can be used as arable land. The area that can be used as arable land will further increase when the lakes have been filled up with sediment and peat. In the future, the proportion of terrestrial areas that can be used for agriculture will be larger than at present since the proportion of regolith, mainly clay, will increase when the present sea floor is uplifted.

In variant 2, all former wetlands that can be cultivated are used as arable land simultaneously. However, many of the wetlands can probably only be cultivated for a short period due to the relatively fast subsidence of the peat layers. It is therefore not likely that all former wetlands will be cultivated simultaneously. The share of arable land in the model area is around 40% at 40,000 AD, which corresponds to an area of 115 km^2 (the total model area is almost 294 km^2). The proportions of mixed coniferous forest and pine forest on bedrock increase until around 6500 AD and are thereafter more or less constant for all following time steps.

The share of wetland increases over time from 500 BC to 8500 AD, when it peaks with an area representing c. 10% of the modelled area. After 8500 AD the share of wetland decreases. The total lake area is largest at 5500 AD (almost 6% of the modelled area). Only 6 of 48 lakes remain at 15,000 AD, but the lake area is still almost 2%, since these lakes are large. Only the deepest lakes are left after 15,000 AD and after 20,000 AD only parts of these lakes still remain. At 40,000 AD all former lakes are filled with sediment and peat and are either used as arable land or covered by forest.

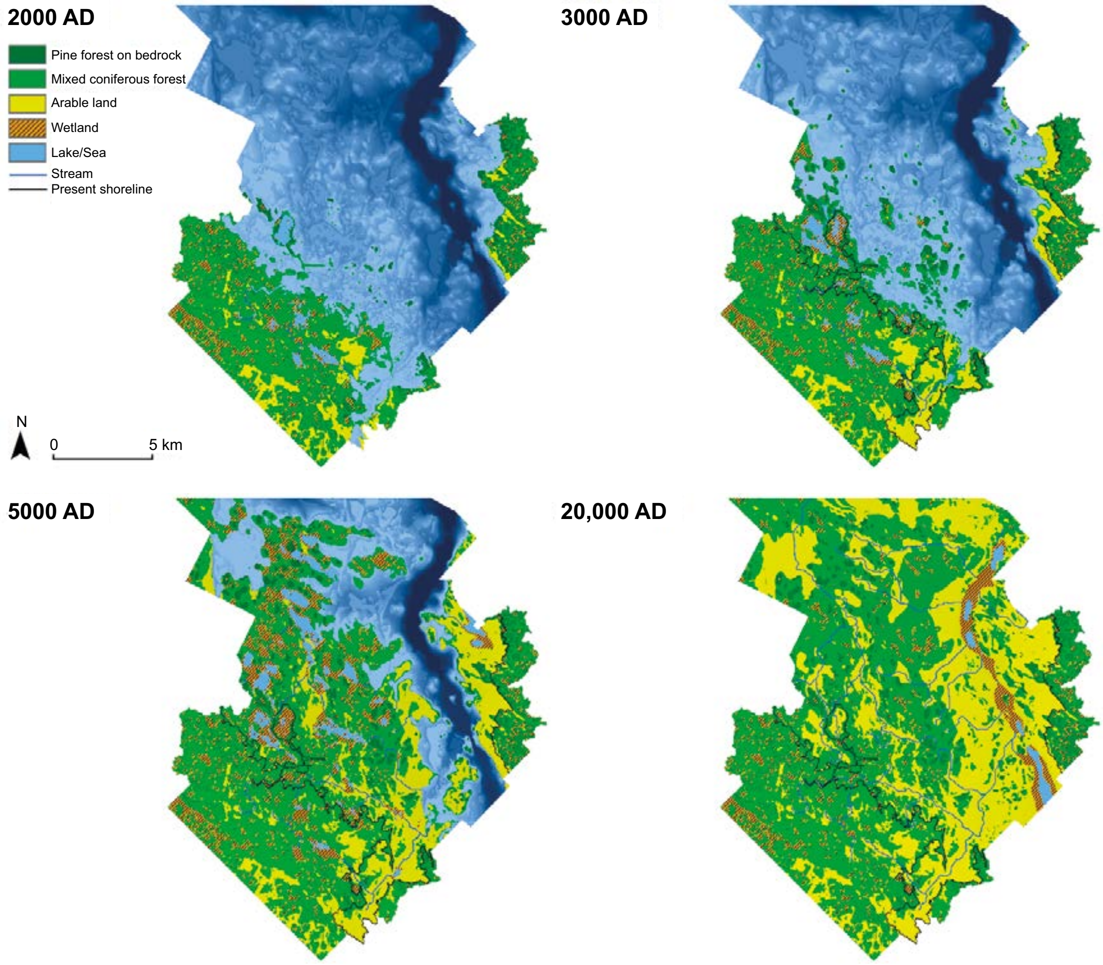


Figure 5-4. *Illustration of the landscape development for the variant characterised by global warming with intensive land use (variant 2) using the time steps 2000 AD, 3000 AD, 5000 AD and 20,000 AD.*

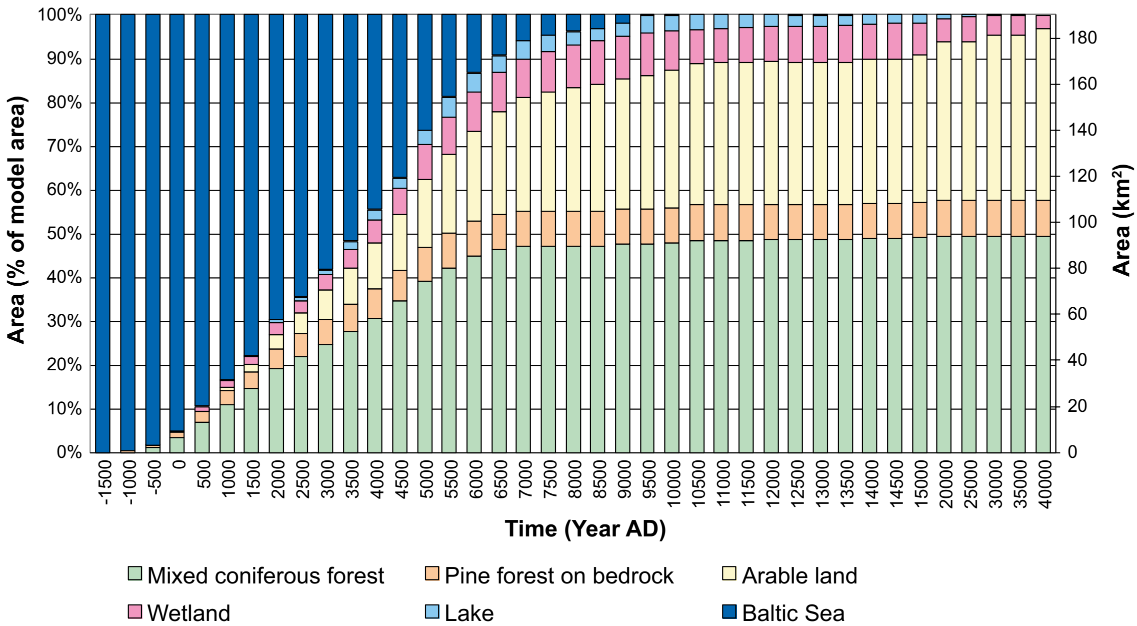


Figure 5-5. *Shares of different ecosystems used in variant 2 for the development from –1500 AD to 40,000 AD. The time scale is in 500-year intervals from –1500 AD to 15,000 AD and 5,000-year intervals from 15,000 AD to 40,000 AD. The time steps between –8500 AD and –1500 AD are not shown since the area was completely covered by the Baltic Sea during that period.*

Figure 5-6 and Figure 5-7 show variants 1 and 3, which represent global warming cases with land use similar to the present, and land use unaffected by humans, respectively, for 2000 AD, 3000 AD, 5000 AD, and 20,000 AD. Variant 4 (Figure 5-8) shows a periglacial landscape at 20,000 AD. Variant 5 is, as explained earlier, a reclassification of the ecosystem classifications used in variant 1. However, compared with variant 1, a delayed shoreline displacement after 2000 AD delays the development of some lakes. Figure 5-9 shows the landscape development for variant 5 for the time steps 3000, 5000 and 20,000 AD.

In Figure 5-10, the shares and areas of the ecosystems modelled in variants 1, 2, and 3 are shown for the time steps 2000 AD, 3000 AD, 5000 AD, and 20,000 AD. In variant 1, the shares of mixed coniferous forest, forest on bedrock, arable land, and wetland increase over time. In that variant, arable land constitutes 28 percent (more than 80 km^2) of the total model area at 20,000 AD. Arable land amounts to around 36 percent (a little less than 107 km^2) of the total area at the same time step in variant 2. In variant 1, all lakes become wetlands when infilled, since peat is not used as arable land. Most of the former lakes are used as arable land in variant 2, which explains the higher proportion of arable land in this variant.

Furthermore, in variant 2, with intensive land use, areas smaller than 1 ha are cultivated, whereas in variant 1, with a similar land use as today, no areas smaller than 1 ha are assumed to be cultivated. The difference between variants 1 and 2 is rather small in the three earliest time steps shown in Figure 5-10, but is obvious at 20,000 AD when a large proportion of the former lakes are infilled. In variant 2, the former lakes are then to a large extent cultivated but they remain wetlands in variant 1. In variant 3, the shares of the ecosystems mixed coniferous forest, forest on bedrock, and wetland increase from 2000 AD to 20,000 AD. Wetland constitutes almost 21 percent (more than 61 km^2) of the total area at 20,000 AD.

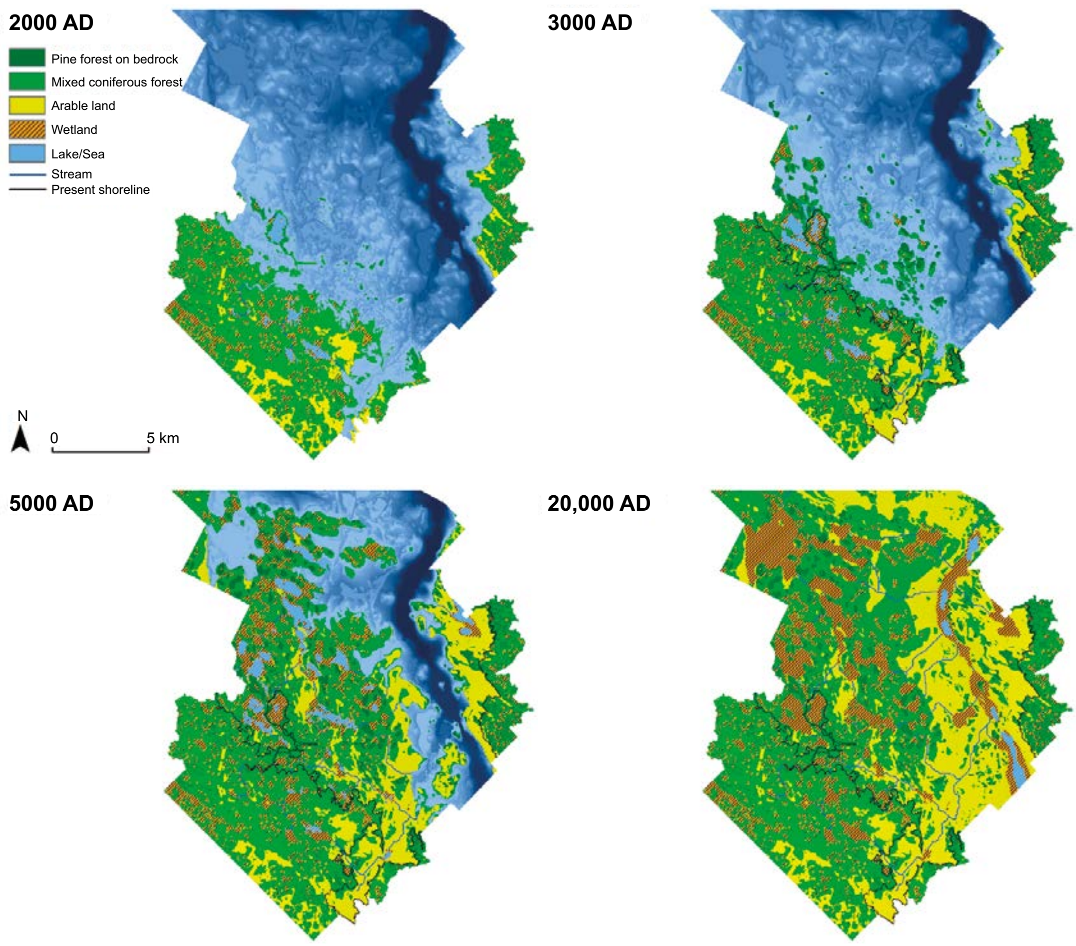


Figure 5-6. *Illustration of the landscape development for the variant characterised by global warming with a land use similar to the present (variant 1) using the time steps 2000 AD, 3000 AD, 5000 AD and 20,000 AD.*

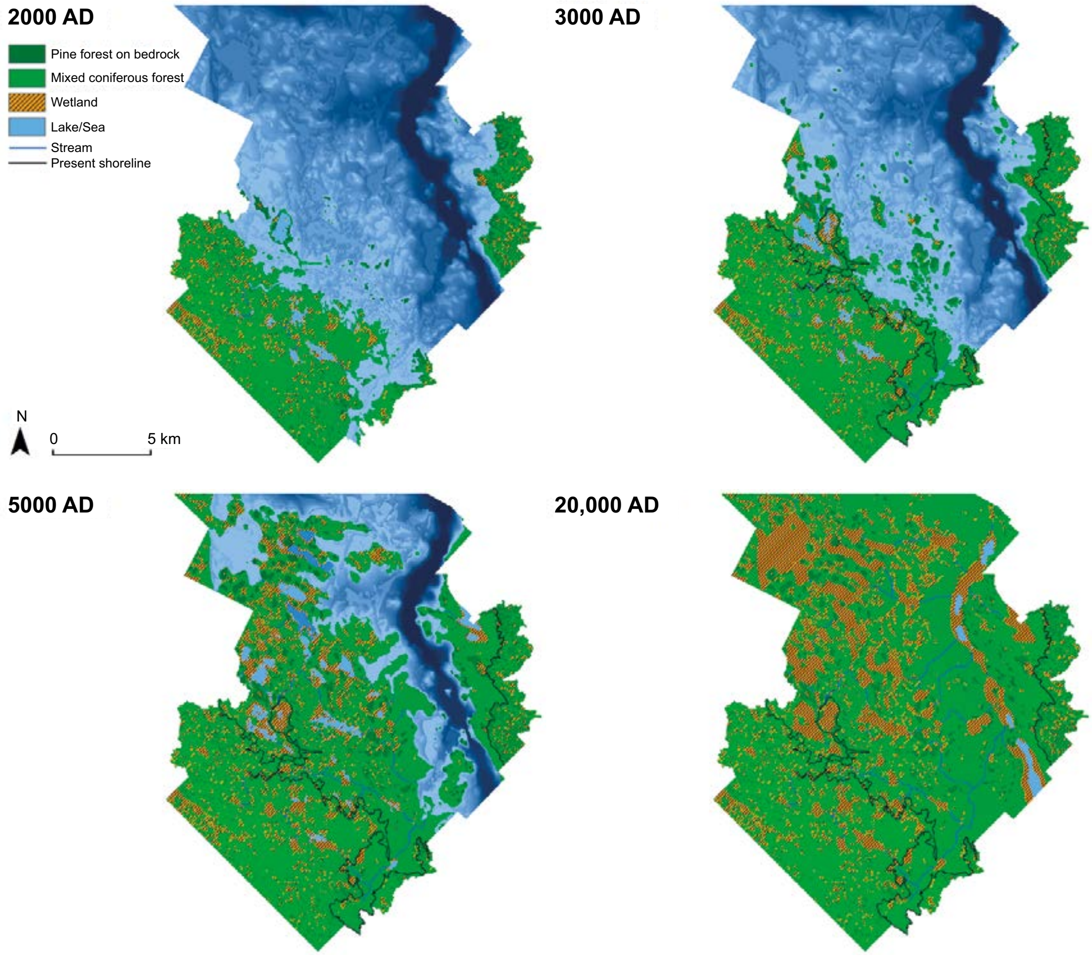


Figure 5-7. *Illustration of the landscape development for the variant characterised by global warming with no land use (variant 3) using the time steps 2000 AD, 3000 AD, 5000 AD and 20,000 AD.*

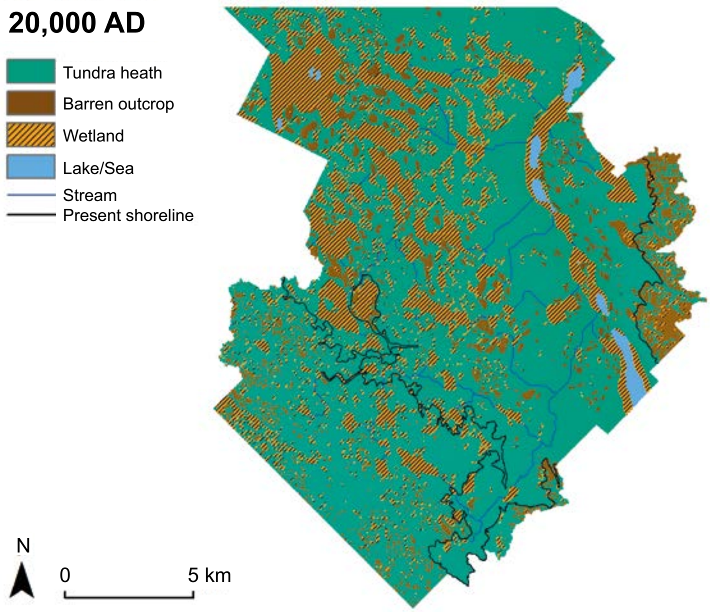


Figure 5-8. *Illustration of the landscape at 20,000 AD for the variant characterised by periglacial conditions and no human land use (variant 4).*

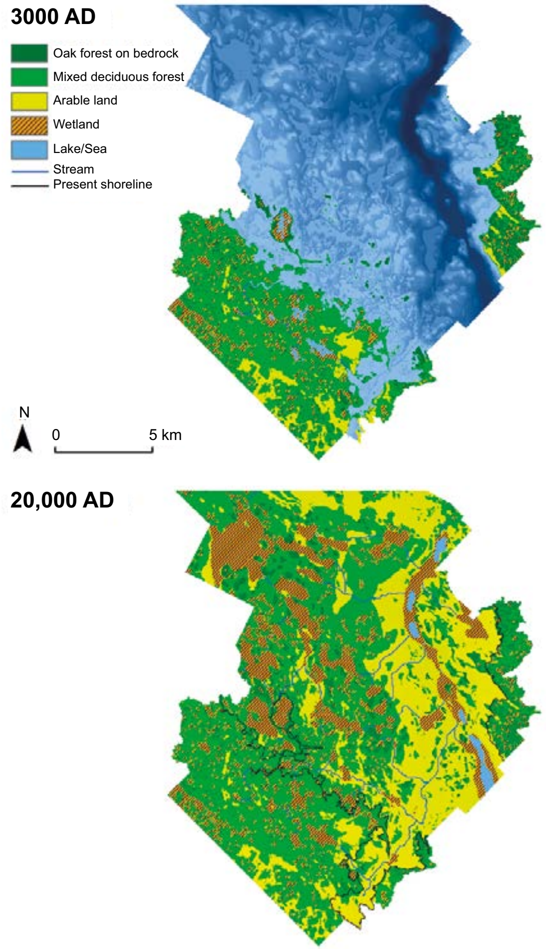


Figure 5-9. *Illustration of the landscape development for the variant characterised by extended global warming with land use similar to the present (variant 5) using the time steps 3000 AD, 5000 AD and 20,000 AD.*

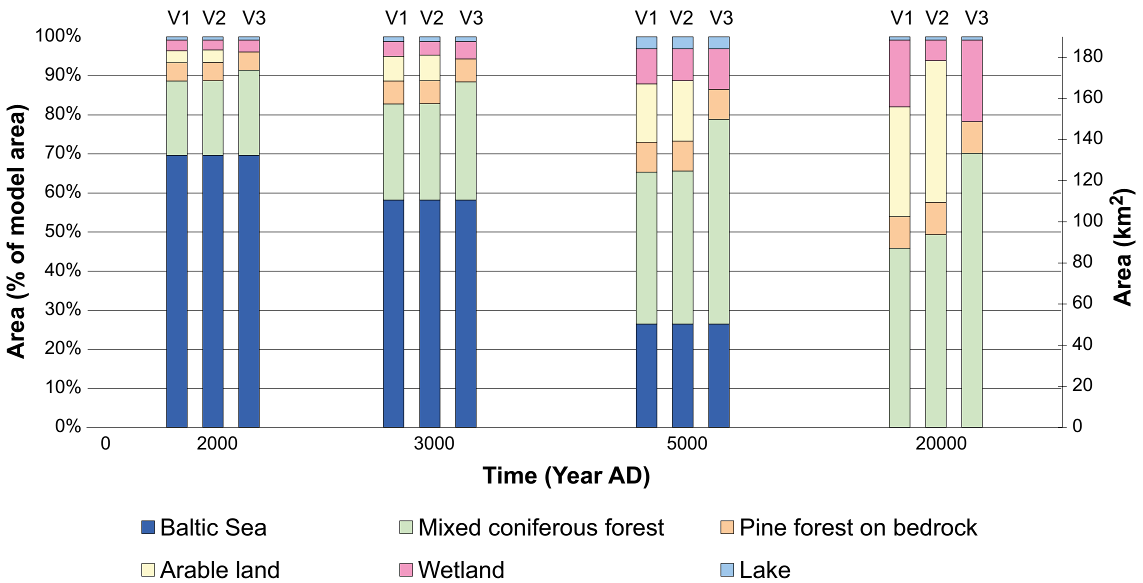


Figure 5-10. *Shares of ecosystems in variants 1 (V1), 2 (V2), and 3 (V3) for the time steps 2000 AD, 3000 AD, 5000 AD, and 20,000 AD.*

5.6 Evaluation of uncertainties in exemplified future landscapes

The five exemplified landscape variants present information on how the landscape in the Forsmark region may develop in the future, given different assumptions. Even though the timing of the development is uncertain, the variants present differences among potential landscapes based on the most important factors for the structure and content of the landscape over time; climate, shoreline displacement, accumulation/erosion processes and land use. The knowledge of these factors and their effect on the landscape are based on historical descriptions and is therefore limited by the assumption that the historical data should also be valid in the far future.

5.6.1 Sources of uncertainties

The modelling of landscape development is based on data from several other models. The uncertainties in these models are thoroughly discussed in the reports describing the models, and Table 5-3 presents a relative ranking in three classes of the model confidence, which is based on a qualitative interpretation of uncertainties associated with each approach. The largest uncertainties concern factors such as future climate and rate of shoreline displacement (**Climate report**). Other uncertainties concern geological data and the DEM. The modelled development of lake and wetland distribution is strongly dependent on the reliability of the DEM (Strömgren and Brydsten 2013). The distribution, extent and date of isolation of future lakes depend on the topographical level of the lake thresholds and the rate of shoreline displacement.

In areas where the uncertainty in the DEM is largest, the modelled extent of future lakes has consequently a relatively high degree of uncertainty, i.e. future lakes in Öregrundsgrepen, close to Gräsö Island. However, the lowest uncertainty in the DEM is found in areas of potential discharge of radionuclides around the present SFR, where a large data set with low uncertainty is available (Strömgren and Brydsten 2013). For some future lakes, the level of the threshold may be lowered by erosion, affecting the size of the lake. This is likely to occur in areas with sand or postglacial clay, since these deposits are easily eroded. Most present and future lakes are situated in environments dominated by clay, i.e. environments with deposits suitable for agriculture, and will therefore end up as arable land when filled with sediment and peat. Even though the extent of the future lakes may differ from the modelled extent, the distribution of areas suitable for arable land is consequently likely to be similar to that shown in variant 2.

The LDM is to a large extent based on the present distribution of regolith (Sohlenius et al. 2013a), for which the information is mainly based on the different maps of regolith. The uncertainties are especially large in deeper parts of the areas that presently are covered by the Baltic Sea, i.e. Öregrundsgrepen, whereas the knowledge of the present distribution of regolith in the near-shore area above the planned repository is well supported. The modelled regolith depths (Sohlenius et al. 2013a) have their main uncertainties in the same geographical areas as in the case of the regolith. The DEM in the marine area is also to a large extent based on data collected during mapping of regolith and has consequently its main uncertainties in the same geographical areas as the map of regolith. The RLDM describes the distribution of glacial clay and postglacial clay, which both are crucial for identifying potential agricultural land and its spatial extent (see also discussion below).

The shoreline displacement is based on projected historical and modelled future isostatic changes and the present knowledge of future global sea level rise (Section 4.2). A complete collapse of the Greenland ice sheet is assumed. The uncertainty in the shore level curve may be up to several tens of metres (**Climate report**). In the *extended global warming climate case*, this type of uncertainty is addressed by assuming a eustatic transgression from 2000 AD that is caught up by the isostatic land upheaval after 1,200 years. The effect of the uncertainties in the shoreline displacement will mainly change the timing of transitions between sea, lake and mire ecosystems and agricultural use.

A sensitivity analysis of an earlier version of the RLDM showed that the model is sensitive to changes in the infill rate of lakes (Brydsten and Strömgren 2010). This will affect the timing of the transition from a lake to a mire that can be of potential use for agriculture. In the present modelling, a static, time independent parameter describing the infill rate was used, based on observations from the northern part of the County of Uppsala. In the periglacial variant, all of the lakes in the immediate vicinity of SFR are already transformed into mires and thus not affected by the lowered infill rate.

Table 5-3. The sub-models used in the LDM. Model extent together with model resolution can be seen. A quality classification in three levels (excellent, good, and acceptable) is shown that relies on quantitative information in the listed references as well as qualitative evaluations made as part of the study presented in this report.

Model	Extent/resolution	Model confidence	References
Climate model	Global/Forsmark	Good	SR-PSU Climate report
Digital elevation model	Forsmark/20 m	Excellent	Strömgren and Brydsten (2013)
Digital elevation model	Fennoscandia/500 m	Acceptable	Brydsten (2009)
Regolith depth and stratigraphy model	Forsmark/20 m	Good	Sohlenius et al. (2013a)
Regolith-lake development model	Forsmark/20 m	Acceptable	Brydsten and Strömgren (2013)
Sub-wave model	Baltic sea	Acceptable	Brydsten and Strömgren (2013)
Sub-lake model	Forsmark	Good	Brydsten and Strömgren (2013)
Sub-marine model	Forsmark	Acceptable	Brydsten and Strömgren (2013)
Shoreline displacement model	Forsmark	Good	SR-PSU Climate report
Shoreline displacement model	Fennoscandia	Acceptable	Brydsten (2009)

5.6.2 A comparison between a modelled landscape and the landscape of today

The LDM was compared with site data describing the present conditions (Figure 5-11). A special effort was made to compare the result from variant 1 with the observed present ecosystem distribution. This is because variant 1 models ecosystems that should be similar to the present conditions. It is important to note that the LDM to a large extent uses the present conditions as input. The shoreline displacement rate is one example of a process that builds upon understanding of historical conditions. Therefore, the evaluation of the LDM made here is not to be taken as an evaluation of the capability to model the future, but rather of its capability to model the historical landscape development at Forsmark. However, as long as the process rates do not change dramatically, we should have a good tool also for modelling a possible future of relevance for the questions at issue.

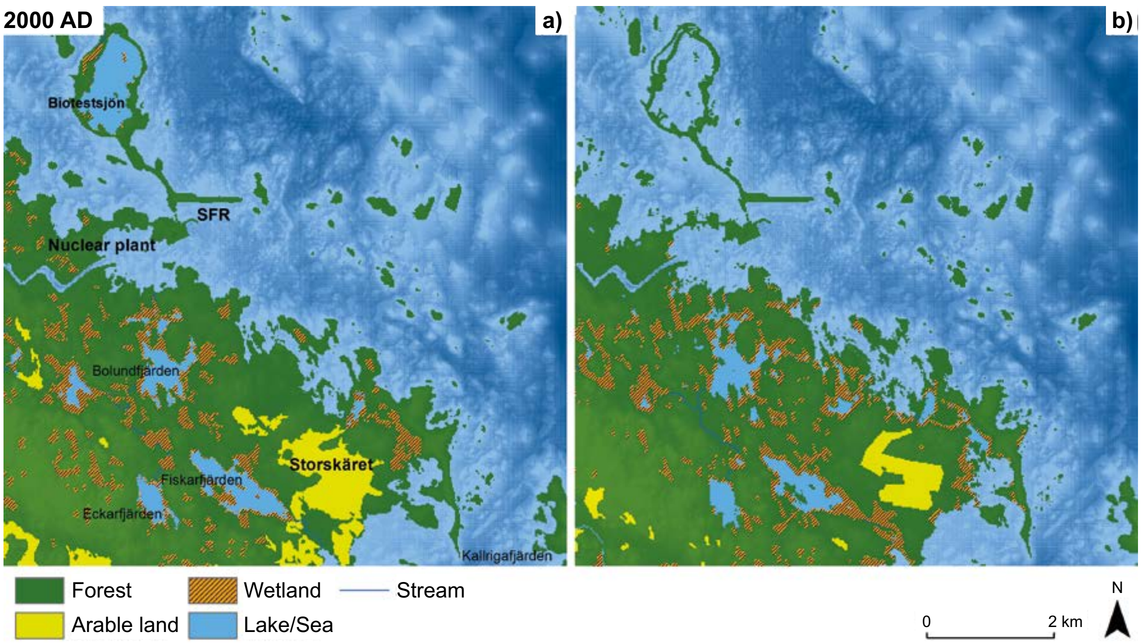


__Figure 5-11.__ Close-up of the LDM for the year 2000 AD with (a) assumed land use as today (variant 1), compared with (b) the present map of Forsmark showing the distribution of five different ecosystems; see text for explanations to differences between the maps.

Maps of regolith and data from Swedish Board of Agriculture and Lantmäteriet (http://www.jordbruksverket.se, accessed 2013-12-01) were used in the comparison. The LDM has captured most of the present features that characterise the landscape. The distribution of large lakes corresponds to the present lake distribution; also the areas with wetlands in the vicinity of the lakes are in good correspondence with the present conditions. However, in the model mirroring the conditions at 2000 AD some of the small lakes are missing and covered by peat, which is the result of an instantaneous infilling of small objects. In the central part of the modelled area, the present and modelled shorelines correspond very well. However, in some areas the modelled shoreline is situated far outside the present location. This discrepancy is obvious in the peripheral parts of the modelled area, e.g. along the coast north of the nuclear power plant and in the inner parts of Kallrigafjärden, and along the coast north of the nuclear plant (Figure 5-11). This is due to small discrepancies between the modelled DEM and the observed shoreline, which become particularly evident in large flat areas.

The modelled area is at present only to a small extent used as arable land, due to a high frequency of till with too high a content of boulders and stones for cultivation. In the future, the proportion of arable land is supposed to increase when deposits suitable for cultivation are uplifted above the present sea level. Variant 1 is intended to resemble the present situation. In that variant, areas with water-deposited clay with an area larger than 1 ha are used for agriculture. Also areas with clayey till and a low surface frequency of boulders are cultivated. At present, the largest cultivated area is situated in an area with clayey till at Storskäret (Figure 5-11), which also is reflected in model variant 1 (2000 AD). The observed distribution of clayey till from the regolith map was used for the LDM. The cultivated area around Storskäret (the largest cultivated area in Figure 5-11b) is, however, larger in the model than in reality, which probably indicates that a larger area could potentially be cultivated at that site.

The spatial distribution of glacial clay and postglacial gyttja clay used in the LDM was modelled by Brydsten and Strömgren (2013). A comparison between the modelled clay distribution and the mapped clay distribution shows some discrepancies, which have implications for the modelled ecosystem distribution. The large areas with clay present at the floor of the Baltic have been captured in the model by Brydsten and Strömgren (2013). However, smaller areas shown on the maps of regolith (Sohlenius et al. 2013a) are not always present in the model, and in some small areas clay coverage has been incorrectly modelled. One reason for this is probably that a uniform 2 metres thick layer of glacial clay was added to the whole model area at the time step following directly after deglaciation. However, in reality there were most likely large variations in the thickness of the initial clay layer. This can explain some of the discrepancies between the modelled and actual distribution of glacial clay.

Erosion and sedimentation in the sea are difficult to predict, and the erosion model does not include streams on the sea floor that may cause erosion in areas with large water depth. Some discrepancies between the modelled and observed clay layers can be explained by the difficulties to model these processes. In the LDM, this has caused the occurrence of arable land in areas where there is no real possibility for cultivation. This is illustrated along the coastline of Gräsö Island, where arable land has been modelled in areas presently dominated by bedrock outcrops. Furthermore, there are several small clay areas on Gräsö Island, which at present are cultivated but lack deposits considered suitable for cultivation in the model by Brydsten and Strömgren (2013).

The topographical wetness index (TWI) and the distribution of peat have been used to model the distribution of wetlands. Most of the present large wetlands are shown in the LDM at 2000 AD (variants 1 and 2). However, some of the fens situated close to the present sea level have not been captured by the use of TWI. The formation of these wetlands is probably a consequence of the small difference in altitude between the ground surface and the sea level, and it is likely that they will disappear in the future as a consequence of the ongoing shoreline displacement.

Variant 2 reflects a scenario where almost all areas suitable for cultivation are used as arable land. In this variant peat and clay gyttja are also cultivated. Former lakes can, however, only be cultivated when completely covered by peat. At 2000 AD, some of the small lakes present today are covered by peat in the model of Brydsten and Strömgren (2013). In variant 2, some of these small present lakes are consequently used as arable land at 2000 AD. It is, however, likely that these lakes can be used as arable land in the near future and the scenario with cultivated peat is regarded as correct, even though somewhat early in time. Consequently, the LDM at 2000 AD is partly reflecting a scenario that may apply within a few hundred years. It is possible that the timing of the potential cultivation of former lake/wetlands is slightly incorrect also for future scenarios.

One possible scenario not demonstrated in the LDM is the lowering of lake levels to facilitate the cultivation of wetlands around lakes. Many Swedish lakes have been lowered for that purpose in the past. A scenario with lowered lake level would make some areas available for cultivation earlier than in the present model. These areas will, however, be cultivated in the LDM, but later in time. A lowering of lake levels only makes cultivation of wetlands surrounding the lake possible somewhat earlier than predicted by the LDM.

In the future, the present sea floor will be uplifted and the large areas with water-deposited clays will potentially be used as arable land. A comparison between the map of regolith (Sohlenius et al. 2013a) and the results from the modelling of regolith at 2000 AD (Brydsten and Strömgren 2013) shows that there are small areas with water-deposited clay not represented in the model. Furthermore, some of the modelled clay deposits are not present on the map of regolith. Since the model by Brydsten and Strömgren (2013) is used as input to the LDM, it is likely that the future distribution of small areas used as arable land is partly incorrect. The large areas of clay at the present sea floor are, however, in better agreement with the modelled clay areas, and it is therefore likely that the large areas that potentially can be used for cultivation are well represented in the LDM.

5.7 Summary and comparison with previous model

The safety assessment is performed on a long time scale on which processes such as shoreline displacement, climate change and human land use may have a large impact on the ecosystems in the landscape. The landscape development model (LDM) is used to produce potential future landscapes based on physical constraints and knowledge of the historical processes that have shaped the resulting landscape of Forsmark today. The model is based on data describing the elevation, shoreline displacement, present distribution of till, sedimentation processes for glacial and postglacial deposits, lake ingrowth, primary mire formation and land use. By assuming climate change and different intensities of land use, alternative landscapes have also been produced in order to study their potential impact on the landscape configuration. The resulting landscapes provide the distribution and abundance of important ecosystems over time, which together with modelled discharge points from the repository are used to model exposures to radiation for both humans and non-human biota.

The landscape modelling performed in SR-Site (Lindborg 2010, Lindborg et al. 2013) has been further developed and a number of improvements have been included in the LDM for SR-PSU. These are summarised below.

- An improved DEM and regolith map for the surroundings of the present SFR has been used.
- The start of ingrowth in shallow bays has been adjusted in order to better fit the pattern of the recent past.
- The distribution and abundance of outcrops in the landscape is now better illustrated.
- The present LDM illustrates a more realistic land use of wetlands. In SR-Site, all wetlands were drained for either agriculture or forestry. In the present LDM, wetlands are not drained if they do not fullfill the criteria of being used as arable land. Moreover, wetlands bordering land that fulfills the citeria of being used as arable land, are also affected by the drainage activities and may turn into forest depending on areal extent.
- In the present model, cultivation is possible in areas situated more than 1 m above sea level, which, compared to the limit used in SR-Site (2 m above sea level), is in better accordance with what has been observed in the recent past.
- Compaction factors for clay gyttja and peat, describing the effect of draining on the regolith thickness, were used as criteria to identify potential areas used for cultivation, with a perspective of at least 50 years of utilisation.
- In this version, the processes affecting glacial clay during the sea stage are included with the aim of introducing a more dynamic description of the glacial clay deposits in the landscape. Glacial clay is an important potential regolith used for agriculture.

One of the most important results from the LDM is the identification of ecosystems known to be potential recipients for deep groundwater, e.g. shallow bays, lakes, mires and streams. These results are based on the DEM, which has a low uncertainty. The areal extent of these identified objects, especially lakes, is however dependent on several factors that are somewhat more uncertain, such as the presence of erodible regolith at the object threshold that has not been accounted for. In some cases, wetlands present in the landscape of today have been missed, but these are generally small. One reason for missing such wetlands may be the presence of semi-permeable fine-grained material that affects the local hydrology. The model seems, in some cases, to miss and, in some cases, to suggest the presence of glacial clay not in correspondence with the present landscape. When this occurs, it concerns mainly small areas, and the larger areas are all identified.

Overall, the attempt to use physical constraints and the knowledge of processes of importance for landscape development, and project these into the future, has resulted in a limited number of potential future landscapes, including variants in which some of the assumptions have been modified based on differences in land use intensity and climate development. These landscape variants are regarded as highly relevant and realistic as a basis for calculations and discussion relating to the exposure of humans and non-human biota in the future.

6 Modelling biosphere objects in the landscape

This chapter describes the development of a model for connected biosphere objects in the landscape. A biosphere object is an area in the present and/or future landscape that potentially, at any time during the considered assessment period, could receive a discharge of radionuclide-containing groundwater associated with the repository. The biosphere objects are used as a basis for the extraction of data used in the biosphere radionuclide model. The succession in time of the biosphere objects is described using the landscape development model (LDM) described in Chapter 5. The other main input used in the identification and description of biosphere objects is the discharge areas obtained from the hydrological modelling.

The SR-PSU biosphere objects were derived using the same basic methodology as in the previous safety assessment SR-Site (Lindborg 2010), although updated models of the evolving landscape were used as input. In this work, as in earlier safety assessments (SR-Site, in particular), the modelling needed to handle future potential discharge areas with different landscape successions in time. Specifically, a division into two types of object succession was made, i.e. objects that go through a future lake succession stage and objects that do not go through a lake stage.

The present chapter describes the modelling of biosphere objects for both temperate and periglacial climate conditions, with emphasis on the temperate case. Furthermore, the identification of the "well interaction area", which can be viewed as a biosphere object used in calculations involving water extraction from wells, is described. Finally, alternative object delineations are presented; these are used as input to the analysis of uncertainties in Chapter 10.

6.1 Hydrological input data

6.1.1 Groundwater flow modelling in SR-PSU

Similar to earlier safety assessments (see, for example, Berglund et al. 2013a, b on SR-Site), quantification of hydrological processes is a central component of the SR-PSU assessment. Hydrological modelling is used in the analysis of conditions within repository caverns and tunnels, and it provides the basis for modelling of radionuclide transport from the repository to the biosphere and for calculations of transport and radiation doses in the biosphere. Therefore, a set of different hydrological models, focusing on different processes, issues, or parts of the hydrological system, was developed during the site investigations and the safety assessment of the SFR repository.

Specifically, surface hydrology/near-surface hydrogeology models (Werner et al. 2013a, Chapter 3 of the present report) were developed for the surface system/biosphere description, and bedrock hydrogeology models (Odén et al. 2014) were developed primarily for the descriptions of the bedrock system/geosphere and the repository. Different numerical modelling tools were used in the development of surface system and bedrock system models, i.e. MIKE SHE in the surface system modelling and DarcyTools in the modelling focusing on the bedrock system.

For the purposes of the present discussion, the DarcyTools (Odén et al. 2014) and MIKE SHE (Werner et al. 2013a) modelling activities are referred to as "bedrock" and "surface" hydrology modelling, respectively. However, this distinction refers to the main focus of each activity and not so much the actual model domains; both models include a relatively large depth interval of the bedrock and a representation of the regolith, although with different degrees of detail. This means that the differences between the two modelling activities concern their purposes and which properties and processes are handled in detail. For example, a detailed representation of the repository and the surrounding fractured bedrock is included in the bedrock model, whereas the surface model includes a detailed representation of the regolith and quantifies the hydrological processes at the surface, including those associated with the surface water system, the unsaturated zone, and exchanges with the atmosphere.

The bedrock models were used to calculate flow paths from the repository to the regolith. The discharge locations obtained from these flow paths, which in the SR-SPU modelling were defined as the areas where the flow paths entered the regolith, were then used as a basis for the identification and description of biosphere objects (see definition above) presented in the remainder of the present chapter, and for the development of biosphere transport and dose models (Saetre et al. 2013a, Chapter 8 of the present report). Essentially, the discharge locations showed where groundwater potentially containing radionuclides could enter the biosphere at different times in the future, and hence which objects and areas needed to be included in the biosphere modelling (see next section for a summary, and Odén et al. (2014) and references therein for detailed presentations of results).

The bedrock modelling providing the discharge locations used to define and analyse biosphere objects was organised in terms of a series of modelling tasks, each defined by a Task description (TD) using TD#, with # being the number of the task, as identification in the reporting (see Odén et al. 2014). Specifically, the discharge locations used in the SR-PSU biosphere modelling of temperate climate conditions (Section 6.1.2) were produced within the TD08 and TD11 tasks, where the TD08 modelling was performed with an earlier model version with slightly different representations of the bedrock and the repository compared with those in TD11 (Öhman et al. 2014). The discharge locations for periglacial climate conditions (Section 6.1.4) with permafrost were obtained from the TD13 task (Vidstrand et al. 2014). Furthermore, the modelling of wells that provided the basis for various calculation cases involving groundwater extraction from bedrock was performed within the TD12 task (Öhman and Vidstrand 2014).

The hydrogeological models used to calculate flow paths from the repository to discharge locations in the regolith involve large model volumes and are of necessity simplified in terms of the representation of, for example, the details of the uppermost part of the system. Therefore, more detailed surface models focusing on the processes in the upper bedrock and the regolith, as well as the interactions between soil, vegetation, and atmosphere, were also developed (Werner et al. 2013a). The main purpose of these models was to provide parameters values, such as water fluxes between different model compartments, to the biosphere transport and dose modelling (see Chapter 8). As explained below, surface hydrology modelling was also used to provide data on surface water conditions, i.e. the extent of areas with water on or very close to the ground surface, which were used for delimiting biosphere objects in areas where landscape succession will lack a lake stage.

6.1.2 Discharge locations for temperate conditions

Similar to the landscape development modelling described in Chapter 5, the hydrogeological modelling that provided discharge locations for the modelling of biosphere objects considered a set of selected times or time steps in the future. For each of these times (which were much fewer than in the main LDM variant, cf. below), a hydrogeological model was developed and used to generate flow fields that were the basis for the particle tracking simulations giving the discharge locations (Odén et al. 2014). Discharge locations for a particular time were obtained from particle tracking in a steady-state flow field representing that time. Given the short travel times of particles between the repository and the regolith, with averages on the order of a few years, or less, in most cases (Odén et al. 2014), steady-state flow was considered a reasonable approximation. In the simulations discussed in this chapter, one million particles were released in SFR 1 and another one million particles in SFR 3 at each time considered in the modelling.

The early (TD08) particle tracking results provided discharge locations that were used as a basis for an initial identification and delimitation of biosphere objects for temperate climate conditions, whereas the later (TD11) results were used in most of the detailed and/or quantitative analyses of discharge areas and biosphere objects undertaken in connection with the SR-PSU assessment. Therefore, consistent with the presentation in Odén et al. (2014), only TD11 discharge locations are discussed in the remainder of this chapter. It should be noted that large amounts of particle tracking data are available, representing both different “model generations” (i.e. TD08 and TD11) and different variants of each “model generation” (i.e. different deterministic variants and stochastic realisations of the bedrock models). Thus, only examples of the results can be shown here. However, comparisons have been made between different “generations” and different variants. These comparisons show that differences can be observed, but that these differences are insignificant for the biosphere assessment. This means that the identification and prioritisation of biosphere objects, i.e. which objects to include and which objects to focus on, would be the same.

Examples of spatial distributions of discharge locations associated with particle releases in SFR 1 and SFR 3 (displayed separately) are shown in Figures 6-1 and 6-2. At early times, i.e. 2000 to 3000 AD (Figure 6-1), the discharge locations are concentrated at deformation-zone traces below the sea.

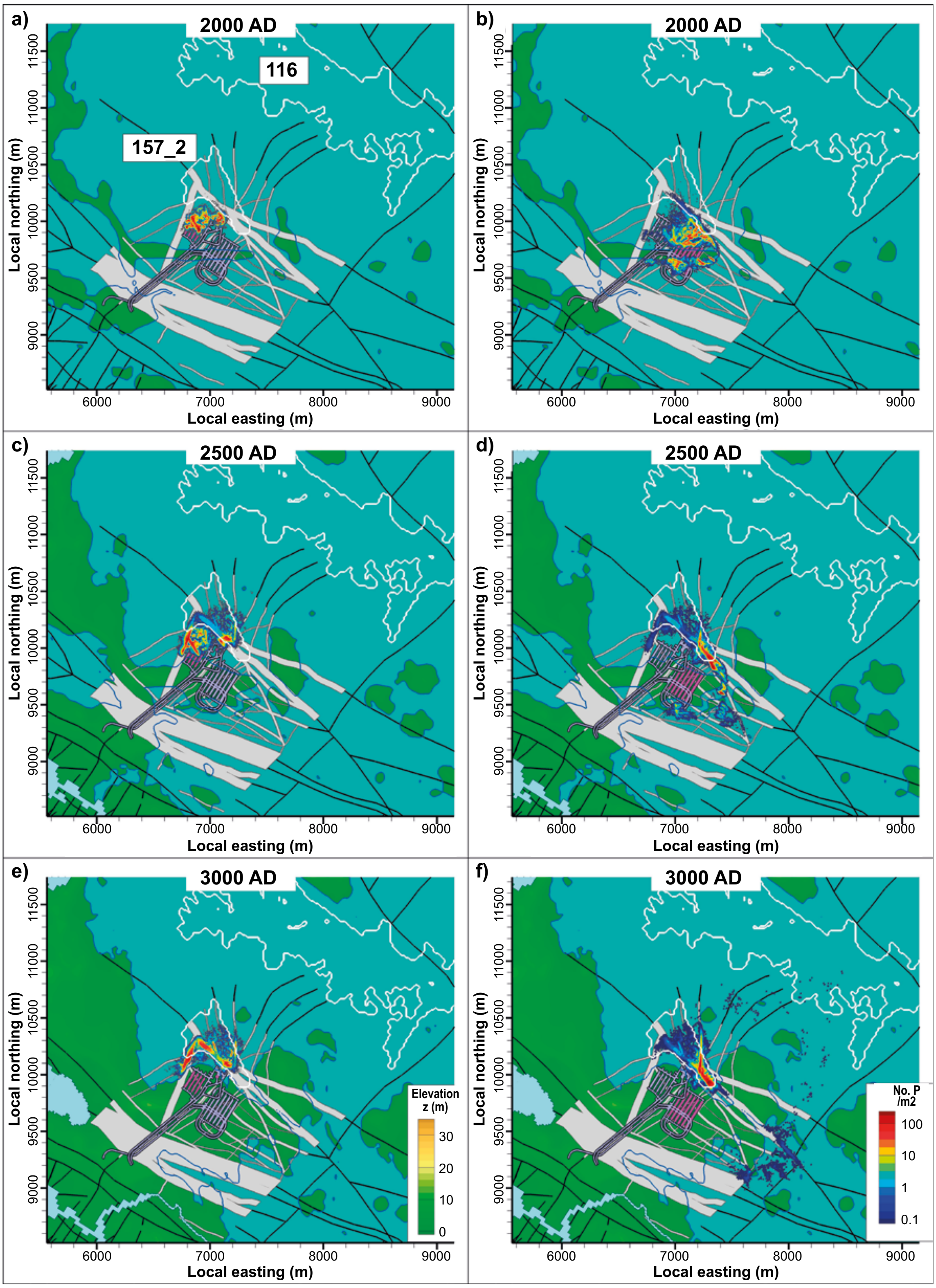


Figure 6-1. *Discharge locations, expressed as particle densities (number of particles per m²), for particles starting in the SFR 1 rock vaults (left column, with SFR 1 pink shaded) and in the SFR 3 rock vaults (right column, with SFR 3 pink shaded), for time steps 2000 to 3000 AD (from Odén et al. 2014). White-contoured areas marked "116" and "157_2" are included for orientation and indicate two of the SR-PSU biosphere objects (cf. below).*

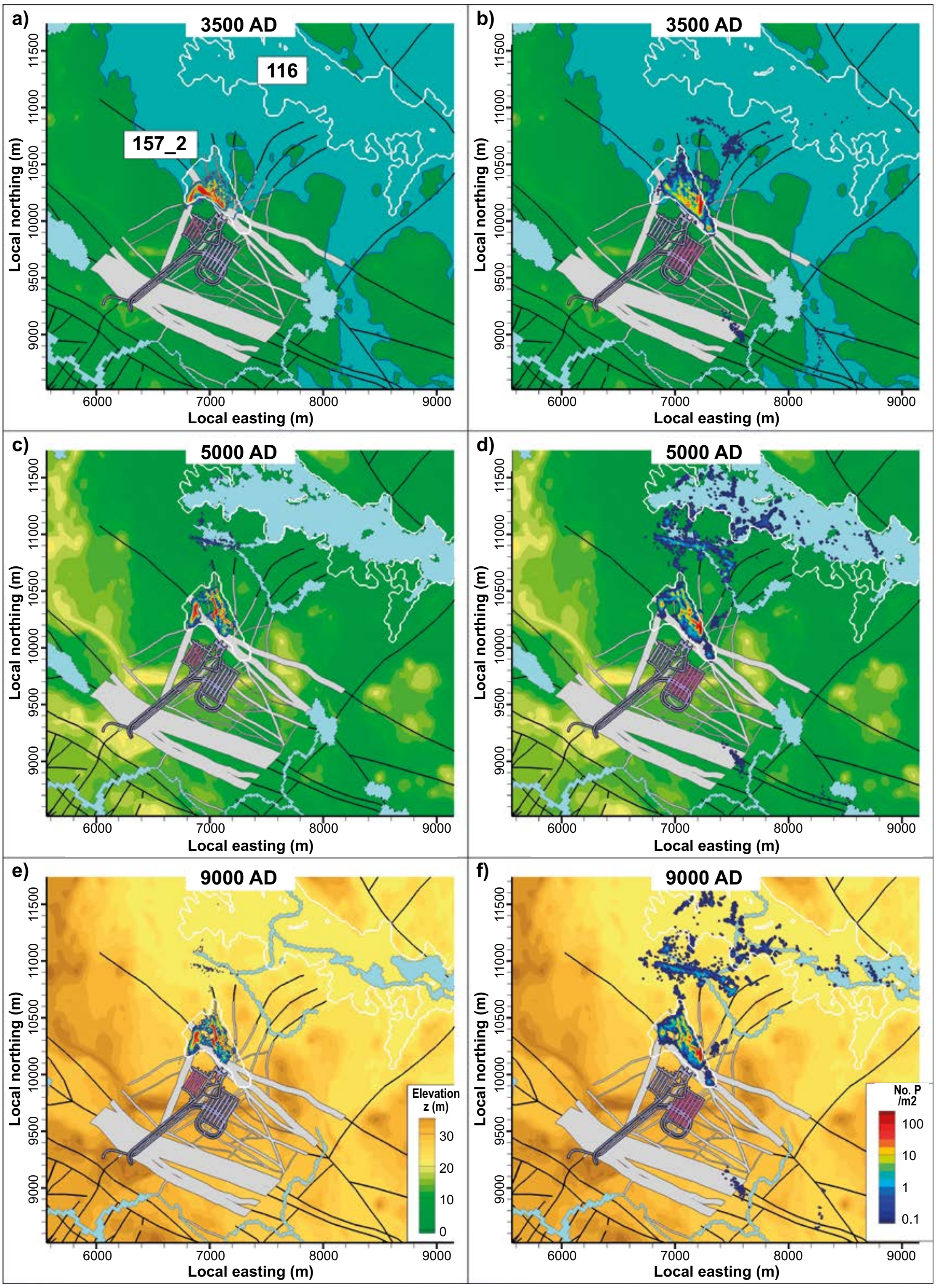


Figure 6-2. *Discharge locations, expressed as particle densities (number of particles per m²), for particles starting in the SFR 1 rock vaults (left column, with SFR 1 pink shaded) and in the SFR 3 rock vaults (right column, with SFR 3 pink shaded), for time steps 3500 to 9000 AD (from Odén et al. 2014). White-contoured areas marked "116" and "157_2" are included for orientation and indicate two of the SR-PSU biosphere objects (cf. below).*

The changing flow regime with shoreline displacement successively redirects some of the discharge locations with the retreating shoreline, whereas the high densities of discharging particles are in the same areas as earlier. At the later stages of land uplift, 5000 and 9000 AD, when most/all of the area shown is land (Figure 6-2), the discharge locations are concentrated along valleys or local topographical depressions.

According to the results in Figures 6-1 and 6-2, SFR 1 has discharge locations north of the SFR repository only. Unlike SFR 1, SFR 3 has discharge locations both north and south (southwest) of the repository. Also in contrast to SFR 1, SFR 3 has minor fractions of remote discharge locations in and around the large lake forming north of SFR during the later stages of the considered time period (i.e. 5000 to 9000 AD). However, it can be observed that the highest particle densities from both SFR 1 and SFR 3 (i.e. red colours in Figures 6-1 and 6-2) still are restricted to a relatively small area slightly north of SFR.

As indicated above, different model variants show slightly different results for spatial distributions of discharge locations. Specifically, these differences concern the more distant discharge locations both north and south of SFR, and their exact positions and fractions of the total number of particles released. However, these discharges generally represent small fractions of the released particles and the area just north of SFR dominates discharge. Odén et al. (2014) give the following reasons for the concentrated discharge in this area:

Geology: Groundwater flow from SFR is more or less enclosed by three deformation zones: two steeply dipping zones and one gently dipping zone located just below the existing SFR facility. The junction between these deformation zones occurs underneath the identified main discharge area.

Location and topography: The high-density discharge area is a local topographical depression just north of SFR, which according to the topographical gradient is downstream of SFR.

Sediment coverage: The thickness of low-conductive sediment layers is small north of SFR.

6.1.3 Additional input data on surface wetness

As further discussed below, lakes are not expected to form in some of the areas where the modelling results described in Section 6.1.2 indicate discharge of potentially radionuclide-bearing groundwater. For these areas, additional input data on modelled surface water conditions were used in the delineation of biosphere objects. Since no results from the SR-PSU surface hydrology modelling were available at the time, results from hydrological modelling originally performed in support of the SR-Site safety assessment were used for this purpose. Specifically, modelling results reported in Bosson et al. (2010) were analysed to identify areas with water on or near the ground surface that formed these terrestrial biosphere objects. Later, these patterns were confirmed with data from SR-PSU surface hydrology modelling (Werner et al. 2013a).

6.1.4 Discharge locations for periglacial conditions

Odén et al. (2014), see also detailed presentation in Vidstrand et al. (2014), used the bedrock hydrology modelling code DarcyTools to simulate steady-state groundwater flow in rock and taliks in a periglacial system with permafrost. This modelling produced discharge locations at the interface between rock and regolith for a case with shallow permafrost (–60 m elevation), for different variants in terms of the locations of potential taliks. Specifically, Figure 6-3 shows discharge locations for a variant with taliks at lakes and streams present at 20,000 AD (Brydsten and Strömgren 2013) and also at surface waters of small extent according to the surface hydrology modelling with MIKE SHE for temperate conditions at 11,000 AD (Werner et al. 2013a). However, in reality these water bodies may be too small to support through taliks.

According to Figure 6-3, the case with potential taliks at lakes, streams and small-area surface waters indicated discharge areas associated with taliks relatively close to the SFR repository. These discharge areas are related to the influence of the local topography on the groundwater flow pattern, especially the influence of topographical differences between taliks. The topographical differences may cause some taliks in higher elevated areas to function as recharge areas. However, other simulation cases based on different assumptions regarding the occurrence of taliks showed a greater significance of larger-scale flow, and hence gave rise to more distant discharge areas (Odén et al. 2014). Specifically, these simulations yielded discharge locations in connection with the lakes at the northeastern model boundary, which indicates that different types and locations of biosphere objects need to be considered in the modelling of the periglacial system.

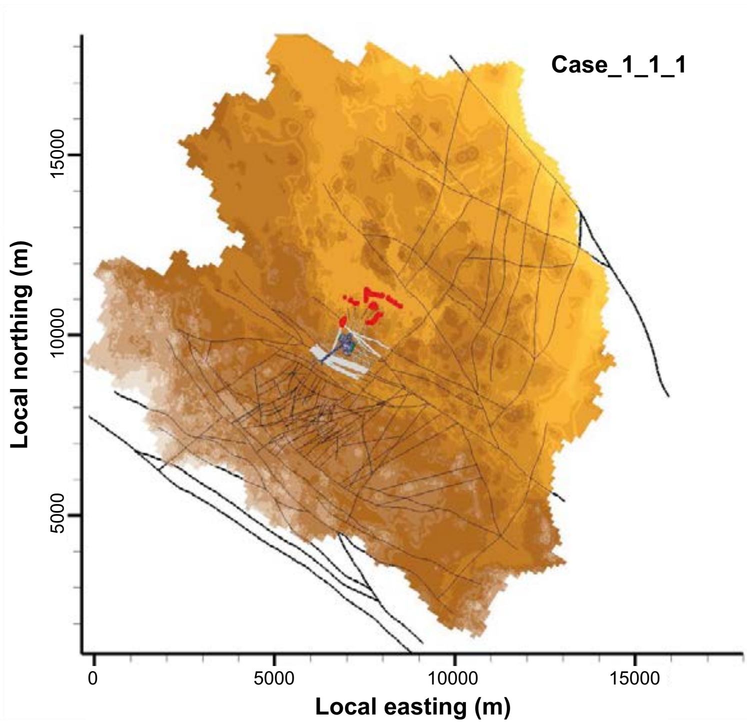


Figure 6-3. *Overview map of discharge locations (red) for a periglacial simulation representing shallow permafrost (down to –60 m elevation) and taliks at lakes and streams present at 20,000 AD according to the landscape modelling and also at small-area surface waters according to the surface hydrology simulations for temperate conditions at 11,000 AD. Figure from Odén et al. (2014).*

6.1.5 Well interaction area

Different types of wells and well locations are considered in the SR-PSU safety assessment, i.e. wells in regolith and in bedrock, including wells in connection with biosphere objects, wells that penetrate the repository (handled in the **Radionuclide transport report** and the **FHA report**) and wells outside the repository that could extract contaminated groundwater from the downstream plume (Öhman and Vidstrand 2014, Werner et al. 2013a). The biosphere assessment considers wells associated with settlements in the vicinity of future arable land areas, i.e. wells that may be drilled and used by agricultural, self-sustaining communities (drained-mire farmers and garden-plot households, Chapter 7). These wells are coupled to land use and biosphere objects and are not further discussed in the present report (see Werner et al. (2013a) for a detailed description).

However, it cannot be ruled out that future drilling of water-supply wells may occur also at locations that are decoupled from any foreseeable land use for a self-sustaining community. Therefore, Werner et al. (2013a) presented an analysis aiming to delineate an interaction area for wells drilled at random locations downstream from SFR, i.e. to determine the size of the area in which wells drilled in the rock would penetrate a volume of groundwater with a high concentrations of radionuclides originating from the repository. This area, termed "well interaction area" in SR-PSU, can be viewed as a specific type of biosphere object and is therefore described separately here.

The well interaction area was delineated using results of particle tracking simulations for undisturbed conditions in the future, i.e. groundwater flow conditions without well discharge, for the DarcyTools base case model setup (cf. Odén et al. 2014, Öhman and Vidstrand 2014). This means that flow paths from particle tracking were used to outline a plume of groundwater potentially containing radionuclides from the repository, which was used as a basis for locating the area within which wells drilled into the bedrock would extract groundwater containing radionuclides from the repository. Specifically, particle trajectories associated to particle releases from individual SFR 1 and SFR 3 facility parts were extracted in piecewise 10-metre elevation intervals within the approximate total elevation interval judged relevant for drilled wells in the area downstream from SFR. Hence, the delineation of the well interaction area takes into account groundwater flow paths at relevant elevations in the rock, and it is not limited to discharge locations at the interface between rock and regolith (Werner et al. 2013a). The result of the analysis is presented in Section 6.3.6.

6.2 Methodology

The physical boundaries of a biosphere object are defined based on the topography and hence reflect the geometry of the bedrock and the overlying till and glacial sediments, which change 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. The basis for the indentification and description of the objects is the LDM, which is described in Chapter 5; the methodology and the various models involved are illustrated in Figure 5-3. In particular, the description of the succession of specific biosphere objects and the associated parameters implies that information on these sub-volumes is extracted from the LDM.

When the glacial ice sheet has disappeared, the biosphere objects will typically go through a similar succession, from being parts of the open sea, over a sea bay phase, to a lake, which eventually transforms into a wetland. However, in the area with highest particle densities (see Section 6.1.2) there will not be a lake, but instead the area transforms from being open sea through a sea bay and then directly to a wetland. The associated work flow for describing the development of a biosphere object is summarised in Section 6.2.2, following the definition of geometrical features in Section 6.2.1.

6.2.1 Geometrical features of the biosphere objects

Biosphere objects can be divided into two geometrical areas depending on development stage: (1) the basin and (2) the basin-associated lake or wetland. In the marine stage, the biosphere object is always the defined basin of a future lake or wetland, see Figure 6-4. In the lake or terrestrial stage, the same object is defined as the lake or wetland.

Each biosphere object always has a watershed (catchment). The watershed is the upstream area at the object outlet including the area of the object itself. A watershed can contain other biosphere objects if they are located upstream of the object defining the watershed (Figure 6-4a). If a biosphere object is located close to a water divide or has no other objects upstream, the watershed equals the basin area. The basin is therefore the watershed of a biosphere object minus the watershed of any upstream object or objects (Figure 6-4b).

The watershed area is used for calculation of discharge with known specific runoff if no other hydrological models are available. The discharge is then used for calculation of, for example, the theoretical renewal time (turnover time) of the lake. It is also used for calculation of the freshwater dilution of sea water in the basin and also of the theoretical renewal time of sea water. All precipitation (minus evapotranspiration) that falls within the watershed is drained through the lake/object outlet.

A basin will have the same area as long as it is submerged in the sea (blue area in Figure 6-4b). If the shore level reaches the basin due to shoreline displacement, the basin area will decrease in proportion to the appearance of emerging land. The land part of the former basin will then be regarded as watershed to the basin. If a biosphere object transforms directly from sea to land, the same geometries are used in the succession description (Figure 6-5). The watershed area is in Forsmark successively increasing over time. The area is zero until land emerges within the biosphere object and reaches its maximum when the biosphere object is isolated.

The geometric object sub-catchment is defined as the catchment of the outlet of a lake/wetland minus the catchment of the inlet of the same lake/wetland (the brown area in Figure 6-4a). This geometrical feature is only present when the biosphere object is above sea level. The sub-catchment is used in the biosphere 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 constant for each object and always smaller than the basin area.

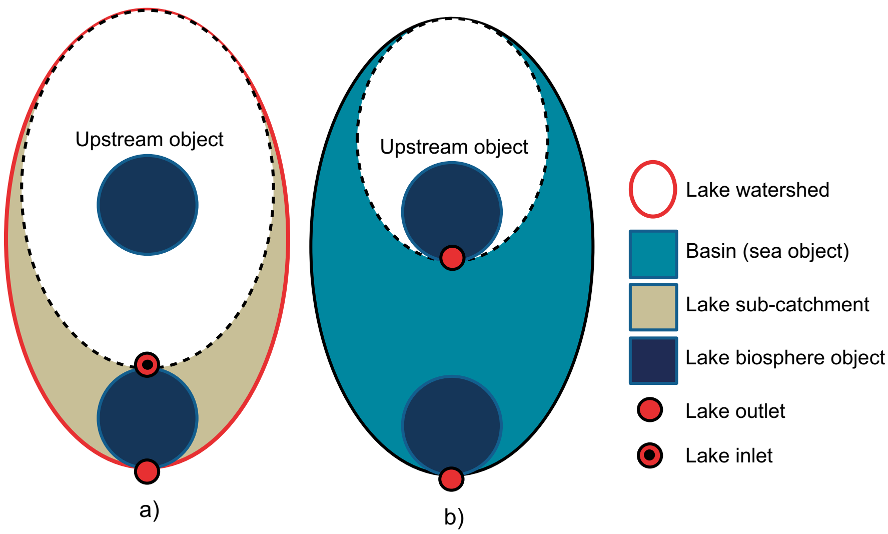


Figure 6-4. *Conceptual illustration of sea-lake-terrestrial type object. a) Two lake objects in a catchment where the bottom lake object has a sub-catchment defined by the outlet catchment area minus the inlet catchment area, and the lake watershed area equals the total lake catchment including upstream objects. b) The basin is the area defined by the catchment of the lake outlet minus the catchment of any upstream object.*

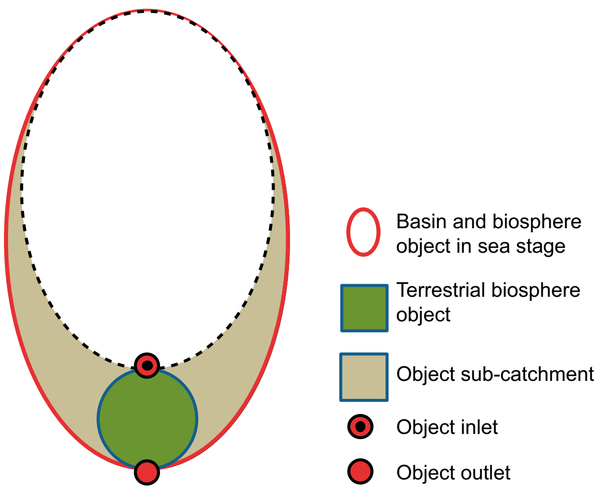


Figure 6-5. *Conceptual illustration of a sea-terrestrial type object with basin, sub-catchment and terrestrial object area.*

6.2.2 Identification of biosphere objects

The identification of biosphere objects was done with the same methodology as in the previous safety assessment SR-Site (Lindborg 2010). This method can be summarised as follows (Figure 6-6):

1. The digital elevation model (DEM, Strömgren and Brydsten 2013) was used to define future lakes and catchment geometries in the landscape.
2. Hydrogeological simulations of water flow paths from the planned repository were used to identify discharge areas on the bedrock surface. This was done for a number of future time steps, in order to understand the time-dependent changes in flow directions for future landscapes.
3. The discharge areas were used to define biosphere objects as sea basins, lakes or wetlands. In the case of discharge areas in future wetlands without a lake stage, the MIKE SHE model (water head calculations) was used to delimit the wetland area used as the biosphere object. These wetland areas were also refined by using the DEM to make sure the object water outlet was correct.

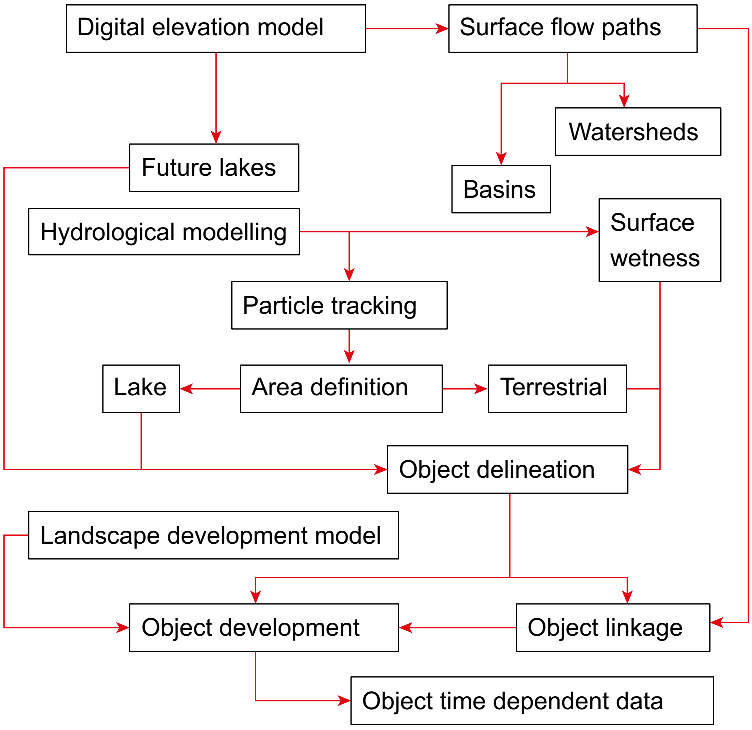


Figure 6-6. *Methodology for identification and description of biosphere objects.*

6.2.3 Temporal development of biosphere objects

The core features of the landscape relief in the Forsmark area are determined mainly by the bedrock topography. 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 (Brydsten and Strömgren 2013). The properties of the biosphere objects change continuously, e.g. due to shoreline displacement, wave erosion and sedimentation, lake infilling and ecosystem succession (see Chapters 4 and 5).

In the Forsmark area two object succession types can be defined, a sea-lake-terrestrial (Figure 6-4) and a sea-terrestrial type (Figure 6-5) (cf. the box "Area definition" in Figure 6-6). The sea-lake-terrestrial succession can be described as follows.

- Sea stage: The biosphere object is a sea basin. As the landscape emerges from the sea, the sea basin 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). The isolation of a lake in the Forsmark area takes approximately 400 years. 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: In this type of succession, the object area has a well-defined threshold, and a lake will emerge. (If not, the transitional stage is followed directly by the terrestrial stage, see sea-terrestrial succession below.) 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 landscape succession occurs. For the majority of discharge areas, the final stage is a wetland that is drained by a small stream. However, in some small objects located upstream no stream develops, and in a few downstream objects a larger stream flows through the objects.

The sea-terrestrial succession consists of the following steps.

- Sea stage: The biosphere object is a sea basin. As the landscape emerges from the sea, the sea basin 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: In this stage, the shoreline moves over the biosphere object. The transformation of a biosphere object from sea to terrestrial in the Forsmark area takes approximately 500 years. During this phase, saltwater flooding will occur periodically.
- Terrestrial stage: The biosphere object has reached a mature state and no further landscape succession occurs. For the objects that go through this type of succession, the final stage is a wetland that is drained by a small stream. However, in some small objects located upstream no stream develops, and in downstream objects larger streams may flow through the objects.

6.3 Resulting basins and biosphere objects

6.3.1 Identified biosphere objects

The resulting biosphere objects and their basins are shown in Figure 6-7. These are the areas possibly affected by future releases of radionuclides from the repository. Depending on the landscape succession, the objects will undergo a time-dependent development from sea to land. This is further

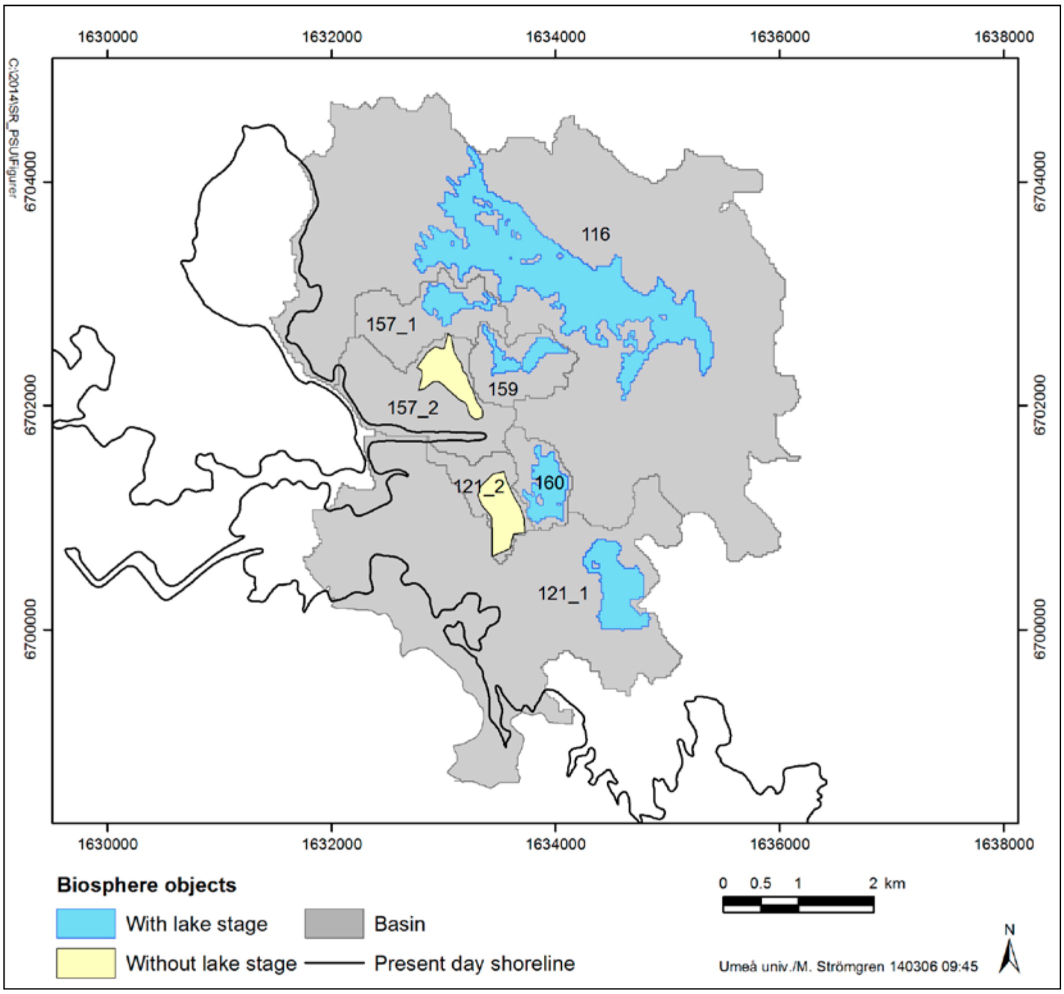


Figure 6-7. The resulting biosphere objects (blue or yellow) and their associated basins (grey). When the area is sea the basin is treated as the biosphere object, but thereafter the initial lake area (blue) is treated as the biosphere object. For the two objects that do not go through a lake stage (yellow), a wetland is formed directly after the sea stage.

described in Section 6.3.2. As explained above, there are two types of biosphere objects, objects with a lake stage in the succession and objects without a lake stage. The size of objects is a result of a number of features and processes. First, all objects have the size of the basin, and then the objects with a lake stage will have the initial lake size as a delimiting factor. The objects that have no lake stage will have a size determined by hydrological simulations and geometries as described above. The object sizes and locations are thereby linked to the discharge areas of groundwater from the repository.

As a part of the landscape development modelling, the DEM is used to locate surface streams in future land areas (Chapter 5). The resulting stream network is the basis for the development of a model for connected biosphere objects. Figure 6-8 illustrates connections and flow directions of surface water between the biosphere objects identified in the SR-PSU biosphere assessment. It can be seen that the connected biosphere objects form two different branches, one northern and one southern branch.

As described in more detail in Werner et al. (2013a), an alternative modelling approach of the stream network using MIKE SHE with a higher temporal resolution suggested an alternative route for the outlet from biosphere object 160. According to the MIKE SHE modelling results, surface water flow from biosphere object 160 would enter biosphere object 121_1 instead of object 121_2 (which was the flow direction obtained from the landscape modelling based on the 2000 AD DEM). The radionuclide transport modelling used the stream network obtained from MIKE SHE, which is the alternative displayed in Figure 6-8. Note that the streams between biosphere objects are not defined as separate biosphere objects, whereas the stream sections in the final stage of lake development in objects that go through a lake succession stage are regarded as parts of the biosphere objects.

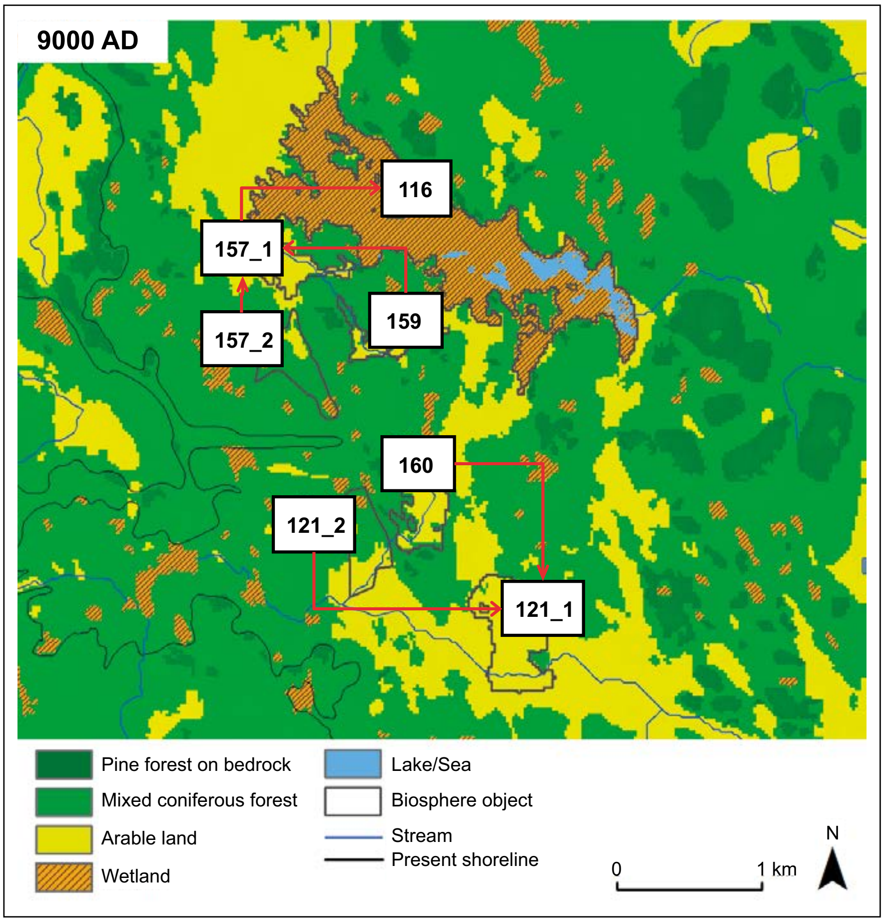


***Figure 6-8.** Connections and flow directions between biosphere objects in the terrestrial stage plotted on a map showing the landscape at 9000 AD according to the LDM (variant 2, see Chapter 5).*

6.3.2 Temporal development of identified biosphere objects

The biosphere object succession can be described for each object using information from the LDM. By displaying the objects on the LDM, changes in ecosystem types can be visualised and analysed (see Figure 6-9). Each biosphere object will have its own development in time. In the following, the development of the seven identified biosphere objects is described for the assessment period.

Object 116

The object is located north of SFR and is the largest biosphere object potentially receiving radionuclides released from the repository. The object is a present sea basin with an average depth of 10 metres. At 4500 AD the future lake will be isolated. The total isolation process takes about 400 years. The mean depth of the lake at isolation will be 1.5 metres with a maximum depth of 5 metres. During the next period of 5,000 years, the lake slowly undergoes sediment accumulation and ingrowth of vegetation. At 9800 AD the lake has been infilled and only a small stream drains the catchment. Large parts of the lake area can be used for agricultural purposes.

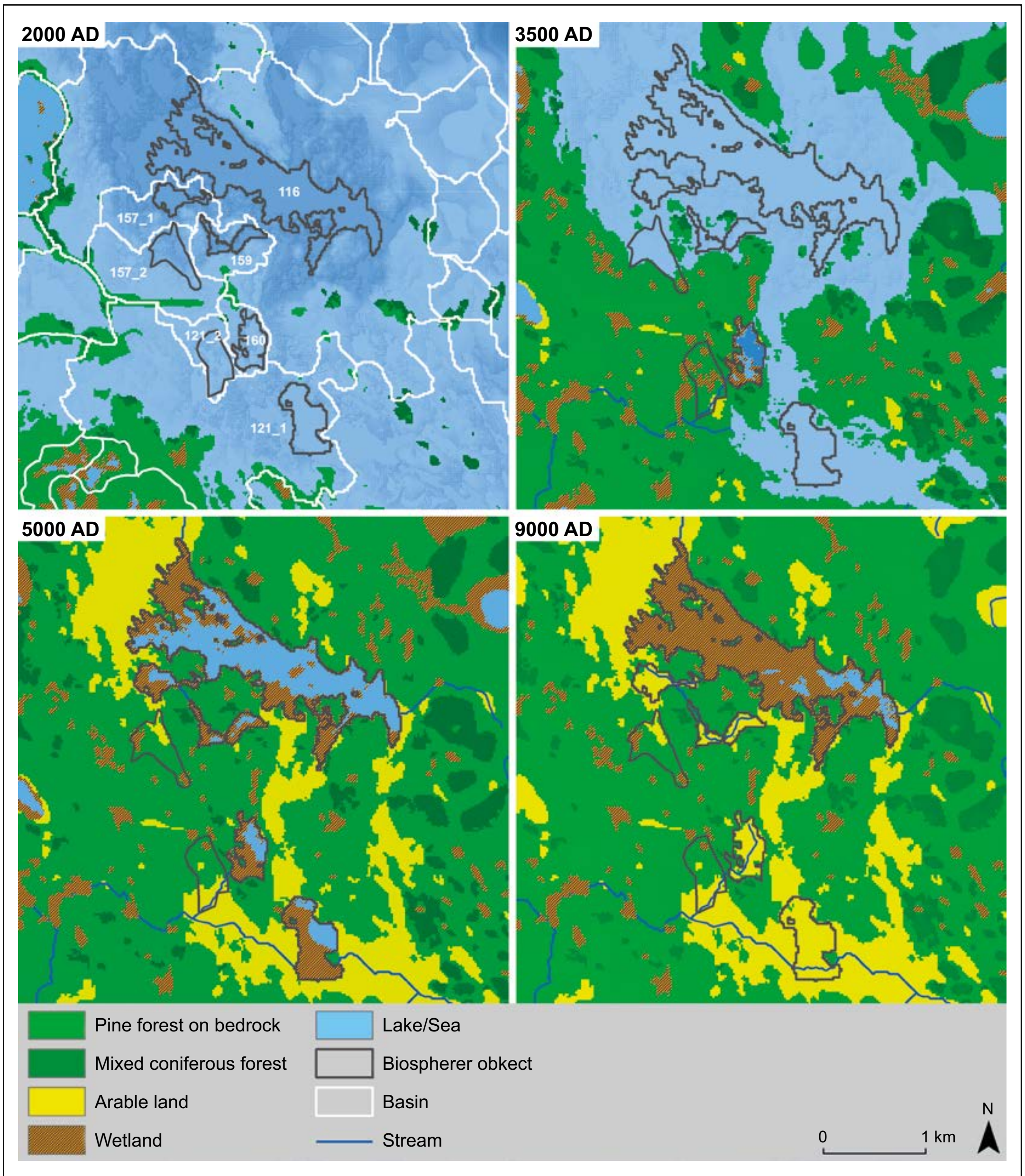


Figure 6-9. *The biosphere object succession and ecosystem development shown for 2000, 3500, 5000 and 9000 AD using the LDM (variant 2, Chapter 5) as background.*

Object 121_1

The biosphere object 121_1 is a present sea basin with an average depth of 6 metres and a maximum depth of 13 metres. At 3900 AD the future lake will be isolated. The total isolation process takes about 400 years. The mean depth of the lake at isolation will be 1.4 metres with a maximum depth of 3.6 metres. During the next period of 2,400 years, the lake slowly undergoes sediment accumulation and ingrowth of vegetation. At 6300 AD the lake will be infilled and only a stream passes through the object area, draining the 121_1 catchment and the upstream area of 121_2 and 160. According to the LDM (see Chapter 5), almost the whole object area will be useful for agricultural practices.

Object 121_2

Object 121_2 is at present below sea level, at average and maximum depths of 6 and 10 metres, respectively. The object area will have no future lake and a succession from marine to terrestrial ecosystems will occur without a lake stage. The starting point for transition from a marine to a terrestrial ecosystem is 3000 AD and the total area is land in the year 4000 AD. Hydrological modelling shows an area with high water levels in the upper soil and a wetland will form after the sea has withdrawn due to shoreline displacement. According to the LDM (Chapter 5), one third of the wetland area will have the potential for use for agricultural purposes.

Object 157_1

The biosphere object 157_1 is a present sea basin with an average depth of 11 metres and a maximum depth of 16.5 metres. At 4500 AD the future lake will become isolated. The total isolation process takes about 400 years. The mean depth of the lake at isolation will be 2 metres with a maximum depth of 3 metres. During the next period of 1,200 years, the lake slowly undergoes sediment accumulation and ingrowth of vegetation. At 5700 AD the lake will be infilled and only a small stream is passing through the object area, draining the 157 catchment and the upstream area of 157_2. According to the LDM (Chapter 5), almost the whole object area can be used for agricultural practices.

Object 157_2

Object 157_2 is at present below sea level (average depth 5.8 and maximum depth 13.5 metres). The object area will have no future lake and the succession from a marine to a terrestrial ecosystem will take place without a lake stage. The starting point of the transition from a marine to a terrestrial ecosystem is at 3000 AD and the total area is land in the year 4500 AD. MIKE SHE modelling suggests that approximately half of the area has an annual average water table depth close to the ground surface and at the same time 80% of the biosphere object is defined as having a net discharge of groundwater originating from the rock surface (Werner et al. 2013a). These areas partly overlap, which is an effect of topographical differences within the biosphere object. Consequently, the total area affected by groundwater input and a resulting high water saturation will cover the vast majority of the biosphere object. Altogether, these conditions suggest that primary mire formation would be the relevant process for peat accumulation in this biosphere object (Section 4.7.1), and consequently a wetland will form after the sea has withdrawn due to shoreline displacement. The object drains to object 157_1 in the surface water flow network (Figure 6-8). According to the LDM (Chapter 5), a rather small area is identified as potential arable land (Figure 6-9).

Object 159

The biosphere object 159 is presently a sea basin with an average depth of 9 metres and a maximum depth of 15 metres. At 4000 AD the future lake will be isolated. The total isolation process takes about 400 years. The mean depth of the lake at isolation will be 2 metres with a maximum depth of 3 metres. During the following period of 1,200 years, the lake slowly undergoes sediment accumulation and ingrowth of vegetation. In the year 7000 AD the lake will be infilled. Due to a small upstream area, surface water will be absent from or present only periodically in small streams and in parts of the object. According to the LDM (Chapter 5), almost the whole object area can be used for agricultural practices.

Object 160

Biosphere object 160 is a present sea basin with an average depth of 7 metres and a maximum depth of 12 metres. At 3300 AD the future lake will be isolated. The total isolation process takes about 400 years. The mean depth of the lake at isolation will be 3 metres with a maximum depth of 5 metres. During the next period of approximately 5,000 years, the lake slowly undergoes sediment accumulation and ingrowth of vegetation. In 8500 AD the lake will be totally infilled. Due to small catchment area, there will be no stream in the object, but the area is hydrologically connected to downstream biosphere object 121_1 (Figure 6-8). According to the LDM (Chapter 5), almost the whole object area can be used for agricultural practices.

6.3.3 Distribution of discharge locations between biosphere objects

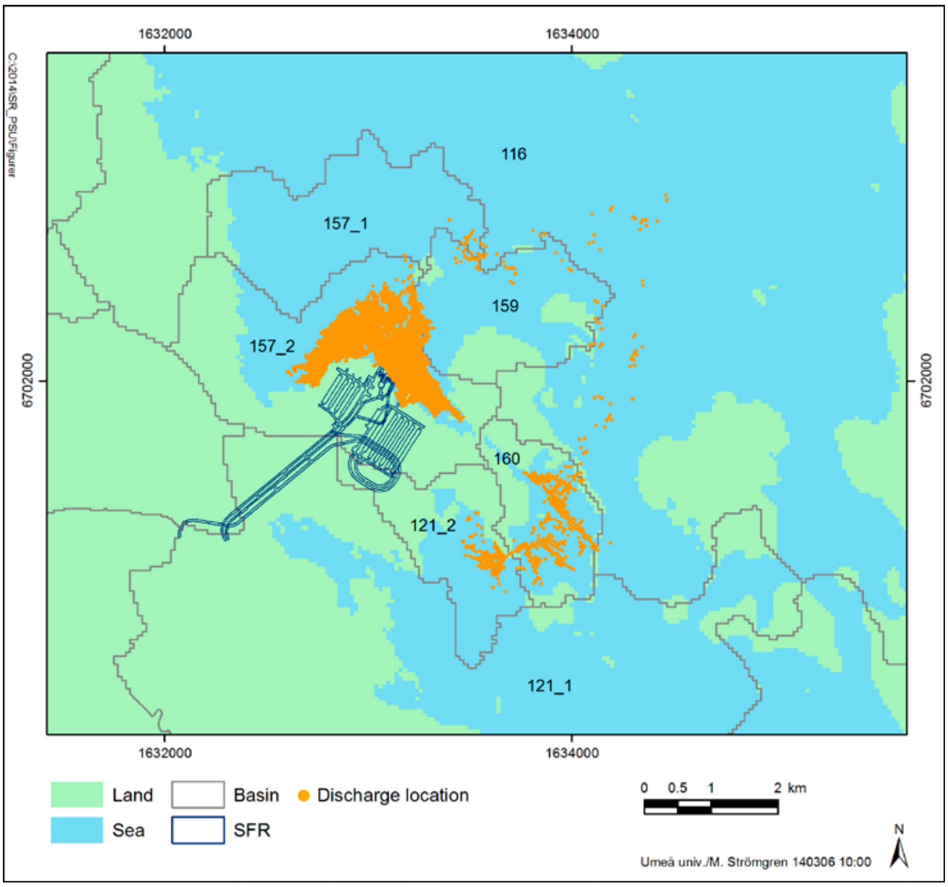
The discharge locations delivered by the bedrock hydrology modelling (Section 6.1.2) have been analysed with the aim of determining whether any object or objects received most of the potentially contaminated groundwater, and hence should be the main focus of the biosphere assessment. As indicated already in Figures 6-1 and 6-2, the highest densities of discharging particles occur in an area just north of the SFR repository, which essentially corresponds to biosphere object 157_2. The present section presents quantitative results that link discharge locations to basins and objects, and confirm the important role of the 157_2 basin/object as the main discharge area for groundwater potentially carrying radionuclides from the repository to the surface.

Results of the analysis of discharge locations (i.e. particle positions at the bedrock-regolith interface) for one bedrock modelling case, "Bedrock model case 1" (Öhman et al. 2014, Odén et al. 2014), are illustrated in Figures 6-10 and 6-11; Figure 6-10 shows discharge locations for the 3000 AD and 9000 AD releases, and Figure 6-11 the corresponding particle densities (number of particles per m^2). The results are displayed on maps that show the basins associated with the biosphere objects (cf. Figure 6-7) and the distribution of sea and land at the two times for which results are illustrated. Note that the whole basins are used as biosphere objects as long as the basin is covered by the sea, whereas the smaller biosphere objects in Figure 6-7 are used in the terrestrial stage.

Figures 6-10 and 6-11 confirm the dominant role of basin/object 157_2 as a discharge area. Discharge takes place also in other basins, most notably basins 121_2 and 160 at 3000 AD and basins 157_1 and 116 at 9000 AD (Figure 6-10), but as indicated by the density maps (Figure 6-11) these discharges involve relatively few particles. With the lower limit for particle density used in Figure 6-11, densities sufficiently high to be shown occur almost exclusively in the 157_2 basin.

A more detailed presentation of the particle tracking results is given in Table 6-1 (particles released in SFR 1) and Table 6-2 (particles released in SFR 3). For particles released in SFR 1, Table 6-1 shows that basin 157_2 always receives at least 99.9% of the total number of particles (one million); the second highest discharge fraction is the 0.1% obtained for 157_1 at 5000 AD. Furthermore, it can be noted that no discharge from SFR 1 takes place in any of the basins associated with the southern branch in Figure 6-8. An analysis of where in the 157_2 basin discharge takes place at different times shows that the discharge locations are more dispersed within the basin at early times (in the sea stage) than at later (terrestrial) times when they indeed are concentrated to the area corresponding to the terrestrial stage object (Figure 6-7). The fraction of the total number of particles in the 157_2 basin that discharge in the subarea of the terrestrial stage object increases from 22% at 2500 AD to 71% at 3000 AD and 100% at the remaining time steps. This concentration of discharge locations to the terrestrial stage object at later times is illustrated in Figure 6-12, which shows the 9000 AD map in Figure 6-10 with the extent of the terrestrial stage object marked.

The discharge of particles released in SFR 3 (Table 6-2) is slightly more dispersed among the basins than that of the SFR 1 particles. However, the lowest fraction obtained for basin/object 157_2 at any time is still nearly 95% (at 5000 AD). Basin 157_1, which in the terrestrial stage includes the biosphere object just downstream of 157_2, receives some 3–4% of the particles at the later times considered in the modelling. The northern branch dominates also in this case; the discharge in the southern branch basins corresponds to c. 4% at 2500 AD and minor fractions at the other times. Similar to the SFR 1 release discussed above, the particles in the 157_2 basin become more concentrated to the terrestrial stage object with time; the fraction of the particles reaching the basin that go to the terrestrial object subarea is about 50% at 2500 AD and more than 90% at all later times.



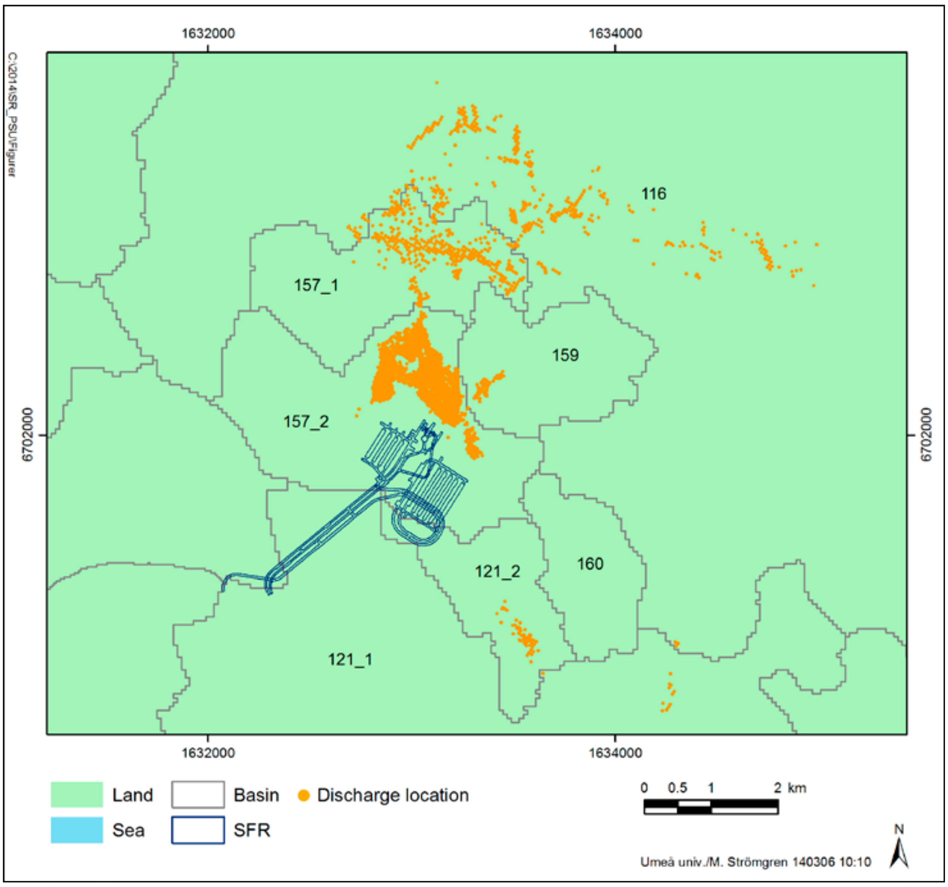


Figure 6-10. *Locations of discharging particles from SFR obtained with models for 3000 AD (top) and 9000 AD (bottom) displayed on maps showing the basins.*

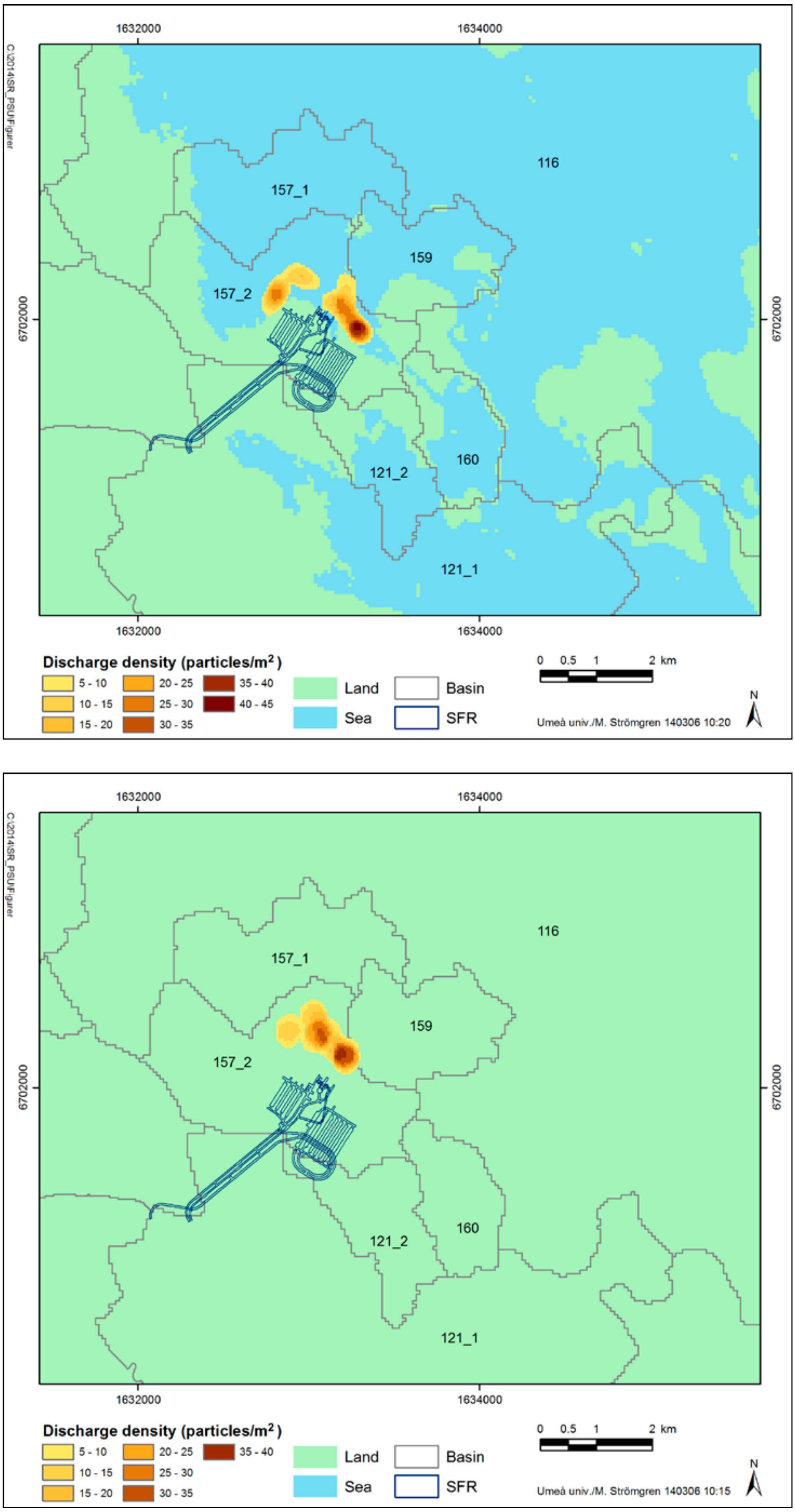


Figure 6-11. *Densities of discharging particles (number of particles per m²) from SFR obtained with models for 3000 AD (top) and 9000 AD (bottom) displayed on maps showing the basins.*

Table 6-1. Discharge per basin measured as number of discharging particles from a release of one million particles in SFR 1. Objects/basins 116, 157_1, 157_2 and 159 belong to the northern branch and 121_1, 121_2 and 160 to the southern branch in Figure 6-8.

Time step	116	157_1	157_2	159	121_1	121_2	160
2500 AD	0	0	999,420	580	0	0	0
3000 AD	0	0	999,334	666	0	0	0
3500 AD	0	0	999,990	10	0	0	0
5000 AD	119	1,183	998,697	1	0	0	0
9000 AD	9	140	999,851	0	0	0	0

Table 6-2. Discharge per basin measured as number of discharging particles from a release of one million particles in SFR 3. Objects/basins 116, 157_1, 157_2 and 159 belong to the northern branch and 121_1, 121_2 and 160 to the southern branch in Figure 6-8.

Time step	116	157_1	157_2	159	121_1	121_1	160
2500 AD	0	0	961,445	81	8,361	30,111	2
3000 AD	94	20	992,190	2,976	0	1,509	3,211
3500 AD	71	411	989,059	10,248	15	196	0
5000 AD	8,069	37,831	947,629	6,332	16	123	0
9000 AD	5,688	30,349	963,673	168	15	107	0

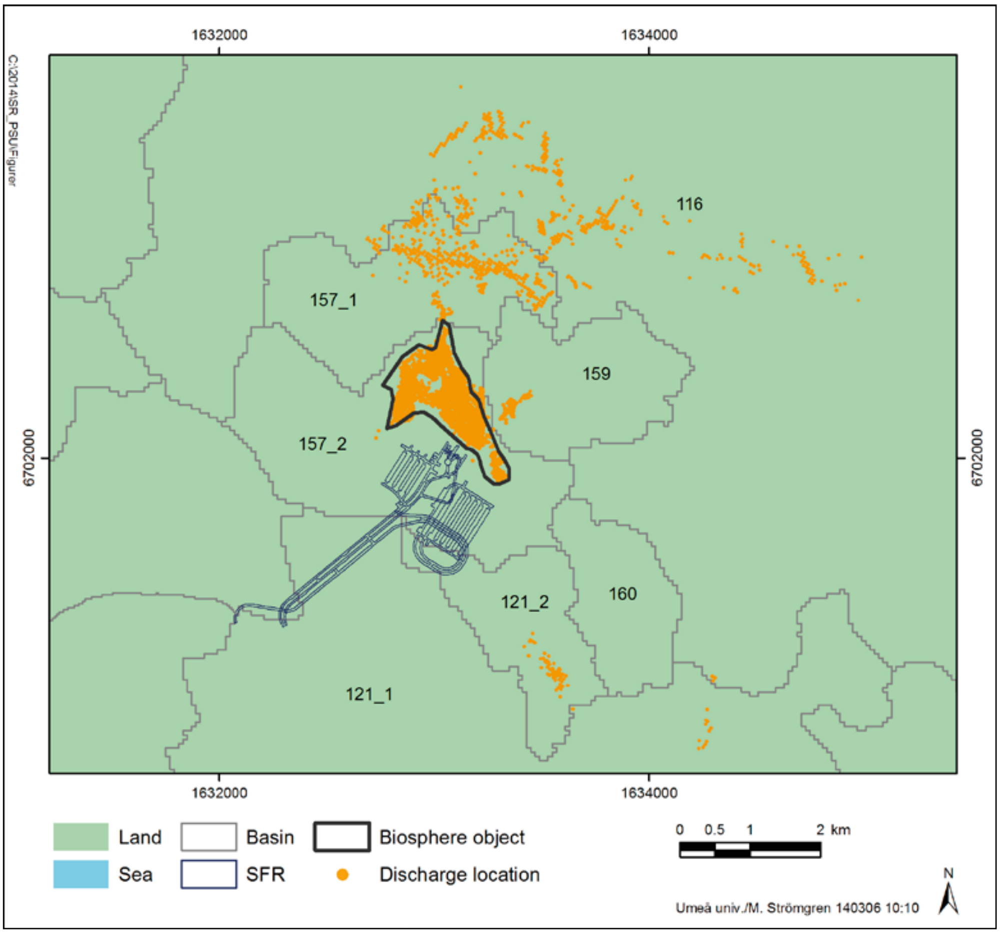


Figure 6-12. Locations of discharging particles from SFR at 9000 AD displayed on a map showing the basins and the 157_2 terrestrial stage biosphere object.

The present analysis is based on one variant of the model in one of the modelling activities providing discharge locations, i.e. "Bedrock case 1" in the TD11 stage of the bedrock modelling (Öhman et al. 2014, Odén et al. 2014). As mentioned in Section 6.1.2, the same type of results is available also from other modelling activities and model variants. Comparisons with some of these results show that the emphasis on 157_2 is smaller in some cases, but that this basin/object still receives most of the discharge. In particular, some of the earlier TD08 results that were used in the initial identification of biosphere objects put somewhat more weight on the southern branch than the results discussed above. However, no observations have been made that would change the identification of which biosphere objects to include in the analysis or the general view of their relative importance for the assessment. In particular, all analysed results support the conclusion that the transport modelling should be focused on the northern branch, with release of contaminated groundwater in object 157_2 as "base case".

6.3.4 Biosphere objects for periglacial conditions

The preceding sections are focused on the identification and analysis of biosphere objects for temperate climate conditions, i.e. biosphere objects derived from hydrological simulations for a climate similar to the present. In a future colder climate with permafrost, groundwater flow will take place only below the permafrost layer and in the through taliks associated primarily with lakes that provide hydrological connections between the surface and the groundwater below the permafrost.

The SR-PSU modelling of a future periglacial system at Forsmark was based on earlier results from the surface hydrology modelling of periglacial conditions in SR-Site (Bosson et al. 2010) and the SR-PSU bedrock hydrology modelling with DarcyTools outlined in Section 6.1.3. Essentially, two taliks, for which water balance results were available that could be used to parameterise the biosphere radionuclide transport and dose model (cf. Chapter 8), were selected to represent the discharge locations calculated with DarcyTools.

One of the selected taliks is at the location of biosphere object 157_1 (Figure 6-7), i.e. in the area north of the SFR repository, whereas the other is talik object 114 of Bosson et al. (2010), coinciding with the discharge locations at the northeastern DarcyTools model boundary in Figure 6-3 (see text in Section 6.1.3). It follows from the description above that the objects considered in the modelling of the periglacial case were selected partly based on the availability of earlier results and to represent typical objects; a more detailed discussion of this modelling is given in Werner et al. (2013a).

6.3.5 Handling biosphere objects in the different climate cases

The landscape will change dramatically during the modelled time period. This does not necessary mean that the configuration of biosphere objects will alter, although the sedimentation and infilling process rates decrease in colder climates. The LDM describes how the areas of biosphere objects undergo a succession from the sea stage to a terrestrial stage under 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 possible period of periglacial domain starts at Forsmark (c. 17,500 AD in the *early periglacial climate case*, Section 4.2). At that time, only one object is still in the lake stage and no object is sea. Under periglacial conditions, ingrowth of mire vegetation and accumulation of lake sediment are expected to be slow (Section 5.4.3 and Löfgren 2010). Since the period with cold climate is relatively short, no succession is assumed, and the lake-mire object retains its initial morphology during the 3,000-year simulation period.

For warmer conditions, i.e. the *extended global warming climate case* (Section 4.2), the same biosphere objects are used as in the *global warming climate case*. However, the shoreline displacement process is slightly modified (delayed) in this case, as described in Section 4.2 and Chapter 5.

6.3.6 Well interaction area

As described by Werner et al. (2013a), trajectories for all elevation intervals and all particle releases were accumulated to visualise the extent of the plume of potentially radionuclide-carrying groundwater within the considered total elevation interval (Section 6.1.5). Specifically, the well interaction area was delineated as the area (volume) of rock with a high density of trajectories. Particle trajectories and the delineated well interaction area, with a size of 0.26 km^2, are shown in Figure 6-13.

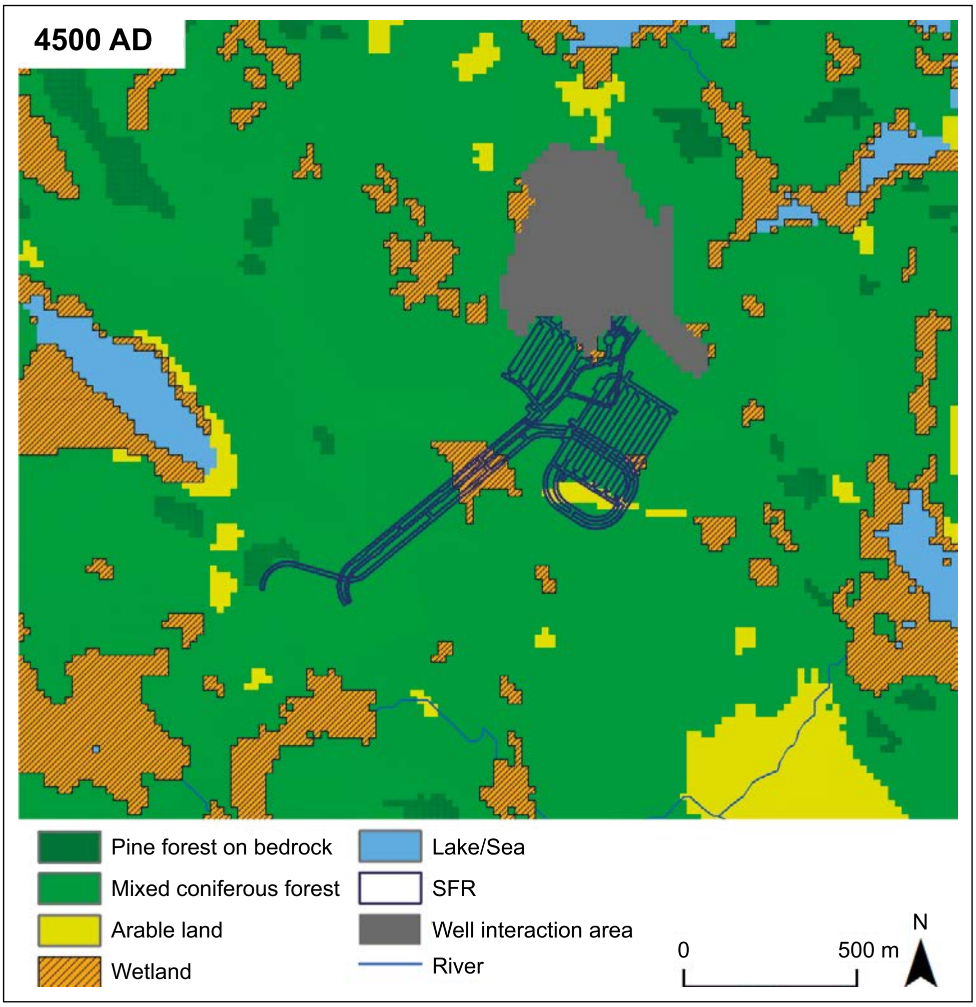


***Figure 6-13.** Delineated well interaction area, located just north of the SFR repository. Figure from Werner et al. (2013a).*

The probability for a well to be located at random within the well interaction area can be calculated as the size of the well interaction area (km^2) times the well density in the area or region of interest (number of wells per km^2). The selection of a well density for SR-PSU and the resulting probability are presented in the **SR-PSU Main report** and Werner et al. (2013a).

6.4 Alternative object delineations

The methodology for delineation of biosphere objects is based on knowledge of the ecosystems in Forsmark and processes affecting the fluxes and distribution of elements in these. Nevertheless, although there is confidence in this methodology, alternative methods for delineating biosphere objects can be applied in order to examine how the object delineation may affect object properties and the environmental concentrations that result from a constant release of radionuclides. Therefore, four alternative delineations of biosphere object 157_2 (Figure 6-7) have been performed in SR-PSU (biosphere calculation case 7, described in Section 7.4.7 and results presented in Chapter 10). Object 157_2 was chosen because the analysis of discharge locations (Section 6.3.3) shows that this is the most important discharge area in the assessment; this object is of the type that has no lake stage. The alternative delineations were derived from different assessment perspectives and are summarised below.

1. *Areas with upward hydraulic gradients (UpwGrad)*. The original biosphere object 157_2 was outlined based on particle discharge at the bedrock-regolith interface. For this alternative delineation, it is assumed that all radionuclides are released to areas that are defined as discharge areas all the way from the bedrock to the surface. Discharge areas are defined based on flow modelling results from MIKE SHE, and calculated using head differences between adjacent calculation layers. Head differences were calculated for layers in the regolith, in the bedrock located just below the regolith, and in the bedrock at a depth of approximately 60 m. Areas defined as discharge areas at all three levels were selected as an alternative delineation of biosphere object 157_2 (Figure 6-14a).
2. *Wetland areas (Wetl)*. In this delineation it was assumed that all radionuclides are released to the area of the object that has wetland properties. Moreover, it was assumed that wetland areas within the object are connected through the flow of surface water and groundwater, at least for parts of the year when they are flooded. In Sweden, wetlands are defined as areas which for most of the year are below or just above the local groundwater level (Löfroth 1991), and where hydrophilic (i.e. moisture-loving) species make up at least 50% of the vegetation. Considering the yearly groundwater fluctuations in the object, this alternative selected and outlined the areas where the yearly average of the groundwater level was above or not more than 25 cm below ground level as wetland areas. The TWI-projected vegetation of the outlined wetland areas confirmed that this criterion was reasonable. That is, the outlined areas were dominated by wetland vegetation (open wetland or wetland forest), and were connected by wetland vegetation (Figure 6-14b).
3. *Main area for discharge points (HD-disch)*. In the delineation based on discharge points from DarcyTools, it is assumed that all radionuclides are released only to the area with the highest density of discharge points. The groundwater flow modelling tool DarcyTools was used to identify particle discharge locations at the interface between rock and regolith for temperate climate conditions (Odén et al. 2014). Discharge locations for particles released in stationary, DarcyTools-calculated groundwater flow fields at different time steps and with different bedrock setups were identified. In the particle tracking, 1,000,000 particles were released uniformly, and proportional to facility volume, in SFR 1 and SFR 3, respectively. Based on results with the base-case setup of the rock, which was the setup also delivered to MIKE SHE, the area with a high density of discharge points was selected as an alternative delineation of biosphere object 157_2 (Figure 6-14c).
4. *Potential arable land (Arabl)*. In the LDM, a future landscape is described in which most of the potential arable land is used (Chapter 5). This case is built upon a historical perspective, where the agricultural use of the landscape was at its maximum (around 1940), and the potential of using the arable land for at least 50 years of continuous farming. Accordingly, wetlands need to have sufficiently thick soil layers for cultivation to make draining feasible. Thus, for this delineation it was assumed that the combined thickness of peat postglacial clay and glacial clay was at least 0.5 m after drainage, accounting for the compaction and oxidation of peat and postglacial clay associated with drainage (Chapters 5 and 9). When these criteria are applied on biosphere object 157_2, only a small area is regarded suitable for long-term agricultural practices (Figure 6-14d)

The alternative delineations resulted in a range of object sizes spanning from 168,000 m^2 (original object) to 29,000 m^2 (potential area for agriculture) (Figure 6-15). As expected there were systematic differences is the average depth of regolith layers between alternative delineations. In relative terms, the largest variation was found in the thickness of glacial clay (RegoGL) and peat (RegoPeat) that varied by factors of 10 and 3, respectively. For example, the thickest peat and glacial clay layers were found in the area which could potentially be drained and cultivated, whereas the thinnest layers of glacial clay were found in the area with a high density of discharge points (Figure 6-15a).

Water balances and groundwater flux rates between regolith layers were determined for each of the delineated areas (see Werner et al. (2013a) for details). As radionuclides are expected to enter the biosphere object from the geosphere, upward water fluxes are key parameters for the transport of radionuclides through the soil horizon. Area-specific upward fluxes ($m^3\ m^{-2}\ y^{-1}$) varied by a factor of two to three between the outlined areas (Figure 6-15b). As expected, the discharge area had the highest flux rates in the lowest regolith layers, whereas the upward flux of groundwater between peat layers was highest in the wetland area. Between object differences in total upward fluxes of ground water ($m^3\ h^{-1}$) were much larger, and varied by a factor of 10 to 20.

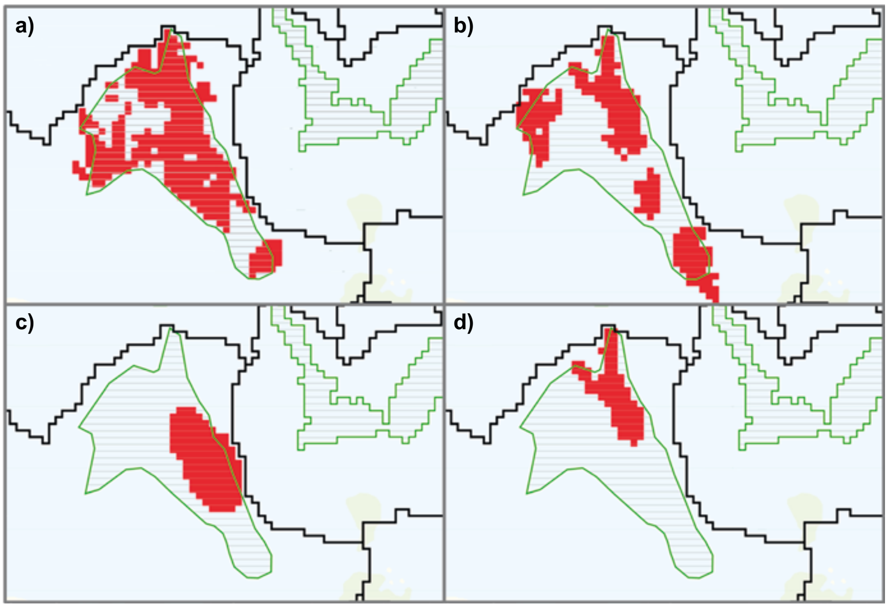


__Figure 6-14.__ Alternative delineations of biosphere object 157_2. The green line indicates the original object and the red areas the alternative outlines of the biosphere object. a) Areas with upward hydraulic gradients (from bedrock to surface). b) Wetland areas (water above surface or not deeper than 0.25 m below the surface). c) Area with a high density of repository discharge points at the bedrock-regolith interface. d) Potential area for cultivation, after drainage of mire.

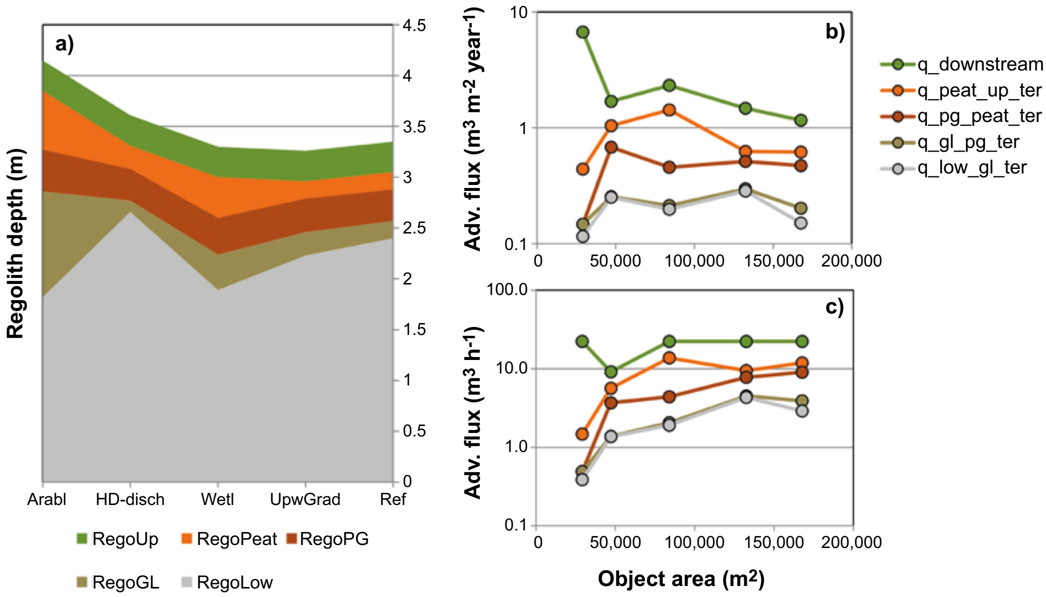


__Figure 6-15.__ Regolith and hydrological flux properties of biosphere object 157_2 and alternative delineations (see text). a) Regolith depth, alternative delineations ordered from smallest (Agri) to largest (Discharge) areas. b) Area-specific flux of groundwater as a function of object surface area. Grey, light brown, brown and orange indicate upward fluxes from till (RegoLow), glacial clay (RegoGL), post-glacial clay (RegoPG) and deep peat (RegoPeat), respectively. Green represents horizontal flux of surface water from surface peat out of the object. c) Total groundwater fluxes summed over the area of the object.

As expected from the area-specific fluxes, variation in total flux was primarily driven by the size of the outlined objects (Figure 6-15c). The horizontal flux of water from surface peat out of the area was similar in all outlined objects, with the exception of the area with a high density of discharge points, where the flux was approximately half of that in the other areas. This was expected as this delineation was elevated above the others and had a somewhat smaller catchment area.

7 FEP handling, exposure pathway analysis, and calculation cases for the biosphere

In this chapter, SKB's work with identifying FEPs important for the evolution of the biosphere, and transport and accumulation of radionuclides are described in Section 7.1. The incorporation of these FEPs in different parts of the biosphere modelling is also described in Section 7.1. Sections 7.2 and 7.3 summarise the (human) exposure pathway analysis and the identification of assessment end-points for non-human biota and Section 7.4 presents the calculation cases for the biosphere used in the radionuclide transport and dose calculations.

7.1 FEP handling

The identification and handling of features, events and processes (FEPs) that are of significance for transport and accumulation of radionuclides in the environment are important in the assessment of human health and safety of the environment. Ecosystems are complex with a large number of structures and functions, and the number of interactions within an ecosystem is virtually 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 those ecosystems, and the processes that affect the transport, accumulation and exposure to radionuclides of organisms and humans that live in or utilize the ecosystem. For the time frame of a deep geological repository, the effects of landscape development and ecosystem succession on transport, accumulation and exposure also need to be considered.

7.1.1 Identification of processes and features important for transport and accumulation of, and exposure to radionuclides in the biosphere

As stated above, a systematic approach is needed for the identification of FEPs in complex systems such as ecosystems. The interaction matrix (IM) is a practical tool to display identified components and pathways that may potentially affect radionuclide transport, 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 are then described in terms of 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 IMs 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. This initial IM has been further developed and updated to reflect the current understanding of ecosystem processes and radionuclide behaviour at the investigated site and in order to more clearly visualise how features of physical components influence both the physical components and the processes (SKB 2013b). The understanding reflected in the IMs has been used as help to guide the planning of site investigations, the modelling of the site and its development, and in development of the radionuclide model.

In SKB's biosphere IM, 10 physical components, 2 boundary components, 6 variables (features), and 50 processes are identified (SKB 2013b). The identified components 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). The variables represent features of these components (geometry, material composition, water composition, temperature, stage of succession, and radionuclide inventory).

Not all processes between the components in the IM are expected to be quantitatively important for transport and accumulation of radionuclides from a repository in the rock at Forsmark. Thus, of the 50 initially identified processes, 45 were considered to be relevant and sufficient for assessing the safety of human health and the environment (Table 7-1). 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 defined, and key processes are briefly described. In addition, features of the physical components are also briefly described. A detailed description of all processes and variables is given in SKB (2013b), where also the IM and the rationale for why some of the initially identified biosphere processes are not relevant for a safety assessment for a repository situated in the rock at Forsmark are given.

Biological processes

Biological processes are those that are dependent on organisms. One pathway of exposure to radionuclides is via intake of water and food, and thus the distribution of biota and food-web interactions are important to consider. In addition, biota may influence the distribution of radionuclides in abiotic pools by, for example, 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 the 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 a large effect on the biosphere, e.g. by introducing species of biota or chemical elements. 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

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 an element available for use by biota and a low element supply may limit biotic 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, diffusion, 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 of radionuclides in water bodies.

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 the 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

Radiological and thermal processes are those processes that concern temperature, solar insolation and radionuclides. Thermal and radiological processes important to consider in safety assessments are radioactive decay, exposure, light-related processes, and radionuclide release. Radionuclide-specific characteristics influence the transport of radionuclides and are, of course, important to consider in the safety assessment. The amount of a radionuclide released, decay rate 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, for example, the 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

The 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, and thresholding. 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, and thresholding, determine the sizes and types of ecosystems at the site.

Features/variables

In addition to processes, features of the physical components are important to consider for the estimation of transport and accumulation of radionuclides and subsequent exposure of humans and biota. Geometry of the components is, for example, depths and areas. Water composition and material composition affects the chemical conditions of the biosphere and thereby affect processes such as reactions. Temperature affects rates of many processes. Stage of succession determines the type of ecosystem that occurs at a given time and thereby affects the processes at the site. In addition to natural succession from sea basin to lake to wetland, stage of succession also includes stages directly affected by humans, as e.g. draining a wetland to be used as agricultural land. Radionuclide inventory is the actual inventory of radionuclides in a physical component and thereby affects the exposure in the biosphere.

7.1.2 Handling of potentially safety-relevant biosphere FEPs in the biosphere assessment SR-PSU

As stated in the previous section, 45 FEPs have been identified as relevant and sufficient to consider for a safety assessment for a repository at Forsmark. The identification of relevant FEPs and model development has been going on in parallel at SKB for the last 20 years and thus knowledge of important FEPs has been considered in the development and improvements of the radionuclide model for the biosphere. However, to incorporate all 45 FEPs into the radionuclide transport model would result in a very complex model. Instead, many of the FEPs are included in supporting modelling used to derive parameter values for the radionuclide model. A mapping of identified biosphere FEPs to the different modelling activities has been performed showing that all the relevant FEPs are included in one or more modelling activities in SR-PSU (see Table 7-1 and SKB 2014).

In addition to mapping all FEPs to modelling activities in SR-PSU, a check of internationally identified FEPs related to the biosphere has also been performed. The handling of NEA FEPs for the biosphere is reported in the SKB FEP database.

Table 7-1. Handling of biosphere FEPs in the different model activities in the assessment. Aqua, Mire, and Agri represents the three ecosystem stages included in the modelling, i.e. aquatic (marine, lake and stream stages), mire (wetland), and agricultural land. NHB is short for non-human biota. K_d/CR represents sorption/desorption parameter values and concentration ratios. X indicates that the process is included in the model.

Process and Variables		Radionuclide model					Supporting activity						
		Transport modelling			Dose calculations		Landscape modelling	Hydrological modelling	Ecosystem-specific parameters				
		Aqua	Mire	Agri	Humans	NHB			Aqua	Mire	Agri	K_d/CR	Human NHB
Biological processes													
Bio01	Bioturbation	X		X					X		X		
Bio02	Consumption	X	X		X	X	X		X	X	X		X
Bio03	Death	X	X				X		X	X			
Bio04	Decomposition	X	X	X			X		X	X	X		
Bio05	Excretion	X	X						X	X	X	X	
Bio06	Food supply				X	X			X	X	X		
Bio07	Growth						X				X		
Bio08	Habitat supply				X	X	X		X	X	X		X
Bio09	Intrusion [(a)]			X	X								X
Bio10	Material supply				X		X		X	X	X		X
Bio12	Particle release/trapping	X	X						X	X	X		
Bio13	Primary production	X	X				X		X	X	X		
Bio14	Stimulation/inhibition						X		X	X	X		
Bio15	Uptake	X	X		X	X			X	X	X	X	X
Processes related to human behaviour													
Bio16	Anthropogenic release			X	X						X		X
Bio17	Material use			X	X						X		X
Bio18	Species introduction/extermination				X	X			X		X		
Bio19	Water use			X	X								X
Chemical, mechanical and physical processes													
Bio21	Consolidation			X							X		
Bio22	Element supply						X		X	X	X	X	
Bio24	Phase transitions	X	X	X				X	X	X	X		
Bio25	Physical properties change	X	X	X				X	X	X	X		
Bio26	Reactions	X	X	X					X	X	X	X	
Bio27	Sorption/desorption	X	X	X	X	X						X	
Bio28	Water supply				X	X	X	X					X
Bio29	Weathering								X	X	X	X	
Bio30	Wind stress						X		X	X	X		
Transport processes													
Bio31	Acceleration							X					
Bio32	Convection	X	X	X				X	X	X	X		
Bio33	Covering	X	X				X	X	X	X			
Bio34	Deposition	X	X				X	X	X	X			
Bio35	Export	X	X	X			X	X					
Bio36	Import	X	X	X			X	X					
Bio37	Interception			X				X			X		
Bio38	Relocation			X			X				X		

Process and Variables		Radionuclide model					Supporting activity						
		Transport modelling			Dose calculations		Landscape modelling	Hydrological modelling	Ecosystem-specific parameters				
		Aqua	Mire	Agri	Humans	NHB			Aqua	Mire	Agri	K_d/CR	Human NHB
Bio39	Resuspension	X			X		X		X				
Bio40	Saturation						X	X			X		
Radiological and thermal processes													
Bio41	Radioactive decay	X	X	X	X	X							X
Bio42	Exposure				X	X							X
Bio43	Heat storage								X	X			
Bio45	Light related processes								X	X	X		
Bio47	Radionuclide release	X	X	X									
Landscape development processes													
Bio48	Change in rock surface location						X	X					
Bio49	Sea level change						X	X					
Bio50	Thresholding						X	X					
Variables													
VarBio01	Geometry	X	X	X	X	X	X	X	X	X	X		X
VarBio02	Material composition	X	X	X			X	X	X	X	X	X	
VarBio03	Radionuclide inventory	X	X	X	X	X							
VarBio04	Stage of succession	X	X	X	X	X	X	X	X	X	X		X
VarBio05	Temperature	X	X	X	X	X	X	X	X	X	X		
VarBio06	Water composition	X	X	X	X	X			X	X	X	X	

7.2 Exposure pathway analysis

A comprehensive exposure pathway analysis has been conducted for SR-PSU (SKB 2014). In the analysis, potential exposure pathways relevant for the long-term safety of a geological disposal facility at the Forsmark site, focusing on exposure of humans, were identified (Figure 7-1). The exposure pathways were evaluated in order to identify those considered significant to include in an assessment of long-term safety. The methodology applied was based upon the exposure pathway evaluation presented in ATSDR (2005). For a geological disposal facility at the Forsmark site, terrestrial environments (such as agricultural land and mires) and aquatic environments (such as lakes, rivers and the sea) may receive repository-derived radionuclides. Environmental media in these environments considered in the analysis were atmosphere (indoors or outdoors), regolith, water (well and surface waters) and biota. Three modes of exposure were identified as relevant to be included in a safety assessment – ingestion, inhalation and external irradiation. The modes of exposure were combined with the receptors in the environment to establish a comprehensive set of cases (exposure route cases) considered potentially safety-relevant (SKB 2014).

A screening evaluation was performed on each case, either qualitatively or quantitatively, to determine if it is insignificant for long-term safety and hence could be excluded from a safety assessment. For the cases screened out, i.e. deemed insignificant for long-term safety, the justifications were documented. Screened-out scenarios included external irradiation during submersion in atmosphere, external irradiation from water, and ingestion of aquatic flora (see SKB 2014). The exposure route cases that could not be screened out were considered to be potentially safety relevant i.e. recommended to be included in a safety assessment. In total, 22 exposure route cases were identified and mapped to one (or more) exposed groups (Figure 7-2, Table 7-2). Of these 22 exposure routes, four (external exposure from outdoor vegetation, external exposure from sediment, and ingestion of inorganic and organic soil) were evaluated with assessment-specific data and showed insignificant contributions to dose. They were therefore not included in the base case calculations (see Chapter 10).

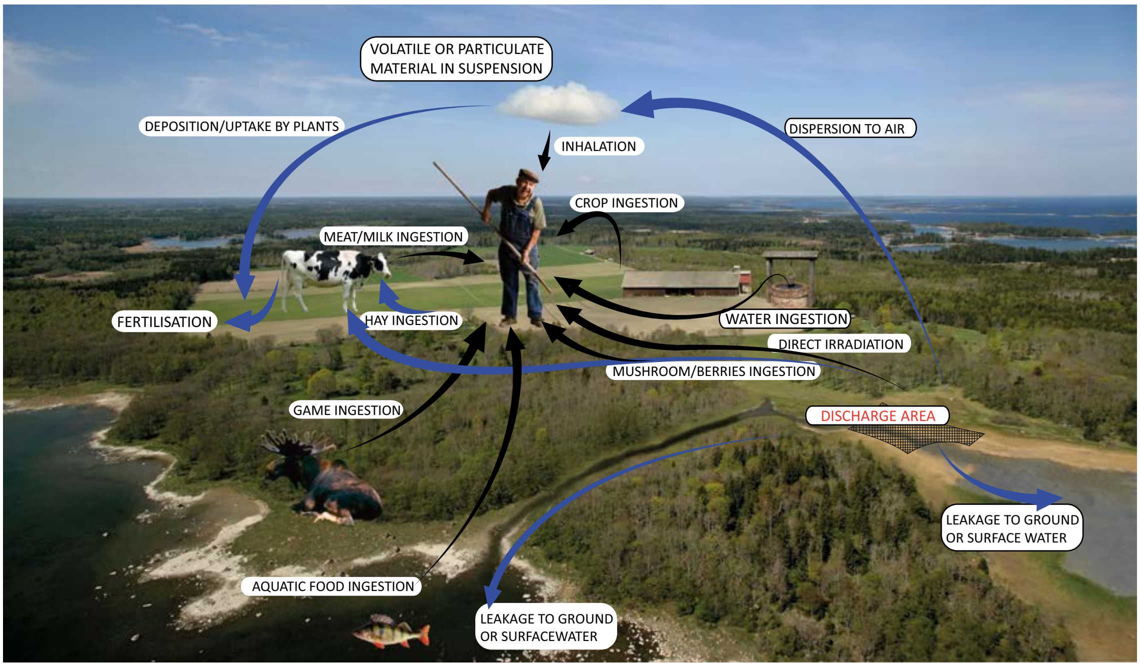


Figure 7-1. Potential exposure pathways for humans.

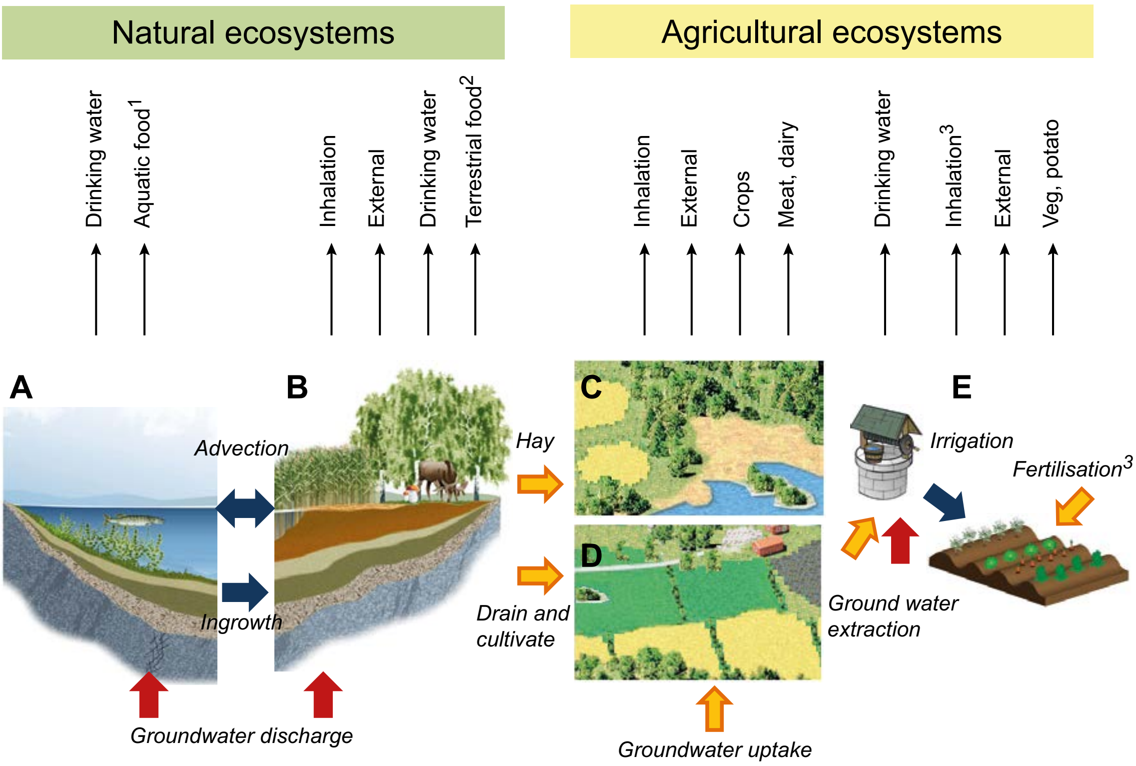


Figure 7-2. Exposure pathways included in the dose calculations for exposed populations using natural resources and/or living in biosphere objects. Hunter-gatherers use natural aquatic (A) and mire (B) ecosystems. The other three exposed populations represent different uses of arable land, namely infield-outland agriculture (C), draining and cultivating the mire (D) and small scale horticulture on a garden-plot (E). Bold arrows represent input of radionuclides from the bedrock (red), from natural ecosystems or deep regolith deposits (orange), or water-bound transfer of radionuclides within the biosphere (blue). The thin arrows (top) represent exposure routes: 1 = fish and crayfish, 2 = game, berries and mushroom, 3 = inhalation and fertilisation that include radionuclides from combustion of biofuel.

Table 7-2. Exposure route cases included in a safety assessment and the corresponding potentially most exposed groups (HG = hunter-gatherers, IO = infield-outland farmers, DM = drained-mire farmers, GP = garden-plot households).

Environmental medium	Exposure route case	Most exposed group	Comment
Atmosphere – outdoor	Inhalation of gases during breathing	HG, IO, DM, GP	Occurs during all outdoor activities.
	Inhalation of dust during breathing	HG, IO, DM, GP	Occurs during all outdoor activities.
Regolith – soil (inorganic)	Inadvertent soil ingestion[2]	GP	Occurs as a consequence of outdoor activities.
	External irradiation from the ground when staying outdoors	IO, GP	Occurs during all outdoor activities where there is soil.
	External irradiation from sediments[2]	HG	Occurs during outdoor activities such as fishing or bathing.
Regolith – peat	Inadvertent peat ingestion[2]	DM	Occurs as a consequence of outdoor activities.
	External irradiation from the ground when staying outdoors	HG, IO, DM	Occurs during all outdoor activities where there are peat soils.
	Indirect[1] contamination of the environment	GP	Inhalation of gas and dust originating from the burning of peat as biofuel.
	Indirect[1] contamination of soil	GP	Burning of peat as biofuel, and depositing ashes as fertilisers.
Well water	Ingestion of well water	IO, DM, GP	Drinking water from a dug well or a bedrock well.
	Indirect[1] contamination of crops and soils	GP	Irrigation of small-scale horticulture.
	Indirect[1] contamination of fauna that drinks water	IO, DM	Drinking water for livestock.
Surface water	Ingestion of water	HG, IO, DM, GP	Drinking water from a stream or a lake.
	Indirect[1] contamination of crops and soils	GP	Use of surface water for irrigation.
	Indirect[1] contamination of fauna that drinks water	IO, DM	Livestock drink or are watered with surface water.
Flora	Ingestion of crops, berries, mushrooms	HG, IO, DM, GP	Fundamental source of foodstuffs.
	External irradiation outdoors from vegetation[2]	HG	Exposure to radionuclides in the standing vegetation.
	Indirect[1] contamination of the environment from burning wood fuel	GP	Inhalation of gas and dust originating from the burning of wood as biofuel.
	Indirect[1] contamination of the environment by ash and manure	IO, GP	Burning of wood as biofuel, and depositing ashes as fertilisers. Depositing manure as fertiliser.
	Indirect[1] contamination of soils by fertilisation with aquatic flora	GP	Fertilisation with sea weed.
Fauna	Ingestion of terrestrial food	HG, IO, DM	Fundamental source of foodstuffs.
	Ingestion of aquatic food	HG	Eating fish.

[1] Indirect exposure routes are those that can lead to transfer of radionuclides from one environmental medium to another as a result of human activities.

[2] The exposure route case was evaluated with assessment-specific data and did not contribute significantly to dose (see Section 10.10). It was therefore excluded from the base case calculations.

Four potential most-exposed populations were included in the analysis. These groups were considered credible to use as bounding cases for the most exposed groups with respect to exposure through all major exposure pathways (SKB 2014). When characterising the most exposed groups, physical and biological characteristics of the biosphere objects, human requirements for energy and nutrients, and habits from historical and present societies were considered (Saetre et al. 2013a, b). The four exposed populations identified were the following.

Hunter-gatherers (HG) – A hunter and gatherer community using the undisturbed biosphere for living space and food. The major exposure pathways are from foraging in the landscape (fishing, hunting, and collecting berries and mushrooms), and from drinking water from surface water (streams or lakes). A typical hunter-gatherer community is assumed to be made up by 30 persons that utilise a forage area of approximately 200 km^2.

Infield-outland farmers (IO) – Self-sustained agriculture in which infield farming of crops is dependent on nutrients from wetlands for haymaking (outland). The major exposure pathways are from wetland hay and from drinking water from either a dug well or from surface water in the biosphere object. A self-sufficient community of infield-outland farmers is assumed to be made up by 10 persons. A wetland area of 0.1 km^2 (10 ha) would be needed to supply winter fodder to the herd of livestock corresponding to the need of manure for infield cultivation of this group.

Drained-mire farmers (DM) – Self-sustained industrial agriculture in which wetlands are drained and used for agriculture (both crop and fodder production). The major exposure pathways are from growing food on land where radionuclides have accumulated for an extended time, and from drinking water from either a well (dug or drilled) or from surface water in the biosphere object. A self-sufficient community of drained-mire farmers is assumed to be made up by 10 persons. A wetland area of 6 ha would be needed for food production.

Garden-plot households (GP) – A type of household that is self-sustained with respect to vegetables and root crops produced through small scale horticulture. The major exposure pathways are from fertilising the garden plot and from using either a well (dug or drilled) or surface water for drinking and irrigation purposes. Exposure from burning biomass is also considered in this population. A garden-plot household is assumed to be made up by 5 persons and a 140 m^2 area garden plot is enough to support the family with vegetables and root crop.

It follows from the description above that the four potential most-exposed groups represent four different types of future land use. In the remainder of the report, especially in the description of modelling results in Chapter 10, they are therefore frequently referred to as "land use variants", not to be confused with the landscape development variants discussed in Chapter 5. However, for the present discussion of exposure and calculation cases the notions of exposed populations and groups are retained.

7.3 Identification of non-human biota endpoints

The exposure pathway analysis identified three relevant exposure routes by which biota can be exposed to radionuclides; through the respiratory tract (inhalation), through the digestive tract (ingestion) and external irradiation (SKB 2014). Exposure via ingestion and inhalation is not modelled separately as the organism is modelled as one unit and has not been divided into different entities. External exposure is estimated from radionuclides in peat in terrestrial ecosystems and from radionuclides in sediment and water in aquatic ecosystems. External exposure from radionuclides in the atmosphere and in other flora and fauna has been neglected due to the much lower concentrations.

Concerning exposure estimates to biota, it is practically impossible to consider and ensure protection of every single population of organisms at the site, so generalisations are necessary to allow assessments to focus on a few representative targets characterising the range of species and their habitats present. The challenge is thus to identify a small enough number of targets to make assessments manageable without reducing the information value of the assessment beyond credibility. This is discussed in more detail in Jaeschke et al. (2013) in which the reference organisms of the ERICA Tool (Beresford et al. 2007) are compared with representative species for marine, limnic and wetland ecosystems of the Forsmark area.

The reference organisms are a set of organism types selected as assessment targets in order to represent organisms that are likely to get the highest exposure in the ecosystems of relevance. As described in SKB (2014), the reference organism concept was acceptable in most cases and only a few changes and additions have been made in this assessment in order to capture important site-specific aspects. For example, one small benthic limnic primary producer has been added to represent the microphytobenthos present in thick layers in the lake sediment in many of the lakes in the Forsmark area today (Andersson 2010). Two site-specific birds and a mammal that utilise aquatic as well as terrestrial habitats have also been added in order to include the combination of exposure from several ecosystem types.

The ecosystem types included are sea, lake/stream and wetlands. Agricultural ecosystems have not been considered relevant in the analysis since future biosphere objects are marine areas, lakes/streams or wetlands (see Chapter 6). Even if wetlands may be drained and cultivated, these agricultural soils are expected to be productive (and thus provide a stable environment) for 100 years or less (Lindborg 2010). Species associated with this land would either be introduced by humans (crop or livestock), or immigrate from adjacent land and consequently they would be part of larger and more stable biological populations. The populations would also be actively manipulated by humans. The exclusion of farmed animals from the assessment is consistent with the ICRP view that the protection of humans themselves is probably sufficient for such managed environmental or ecological situations (ICRP 2008). In total, 41 organism types have been included in the safety assessment (13 limnic, 11 marine, 14 terrestrial, 2 marine and terrestrial, and one limnic and terrestrial, i.e. the latter two types utilise two ecosystems), see Table 7-3.

Table 7-3. Organism types included in the safety assessment SR-PSU.

Terrestrial ecosystem	Marine ecosystem	Limnic ecosystem	Marine and terrestrial ecosystems	Limnic and terrestrial ecosystems
Lichen and bryophytes	Phytoplankton	Phytoplankton	European otter	Black tern
Grasses and herbs	Macroalgae	Microphytobenthos	Ruddy turnstone	
Shrub	Vascular plant	Vascular plant		
Tree	Zooplankton	Zooplankton		
Soil Invertebrate	Polychaete worm	Insect larvae		
Detritivorous invertebrate	Benthic mollusc	Bivalve mollusc		
Flying insects	Crustacean	Gastropod		
Gastropod	Benthic fish	Crustacean		
Amphibian	Pelagic fish	Benthic fish		
Reptile	(Wading) bird	Pelagic fish		
Bird	Mammal	Amphibian		
Bird egg		Bird		
Mammal (small)		Mammal		
Mammal (large)				

7.4 Calculation cases for the biosphere

Radionuclide transport and dose calculations have been undertaken to provide a basis for estimation of radiological risks for various release scenarios assessed in SR-PSU. For each release scenario, at least one calculation case has been identified to provide a basis for estimation of radiological risk. The calculation cases account for systematic variations in chemical and physical processes in the repository (near-field), and the rock (far-field). Other calculation cases illustrate the influence of external factors (e.g. permafrost or earthquakes) on radionuclide transport, and other conceptual uncertainties. The calculation cases identified and analysed in SR-PSU are described in the **SR-PSU Main report** and the **Radionuclide transport report**.

In order to evaluate risk, and to handle uncertainties within scenarios, a number of biosphere calculation cases have been set up. Due to the long time-span of the analysis, different biosphere calculation cases are used to handle uncertainties with respect to the future development of the surface system in the Forsmark area (some more likely than others). However, a number of the main calculation cases are associated with uncertainties only in near-field and geosphere, and a limited number of biosphere calculations cases were found sufficient to cover the surface system corresponding to the main calculation cases. In addition, calculation cases were set up to investigate conceptual uncertainties regarding distribution of radionuclide release in the landscape and biosphere object delineation within the biosphere modelling. The formulation of calculation cases for the biosphere is based on regulatory guidelines and on uncertainties identified both in previous safety assessments and in SR-PSU.

The release location and fate of radionuclides in the biosphere and the choice of exposure pathways are major factors affecting potential doses and dose rates to humans and wild life. Climate may have significant effect on both radionuclide fate and subsequent exposure, and thus climate evolution is an important driver of calculation cases.

Climate affects the release and distribution of radionuclides, ecosystem functioning and exposure pathways. In SR-PSU, four climate cases have been identified: the *global warming*, *early periglacial*, *extended global warming* and *Weichselian glacial cycle climate cases* (see Section 4.2 of the present report, **Climate report**). Of these, the *global warming climate case* and the *early periglacial climate case* are calculation cases used to illustrate likely evolutions of the climate, whereas the *extended global warming climate case* is used to illustrate an even higher effect of global warming than the base case, and the *Weichselian glacial cycle climate case* is used to illustrate effects of fully natural climate variability including glacial conditions. The climate cases cover both warmer and colder climate conditions than at present, since climate can have large effects on transport of radionuclides in the biosphere and possible exposure pathways for humans and non-human biota. Therefore separate biosphere calculation cases were identified for these climate conditions.

The radionuclide release to the biosphere is mainly dependent on factors in the near-field and geosphere, i.e. the location of the release at the geosphere-biosphere interface and the distribution of release among different release locations are mainly dependent on transport in the geosphere (further described in Odén et al. 2014). Nevertheless, the effect on the biosphere can be large and uncertainties in release locations may have a large effect on doses to humans and non-human biota. Therefore, it is of interest to evaluate the effects of alternative release locations and size of release areas for the biosphere.

As described in Section 7.2, an exposure pathway analysis has been performed within SR-PSU, evaluating different possible exposure pathways. Even after identifying possible exposure pathways the doses to humans may differ depending on different diets and habits. It is impossible to predict the habits and diets of future humans. However, by assuming a range of human habits a range of exposure pathways can be identified and parameterised for use as bounding cases to identify possible exposures to humans in the future. Four types of exposed populations are used in the base case, including different exposure pathways from the landscape related to self-sustainable communities (further described in Section 7.2). These exposed populations are combined with the calculation cases as described for each calculation case below.

Analyses of FEPs are important for identifying the main processes to be incorporated into the base case. However, the FEP analysis is detailed and identifies processes at the biosphere object level. Thus, the FEP analysis has not been used to identify calculation cases. Data uncertainties are handled by describing parameters with probability density functions used in probabilistic calculations and for some parameters by choice of cautious parameter values (see Chapter 9).

As radionuclide transport and dose consequences are calculated with a chain of models and the calculation cases for the biosphere are combined with results from the near-field and geosphere it can be difficult to use the resulting dose calculations to evaluate the effect on the biosphere results of different assumptions in the scenarios. This is because the results are also dependent on effects in the other parts of the system. To evaluate the effect of assumptions in the different calculation cases for the biosphere model, dose conversion factors for unit release rate (giving radionuclide-specific landscape dose conversion factor (LDF) values) are estimated for the different calculation cases. The seven identified biosphere calculation cases (BCC) are described below with a focus on the handling in the main calculation chain. However, when there are special assumptions applied for the unit release calculations these are noted in the description below. The calculation cases are summarised in Table 7-4.

7.4.1 Base case – global warming (BCC1)

The global warming calculation case is based on the reference evolution presented in the **SR-PSU Main report**, which describes a reasonable evolution of the repository, the geosphere and the biosphere. The aim of the calculation case is to provide a benchmark for the long-term safety assessment. The biosphere base calculation case (BCC1) handles the fate of radionuclides in the biosphere, and the subsequent exposure and dose calculations, for this calculation case. Similarly to the main calculation case, it is the benchmark for all subsequent biosphere calculation cases.

The evolution of the Forsmark landscape in BCC1 follows that for the *global warming climate case* (Chapter 4), and the climate is assumed to be temperate for the entire modelling period, i.e. from 2000 to 102,000 AD. This is in contrast to the near-field and far-field modelling where the radionuclide transport in near-field and geosphere is halted during the periglacial periods. Periglacial conditions in the biosphere are instead treated in BCC 2 (the talik case). For unit release calculations, the period 2000 to 20,000 AD is simulated, which is approximately the same time period as that used to simulate ecosystems in SAR-08 and SR-Site.

In the *global warming climate case* the annual average air temperature may increase by up to 3.7°C, but will return to present conditions after c. 25,000 years (**Climate report**). Although temperature will increase, the degree of warming and the response in the biosphere is uncertain (see Andersson 2010, Aquilonius 2010 and Löfgren 2010 for further discussion on potential responses to warming by the ecosystems at Forsmark). Therefore, the most reliable data available for temperate conditions, i.e. site data under present conditions, are used for the entire period of this calculation case.

Table 7-4. Biosphere calculation cases. * indicates calculation cases used to study specific conditions in the biosphere or to evaluate uncertainties in the biosphere model and not propagated onward in the dose calculations. "Calculation case driver" shows the main driver affecting the calculation case. "Exposed human population" shows the endpoint for dose to humans where HG = hunter-gatherers, IO = infield-outland farmers, DM = drained-mire farmers, GP = garden-plot households. "NHB" stands for non-human biota. Considered ecosystems for organism exposure show the endpoint for dose rates to biota where M = Marine, F = Freshwater; T = Terrestrial ecosystem. "Biosphere objects" shows the object(s) receiving the initial release. The columns Landscape, Hydrology, and Ecosystem identifies where alternative parameter values to those in BCC1 are used. Note that there are also parameter values (e.g. K_d/CR values and dose coefficients) that are not altered in the different calculation cases. All parameters sets, including the alternative parameters are described in Grolander (2013).

Biosphere calculation case		Calculation case driver	Exposed human population	Considered ecosystem for NHB exposure	Biosphere objects with geosphere release	Landscape	Hydrology	Ecosystem
BCC1	Base case – global warming		HG, IO, DM, GP	M, F, T	157_2	BCC1	BCC1	BCC1
BCC2	Talik	Climate	HG	F, T	157_1[1], 114	BCC1	Cold	Cold
BCC3	Extended global warming	Climate	HG, IO, DM, GP	M, F, T	157_2	Warm	Warm	Warm
BCC4	Submerged conditions	Climate	HG	M	157_2	Glacial	Glacial	Glacial
BCC5	Well [2]	Exposure pathway	GP	–	157_2	BCC1	BCC1	BCC1
BCC6*	Distributed release	Radio-nuclide release and distribution	HG, IO, DM, GP	M, F, T	Distributed release across all biosphere objects	BCC1	BCC1	BCC1
BCC7 *	Alternative object delineation	Radio-nuclide release and distribution	–	–	157_2	BCC1	Alternative biosphere object sizes	BCC1

[1] Biosphere object 157_1 also receives radionuclides from upstream biosphere object 157_2, which received radionuclides from the geosphere during the temperate period prior to the periglacial period.

[2] Well in the well interaction area or into the repository.

Thereby, this calculation case also takes into account the regulations in SSMFS 2008:37 §10 (SSM 2008a) stating that "The description shall include a case based on the assumption that the biospheric conditions prevailing at the time when an application for a licence to construct the repository is submitted will not change". Transport and fate of radionuclides during periods of permafrost are handled with the talik biosphere calculation case (BCC2), and the effects of warmer temperatures on ecosystem structures and process rates are handled in the extended global warming biosphere calculation case (BCC3).

Geosphere-biosphere link

As described in Chapter 6 the majority of release from the repository will reach the biosphere in biosphere object 157_2. Hydrogeological modelling of release locations in the landscape in 17 realisations show that on average more than 80% (and in most cases more than 90%) of the total potential release from the repository parts of SFR would end up in biosphere object 157_2 (Figure 7-3). In this calculation case, the entire release is assumed to occur to the biosphere object 157_2, and thereafter radionuclides are transported to other objects through water exchange or through diffuse groundwater and stream water (see below).

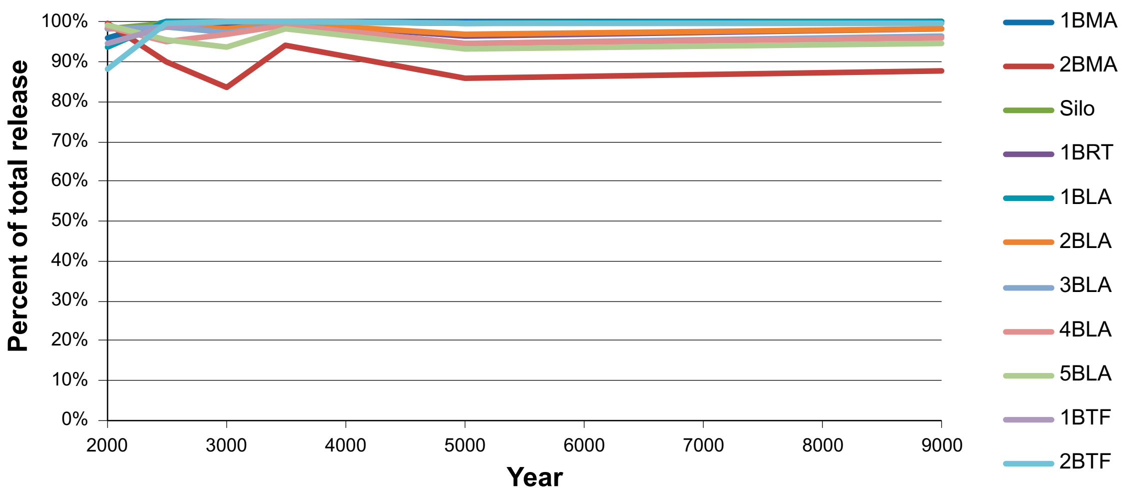


Figure 7-3. *Fractions (%) of total potential release from the repository parts that reach the biosphere in object 157_2 over time, average of 17 hydrogeological realisations.*

Landscape development

Shore level displacement occurs at Forsmark and areas that are presently situated below the sea gradually rise above sea level. Thus, 157_2 that is presently a marine basin will be transformed into a wetland area with time. During the submerged period, radionuclides will reach all basins in direct or indirect contact with basin 157_2, through lateral exchange of water (Figure 7-4). However, during the land period, radionuclides from 157_2 will only reach objects in the surface water chain downstream of object 157_2 (namely 157_1 and 116, Figure 7-5).

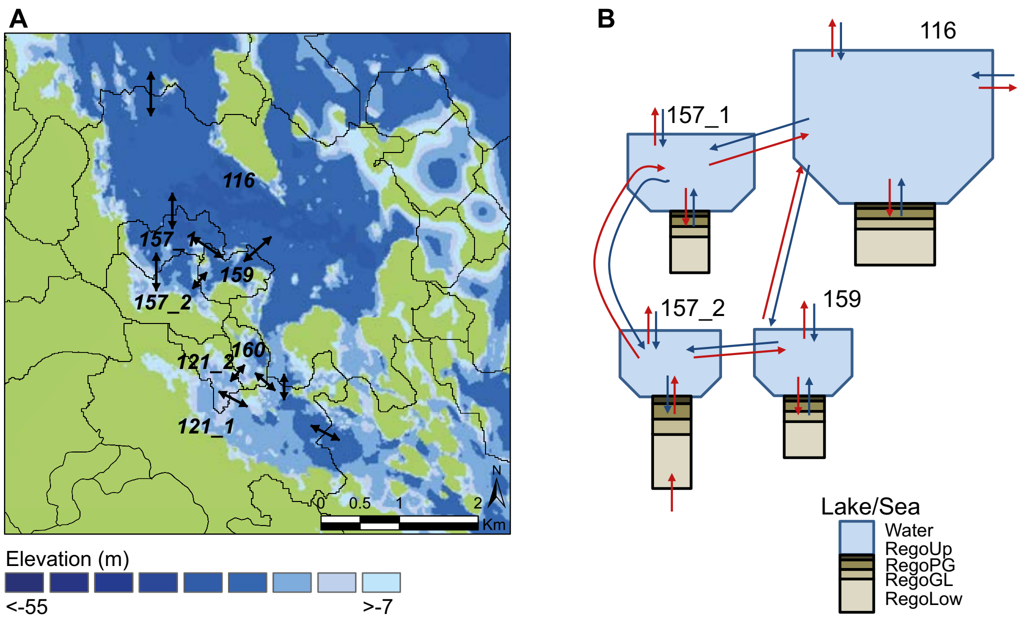


Figure 7-4. *Conceptual model of discharge and dispersion of radionuclides that reach the biosphere via groundwater from the geosphere during the marine stage. A) Water depth and dispersion between basins at 3000 AD. Biosphere object 157_2 receives radionuclide-containing groundwater from below. All biosphere objects downstream of 157_2 receive radionuclides via surface water flow during the marine stage. B) Schematic sketch over the dispersion of radionuclides between regolith layers and surface waters within and between biosphere objects is shown in cross section. Red arrows show dispersion of water containing radionuclides whereas blue arrows show dispersion of water initially without radionuclides. For clearness, not all basins and water flows are shown in figure B.*

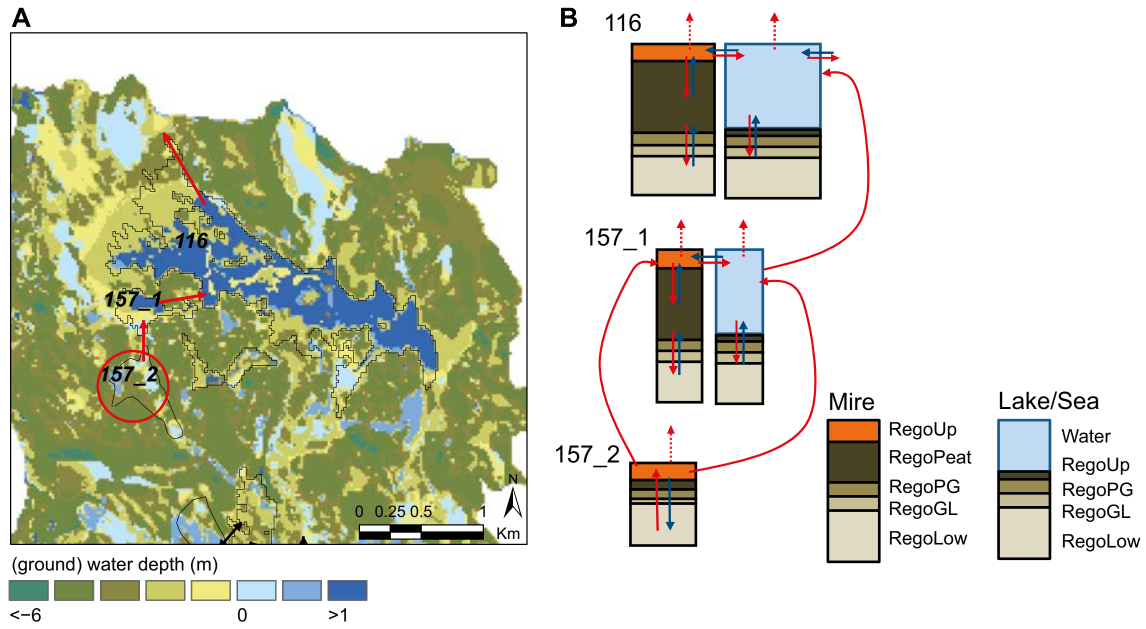


Figure 7-5. *Conceptual model of discharge and dispersion of radionuclides that reach the biosphere via groundwater from the geosphere during the terrestrial stage. A) Ground water depth in terrestrial areas and water depths in lakes at 5000 AD. The biosphere object 157_2 that receives discharge directly is marked with a red circle. Downstream biosphere objects 157_1 and 116 receive radionuclides via surface water during the terrestrial stage. B) Schematic sketch over the dispersion of radionuclides between regolith layers and surface waters within and between biosphere objects is shown in cross section. Red arrows show dispersion of water containing radionuclides whereas blue arrows show dispersion of water initially without radionuclides.*

Thus, in this biosphere calculation case the transport and fate of radionuclides are simultaneously simulated in multiple connected objects, and each of these objects goes through a transition from a marine basin, to a lake/wetland complex or a wetland area without a proper lake. Note that the continuous transport and fate of radionuclides is simulated in a landscape that is undisturbed by human inhabitants. However, once biosphere objects have emerged sufficiently above sea level to prevent saltwater intrusion, the consequences of draining and cultivating the lake-mire complex are also evaluated at each point in time by parallel simulations (conditioned on the state of the natural ecosystems), i.e. both natural and agricultural systems are evaluated at each time step.

Hydrological water fluxes

Hydrological water fluxes were modelled with MIKE SHE for future biosphere objects (areas where releases could occur) at three points in time: 3000 AD (submerged period for all objects), 5000 AD (land period, when objects are either lake-mire complexes or mires) and 11,000 AD (land period, all objects are mires). For each point in time, groundwater hydrology was simulated in a landscape based on a separate (stationary) three-dimensional regolith map, with streams connecting water bodies on land. Present day temperature and site data (with respect to precipitation, evaporation, and runoff) were used in the MIKE SHE simulations. Hydrological modelling and parameter values are further described in Grolander (2013) and Werner et al. (2013a).

Ecosystem parameters

Ecosystem parameters are based on site data from lakes, wetlands and marine basins in the area and applied to future ecosystems assuming present-day conditions concerning nutrients and temperature (parameters are further described in Grolander (2013).

Exposed population

The dose to a representative human is calculated for four different exposed populations, representing bounding cases to cover the highest exposure from different radionuclides: 1) hunter-gatherers (HG),

2) infield-outland farmers (IO), 3) drained-mire farmers (DM), and 4) garden-plot households (GP). The different populations are described further in Section 7.2 and in SKB (2014). IO, DM, and GP are stationary within biosphere objects. HG, on the other hand, are assumed to collect food from several biosphere objects. If the production in the biosphere objects is not enough to provide enough food for the HG community, the remaining food are assumed to be produced outside the biosphere objects, i.e. not containing radionuclides from the repository.

Dose rates to non-human biota are calculated for 11 marine, 13 limnic and 14 terrestrial organism types and 1 organism type living in both limnic and terrestrial ecosystems and 2 types living in both marine and terrestrial systems (combined habitats) (see details in Section 7.3 and SKB 2014). The biosphere object 157_2 has no limnic successional stage (evolves from a marine bay directly into a wetland) but since it cannot be ruled out that small ponds (limnic ecosystems) are present in the object during the early wetland period exposure to limnic species has cautiously been considered for the entire assessment period using the radionuclide concentrations in wetland pore water and peat as further described in Saetre et al. (2013a).

7.4.2 Talik (BCC2)

This calculation case is developed to evaluate doses to humans and dose rates to non-human biota under permafrost conditions. The first period of colder climate that can cause deep permafrost arises at around 17,500 AD and prevails until 20,500 AD in the *early periglacial climate case* (**Climate report**). At this time all of the model area is above the shoreline, and the regolith layers of the Forsmark landscape will be frozen. Therefore, discharge of deep ground water will be restricted to areas on top of unfrozen land areas, so-called discharge taliks. Taliks are typically formed below lakes but with shallow permafrost depths they might also form below other low points in the landscape such as wetlands (Werner et al. 2013a).

The evolution of the Forsmark landscape in BCC2 follows that for the *early periglacial climate case* (Chapter 4), and the climate is assumed to be alternating between temperate and periglacial (see the **Climate report** and Section 4-2 in present report). This calculation case is simulated for the period 2000–20,500 AD, with the periglacial period between 17,500 and 20,500 AD. The initial period up to 17,500 is used to achieve correct initial conditions for the permafrost period, but only the doses for the periglacial period 17,500 and 20,500 are used (the initial doses are the same as in the global warming calculation case). Also for unit release calculations, the period 2000 to 20,500 AD are simulated and results for the period 17,500 to 20,500 were used to evaluate results. The same biosphere model and parameter values as in BCC1 was used for BCC2, but altered parameter values and biosphere objects were applied for the periglacial period (17,500 to 20,500 AD) in BCC2. Up to 17,500 BCC2 is modelled identically to BCC1.

Geosphere-biosphere link

Up to the periglacial period at 17,500 AD, discharge is assumed to reach biosphere object 157_2 as in BCC1. Results from bedrock hydrogeology modelling suggest that groundwater from the extended repository may be discharged to wetlands northeast of the present repository, and to large lakes formed in Öregrundsgrepen (Odén et al. 2014). Simulations of surface hydrology under permafrost conditions suggest that a discharge talik may be formed under a small wetland area in 157_1 (just north of the primary release area during periods of temperate conditions). Moreover, the deep lake 114, located in Öregrundsgrepen, will still be open, and is thus likely to be connected with a discharge talik (Bosson et al. 2013, Werner et al. 2013a). In this calculation case, the entire release between 17,500 and 20,500 AD is either directed to object 157_1 or to object 114.

Landscape development

At 17,500 AD (the time of the first permafrost episode) the effects of isostatic rebound are insignificant for the model area, and ecosystem succession due to infilling of lakes is very slow during periglacial conditions (Brydsten and Strömgren 2010). Thus, effects of land uplift and ecosystem succession are not considered for the permafrost period in this calculation case.

Hydrological water fluxes

Hydrological water fluxes for colder and dryer conditions were modelled with MIKE SHE (data from the **Climate report**) for both wetlands and lake taliks based on talik modelling in SR-Site. The hydrological modelling of taliks is further described in Werner et al. (2013a) and parameters are presented in Grolander (2013).

Ecosystem parameters

Ecosystem parameters on primary production, production of edible fish and crayfish were altered to better reflect permafrost conditions based on literature data from colder environments. Parameter changes are further described in Grolander (2013).

Exposed population

During periglacial climate conditions, cultivation is not possible due to permafrost, and wells will not yield any water from the frozen ground. Thus, in the talik calculation case the exposed population are hunters and gatherers (HG) foraging in the Forsmark landscape. HG are assumed to collect food from a large area and can thereby utilise several biosphere objects at the same time. For the calculation case where the release is directed to 157_1 during permafrost period, HG are calculated to utilise biosphere object 157_1, downstream 116, and 157_2 (that has received radionuclide release during the initial temperate 17,500 years). In the calculation where the release is directed to 114, the only biosphere object calculated to contribute to dose is 114. For non-human biota, exposure is estimated to freshwater and terrestrial organisms. The same organisms as in BCC1 were assessed with the exception that no limnic amphibians or mammals, and no terrestrial trees, gastropods, amphibians or reptiles are assumed to occur (see Sections 4.5.3, 4.6.3, and 4.7.3 in this report, and Jaeschke et al. 2013).

7.4.3 Extended global warming (BCC3)

The extended global warming calculation case is developed to evaluate the effects of warmer and wetter climate on repository safety (**SR-PSU Main report**). In the *extended global warming climate case*, temperatures may increase by c. 6°C and it may take 50,000 years before temperatures returns to present day values (**Climate report**). BCC3 handles the fate of radionuclides in the biosphere, and the subsequent exposure and dose calculations, for this calculation case. To fully investigate the effect of warmer and wetter climate in the biosphere, parameter values for increased temperatures were applied for the entire modelling period from 2000 to 102,000 AD. For the unit release rate calculations, the model is run from 2000 to 20,000 AD.

Geosphere-biosphere link

The transport pathways in the near and far-field are not expected to be affected by the surface climate. Thus, the entire release is assumed to occur in the biosphere object 157_2, as in BCC1.

Landscape development

In the *extended global warming climate case*, the maximum contributions to sea level rise in the Forsmark region from various processes are added, pessimistically and unrealistically assuming that they all occur within the next millennium. It would take c 1,200 years for the isostatic uplift in Forsmark, to compensate for the resulting sea level rise of c 10 m (see Sections 3.3.4 and 4.3.3 in the **Climate report**). The evolution of the sea level rise during this period is uncertain and periods of a sea transgression cannot be excluded. However, in this calculation case, the shore level at Forsmark is assumed to be at about the same location as at present after c. 1,000 years (which is the closest time step to 1,200 years for the marine basins in the landscape model, where marine basins are modelled in 500-year time steps). Thereafter, shoreline displacement is assumed to be identical to BCC1, i.e. the shore level will reach present conditions in the year 3000 AD and the landscape development is delayed 1,000 years compared with BCC1.

Hydrological water fluxes

Water balances for the biosphere objects were modelled with MIKE SHE using information on increased temperature and wetter conditions from the **Climate report**. The modelling and resulting parameter values are presented in Grolander (2013) and Werner et al. (2013a).

Ecosystem parameters

Ecosystem parameter values such as primary production and concentration of carbon in the atmosphere are altered due to increased temperature based on literature data from warmer locations. Parameter changes are further described in Grolander (2013).

Exposed population

The exposed populations of humans and non-human biota are identical to BCC1.

7.4.4 Submerged conditions (BCC4)

This biosphere calculation case is developed to examine the effects of an extended period of marine conditions. Extended submerged conditions at the site could occur after a glaciation, similar to the situation after the ending of the last (Weichselian) glaciation –9400 AD. In the glacial calculation case, a period with 8,000 years of submerged conditions is modelled between 68,200 and 76,200 AD, after which temperate conditions are modelled for the remaining part of the assessment period up to 102,000 AD (as further described in the **SR-PSU Main report**). For the unit release calculations, BCC4 is run only for the submerged period after the Weichselian glaciation up to present conditions, i.e. from 68,200 to 79,600 AD (corresponding to –9400 to 2000 AD in the landscape evolution).

Geosphere-biosphere link

The transport pathways is not expected to be affected by altered climate in the surface systems and the entire release is assumed to occur in biosphere object 157_2 as in BCC1 (see above).

Landscape development

During glacial periods, the bedrock is depressed due to the ice sheet load. The landscape development, under the *Weichselian glacial cycle climate case*, describes the effects of the isostatic rebound for a full interglacial period, including the submerged conditions expected directly after the glacial retreat. In the glacial calculation case, the situation after the first glacial period in the Weichselian cycle is envisaged, corresponding to the year –5000 AD. In the unit release calculations, it has been assumed that the sea level after a glacial period is identical to the sea level at the end of the last glaciation, i.e. at –9400 AD. This is to make the LDFs comparable to those from earlier safety assessments. Geometries of the marine basins are modelled from –8500 AD and these parameters are used also for the period between –9400 AD and –8500 AD. The landscape development is thereafter assumed to follow the development in the *Weichselian glacial cycle climate case*.

Hydrological parameters

Hydrological parameter values for marine basins are modelled from –6500 AD and forward. The values for –6500 are used from the period from –9400AD up to –6500 AD. The hydrological parameter values are described in Grolander (2013).

Ecosystem parameters

Marine ecosystem parameters specific for the period from –9400 to 2000 AD are biomass and production of aquatic primary producers, which are dependent on water depth and thereby change over time. The ecosystem parameters are described in Grolander (2013).

Exposed populations

The exposed populations of humans and non-human biota are identical to BCC1 with the exception that hunter-gatherers (HG) are assumed to forage only within biosphere objects (i.e. not utilising several object simultaneously). The unit release calculations only consider exposure to HG and marine organisms since only marine ecosystems are present during the time period simulated.

7.4.5 Well in the well interaction area or into the repository (BCC5)

The safety of the repository with respect to exposure from a geological well drilled in the rock in the well interaction area, or drilled direct into the repository, is evaluated with the two calculation cases "wells downstream of the repository" and "intrusion wells". The biosphere calculation case BCC5 is combined with these calculation cases and is developed to evaluate the dose to humans when utilisation of well water for drinking and irrigation is the major exposure pathway. Note that this biosphere calculation case does not consider any exposure from radionuclides directly discharged into the biosphere. The same model assumptions for irrigation used for the garden-plot households in the base case were used for modelling the irrigation with water from the intrusion well and the well in the well interaction area in BCC5. Irrigation of the garden plot is assumed for a life time of 50 years and an integrated dose is used as mean dose for this calculation case. The model is further described in Saetre et al. (2013a).

Geosphere-biosphere link

In this biosphere calculation case, the extraction of water directly from the geosphere or from the repository is the link between the geosphere and the biosphere. For the "wells downstream of the repository" calculation case, particle tracking at the 80–10 m depth interval in the geosphere was used to delineate a volume in the bedrock downstream of the repository with a high density of particles originating from the repository. The well interaction volume represents transport pathways from all repository parts, and its projection onto the surface (well interaction area) that may be intersected by a well is 0.26 km^2. The radionuclide concentration in well water is calculated based on hydrogeological particle tracking of particles originating from the repository in combination with extracted water volume from wells. For further descriptions of the well interaction area, particle tracking and water extraction from wells, see Werner et al. (2013a).

Landscape development

The landscape development is identical to BCC1. The wells are assumed to be drilled when the well interaction area is situated more than 1 m above sea level (to enable good enough water quality). The well into the repository is assumed to be drilled at the earliest at 3000 AD when the entire repository footprint is situated above sea level.

Hydrological water fluxes

No hydrological water fluxes from deeper regolith layers are used for the garden-plot households, which is the only evaluated group for this calculation case (see below). Instead the water for the crop in the garden plot is provided by irrigation. For the runoff from the garden plot, the same parameter values as in BCC1 are used.

Ecosystem parameters

Ecosystem parameter values describing the garden-plot households are used in this biosphere calculation case, and the parameters used are identical to BCC1.

Exposed population

Exposure from a single drilled well is assumed to affect a limited number of individuals. Thus, a small scale garden-plot household was deemed appropriate in this biosphere calculation case.

7.4.6 Distributed release (BCC6)

The calculation BCC6 is developed to examine uncertainties in the distribution of the radionuclide release in the landscape. The calculation case is only investigated with unit release rate and compared against the base case. In the base case, the entire release is assumed to occur in biosphere object 157_2 (see BCC1 above). In this calculation case, the release is assumed to be distributed in the landscape. BCC6 handles the fate of radionuclides in the biosphere, and the subsequent exposure and dose calculations. The period 2000 to 20,000 AD is simulated.

Geosphere-biosphere link

The general assumption used in the biosphere assessment is that exfiltration of radionuclides from the geosphere takes place only in biosphere object 157_2, so this object receives the total release of radionuclides from the repository. However, according to the hydrological modelling, a small fraction of the release reaches other biosphere objects. In order to investigate the impact of the uncertainty in the allocation of release points, a unit release simulation for the repository part with largest spatial distribution (2BMA) was performed. The release was distributed over the biosphere objects, with its distribution changing in time according to Table 7-5, which is based on the forward particle tracking performed in Odén et al. (2014). This was the worst case (i.e. the highest proportion of the discharge) across 17 hydrogeological realisations for each object and point in time, and the approach is deliberately cautious as the sum of the release across all biosphere objects was always greater than the total release. As evident below, the major part of the release was still allocated in object 157_2, but significant fractions of release were also directed to other objects, particularly to the objects 121_2, 121_1 and 159. The simulations were performed for the four selected radionuclides C-14, Cl-36, Mo-93 and Ni-59.

Landscape development

The landscape modelling is identical to BCC1.

Hydrological parameters

Hydrological parameters are identical to BCC1.

Ecosystem parameters

Ecosystem parameter values are identical to BCC1.

Exposed populations

The exposed populations for humans and non-human biota are identical to BCC1 with the exception that hunters and gatherers only forage within biosphere objects (i.e. not utilising several biosphere objects simultaneously). Results are presented as dose factors for unit release

Table 7-5. Distribution of maximum proportions of radionuclide releases (in % of total potential release from 2BMA) between the different biosphere objects in the 17 performed hydrological simulations.

Time (AD)	157_2	159	157_1	116	121_2	160	121_1
2000	100.0	0.0	0.0	0.1	0.3	0.0	0.0
2500	97.4	0.0	0.0	0.0	22.4	0.0	0.1
3000	97.7	0.2	0.6	0.0	12.8	1.8	23.7
3500	99.1	2.7	6.6	1.4	10.0	3.3	0.0
5000	94.6	15.5	9.4	3.5	7.2	1.8	0.0
9000	95.8	13.2	10.2	1.7	8.4	0.4	0.0

7.4.7 Alternative object delineation (BCC7)

This calculation case is developed to investigate uncertainties in delineation of biosphere objects. The calculation case is only investigated with unit release rate and compared against the other biosphere calculation cases. The simulated period is 2000 to 20,000 AD. The concentrations of radionuclides in environmental media obtained with the initial delineation of biosphere object 157_2 in BCC 1 are compared to the concentrations obtained with alternative delineations. The methodology used to delineate biosphere objects in the base case was based upon knowledge of the ecosystems and processes affecting fluxes and distribution of elements in these. Nevertheless, the effects of alternative delineations of biosphere objects were assessed for four alternative delineations, summarised below (the delineations are more thoroughly described in Chapter 6).

1. *Areas with upward hydraulic gradients.* The biosphere object is defined based upon discharge areas at the geosphere/biosphere interface.
2. *Wetland areas*. In this delineation, it was assumed that all radionuclides are released to the area of the object that has wetland properties.
3. *Main area for discharge points*. In the delineation based on discharge points from DarcyTools it is assumed that all radionuclides are released only to the area with the highest density of discharge points.
4. *Potential arable land*. In the landscape developmental model (LDM) a future landscape is described in which most of the potential arable land is used (Chapter 5). Here, the fraction of 157_2 with regolith most likely to be used as arable land is defined as the biosphere object.

Geosphere-biosphere link

The release from the geosphere is considered to reach only a part of the original biosphere object 157_2 (see above).

Landscape development

The landscape development is identical to that in BCC1.

Hydrological water fluxes

Water balances for all alternative object delineations were modelled with MIKE SHE and model parameters were derived for these objects (Werner et al. 2013a, Grolander et al. 2013).

Ecosystem parameters

Regolith depths were derived for the alternative object delineations, and deep peat mineralization rates were adjusted for the potential peat depth in the different areas (Grolander et al. 2013). All other parameters were identical to BCC1.

Exposed population

The results are evaluated in terms of radionuclide concentrations in environmental media only, and exposure of humans or non-human biota is not considered for this calculation case.

8 The radionuclide model for the biosphere

This chapter provides a description of the radionuclide model for the biosphere, i.e. the model that was used for the calculations of radionuclide transport and doses to humans and dose rates to non-human biota in the surface and near-surface parts of the considered system. The present description is a summary of the background report "The biosphere model for radionuclide transport and dose assessment in SR-PSU" (Saetre et al. 2013a), to which the reader is referred for detailed presentations of approaches, assumptions and models.

Note that this chapter is focused on the model itself and information directly related to the model and its development, whereas other aspects of the biosphere modelling that are discussed in Saetre et al. (2013a) are covered elsewhere in the present report. In particular, descriptions of processes, exposure pathways and land use variants are given in Chapter 7 and the overall assessment context is outlined in Chapter 2. Furthermore, it should also be observed that this chapter considers the biosphere part of the radionuclide model; descriptions of the models for the repository and its barriers, and the bedrock are given in the **Radionuclide transport report.**

8.1 Background

A safety assessment of a geological repository for nuclear waste should demonstrate that the repository remains safe for humans and the environment over a time period ranging from several thousand to one hundred thousand years into the future. Therefore, a model used in such a safety assessment needs to describe the consequences of a potential release of radionuclides to surface ecosystems in the far future, by which time the landscape will have undergone considerable changes.

Given the requirements of the safety assessment and the features of the potentially impacted environments, the radionuclide model of the biosphere should be capable of

1. incorporating temporal changes in ecosystems driven by, primarily, shoreline displacement, ecosystem succession and/or climate change,
2. handling time-dependent releases of radionuclides with groundwater discharges and their distribution in a heterogeneous landscape,
3. handling transport, accumulation and decay of radionuclides (including in-growth of progeny radionuclides) with different geochemical behaviour,
4. accounting for transport of radionuclides between different areas of the landscape (driven by advection or surface runoff, for example), and
5. assessing exposures of humans and non-human biota to radionuclides.

In the previous safety assessment of the final repository for spent nuclear fuel (SKB 2011), we developed a model that simulated the fate of radionuclides in the potentially affected Forsmark landscape (Avila et al. 2010, 2013). That model had the above-mentioned capabilities, and thus handled radionuclide inventories and transport processes within a transforming landscape. The model was applied to multiple areas of the landscape where radionuclides could be released, either through groundwater discharge or from contaminated surface water. It simulated transport and accumulation of radionuclides in two linked ecosystems (i.e. an aquatic and a mire ecosystem), and the transitions between ecosystems (i.e. lake isolation and lake ingrowth) were handled in a continuous manner.

The model presented in this report is in essence similar to the one used in the previous SR-Site assessment. However, due to the expected exposure from radiocarbon (C-14), the model has been developed in several ways to better capture the fate of radiocarbon, hopefully resulting in more complete estimates of activity concentrations in air, soil and water. Moreover, the most exposed groups have been defined to explicitly reflect the behaviour of self-sustained historical and present communities (see Chapter 7) and the calculations of dose rates to non-human biota, previously carried out in the ERICA Tool, have been included in the model code.

8.2 Overview and structure of the transport model

The mathematical approach used in the radionuclide model of the biosphere is that of compartment modelling. This approach has been described in detail in Saetre et al. (2013a) and the references cited there. It assumes that a system can be sufficiently represented by a finite number of compartments or pools, each of which is homogeneous and connected to other compartments. Discharge of radionuclides into the biosphere is assessed over thousands of years. The contaminated area is considered at the scale of a coastal basin, a lake mire complex, or an agricultural field, and dose is calculated over the life-time of future inhabitants. At these scales, it is assumed that most biogeochemical interactions can be approximated by equilibrium or steady-state conditions (see Saetre et al. (2013a) and Tröjbom et al. (2013) for discussions on this assumption). Thus ecosystem states are represented by average conditions, and fluxes of water, solid matter and gas are described as functions of aggregated empirical parameters, which are assumed to capture the outcome of the underlying processes.

In the SR-PSU assessment scenarios, radionuclides released from SFR may enter the surface system through deep groundwater discharge and then reach soil, water and air. Two types of ecosystems are simulated in SR-PSU, namely aquatic ecosystems (sea, lake and stream ecosystems), and terrestrial ecosystems (mire ecosystems, and agricultural ecosystems). In the compartment (or mass balance) models used in the transport and dose calculations, each compartment represents a radionuclide inventory associated with a physical (or biological) component in the surface ecosystems. The dynamic change of each compartment is the result of one or more radionuclide fluxes, associated with mass fluxes of water, solids (including organic matter) or gas, with the transition between inorganic and organic forms, or with diffusion.

As the endpoints of the radionuclide transport model are the concentrations of radionuclides in environmental surface media in contaminated areas, the identification areas reached by radionuclides (i.e. biosphere objects) is a prerequisite for the modelling. The transport and distribution of radionuclides in the landscape are represented by linking biosphere objects via surface water fluxes. Parameters describing the properties of biosphere objects (and their changes in time) and the configuration of contaminated areas in the landscape, were derived using information from extensive site investigations and modelling of the development of the Forsmark area (Chapters 4 and 5). The final step in the biosphere modelling is then to calculate doses and dose rates to humans and non-human biota that are exposed to environmental contaminants. These calculations are based on the environmental concentrations simulated with the transport model and exposure pathways identified as relevant for the SR-PSU safety assessment (Chapter 7).

The following Section 8.3 describes the physical compartments and the radionuclide fluxes that were used to simulate transport and accumulation of radionuclides in surface ecosystems. A graphical representation of the compartments and radionuclide fluxes identified for a coupled lake and mire ecosystem is presented in Figure 8-1. The details, including the mathematical description of the radionuclide transport model, are given in the background report Saetre et al. (2013a), where the presentation is divided into sections describing natural aquatic and mire ecosystems, and agricultural ecosystems. The advective transport by groundwater and surface water is an important part of the transport model, and therefore the application of flow modelling results is summarised in Section 8.4.2 below. In the final section of this chapter (Section 8.5), the methods for dose and dose rate calculations used in the SR-PSU safety assessment are presented.

8.3 Model compartments

The conceptual ecosystem models presented for marine, freshwater and terrestrial ecosystems (Aquilonius 2010, Andersson 2010, Löfgren 2010), the description of the Forsmark landscape and its development (Lindborg 2010, Lindborg et al. 2013, Chapter 5 of this report), and the biosphere components identified to be important in safety assessments for radioactive waste disposal by SKB (SKB 2011, SKB 2013b), together served as the starting point for the selection of model compartments in the radionuclide transport model and its ecosystem sub-models. Based on the previous safety assessment of the existing SFR 1, C-14 was expected to be the major dose-contributing radionuclide (e.g. SKB 2008b). Thus, special attention was given to potential storage and subsequent release of C-14 in the identification of model compartments.

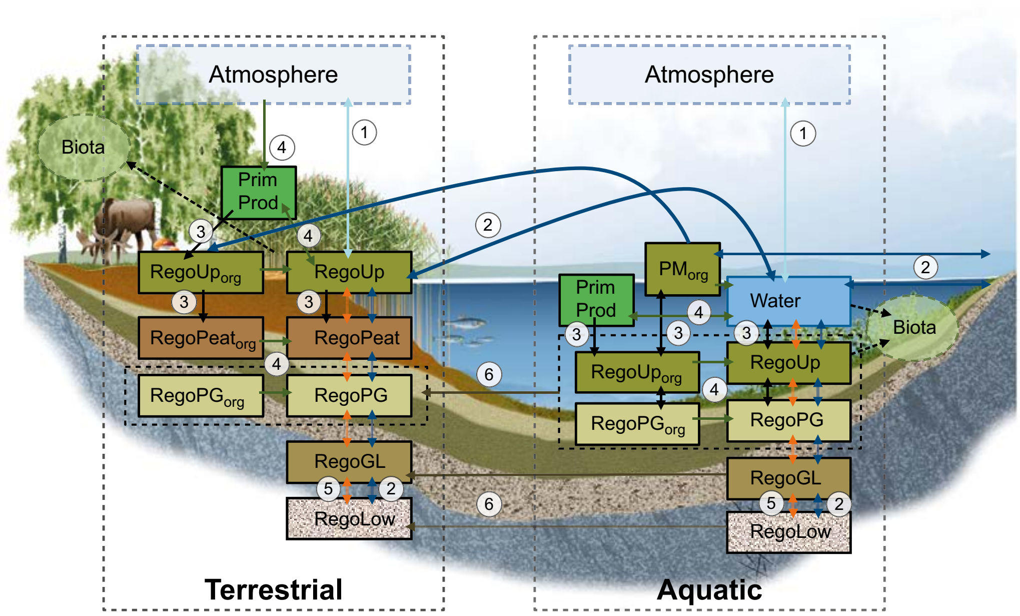


Figure 8-1. *A graphical representation of the radionuclide transport model used to simulate transport and accumulation in a discharge area with two natural ecosystems, the terrestrial and aquatic system (each delimited by thin dotted black lines). Each box in the two ecosystems corresponds to a radionuclide inventory associated with a physical compartment. Arrows represent radionuclide fluxes between compartments and fluxes into and out of the system. Radionuclide fluxes are linked to mass fluxes of gas (1, light blue), water (2, dark blue) and solid matter (3, black), to transitions between inorganic and organic forms of radionuclides (4, green), to diffusion in soil pore water (5, red), and to ingrowth of wetland vegetation (6). The atmosphere serves as a source and sink of radionuclides.*

In practice, we interpreted general biosphere components (SKB 2013b) in the context of potentially contaminated ecosystems in the Forsmark landscape (Chapter 5). Moreover, we aimed for compartments that were meaningful and homogeneous units with respect to the physical, chemical and biological properties influencing radionuclide transport and accumulation. The initial analysis frequently resulted in a split of highly aggregated biosphere components (e.g. the regolith component was split into several compartments representing different geological deposits, and their inorganic and organic fractions). On the other hand, components that were considered to have small or insignificant radionuclide inventories were not included as dynamic compartments (e.g. consumers). Compartments with a fast turnover of radionuclides, (e.g. liquid phase), were in many cases combined with compartments having slower dynamics (e.g. solid phase), assuming that equilibrium would be approached within each time step of the simulation.

8.3.1 Aquatic ecosystems

SKB recognises two major types of aquatic ecosystems: marine ecosystems (Aquilonius 2010) and limnic ecosystems (Andersson 2010). For the purpose of the present biosphere assessment, these two systems have been regarded as structurally and functionally similar, and consequently a common set of physical compartments for all aquatic ecosystems was identified in Saetre et al. (2013a). Based on Saetre et al. (2013a) and the references therein (especially Andersson 2010, Aquilonius 2010, SKB 2013b), the main considerations and assumptions underlying the modelling of aquatic ecosystems at Forsmark are summarised as follows. The model compartments mentioned below are listed in Table 8-1 and illustrated in Figure 8-1.

All aquatic organism compartments identified in SKB (2013b) were considered to have fast dynamics, and pools in consumers were considered small in relation to pools in sediment and water. Consequently, filter feeders, herbivores, carnivores and decomposers were not included as dynamic model compartments. For a few elements, e.g. Mn in the sea (Aquilonius 2010), the inventory in primary producers made up a substantial fraction of that in water. Primary production is also the main source of organic carbon (and C-14) in sediments, and thus we found it appropriate to include aquatic primary producers (PrimProd, cf. Figure 8-1) as an explicit model compartment.

Table 8-1. Brief description of compartments representing radionuclide inventories in the radionuclide transport model for the biosphere (see also Figure 8-1); note that the PM_{org} compartment is also referred to as $Water_{org}$ in the technical model description (Saetre et al. 2013a).

Model compartment	Description
Aquatic	
Water	Radionuclides in open water of sea basins, lakes and streams, including radionuclides solved in water and adsorbed to particular matter.
PM_{org}	Radionuclides stored in organic particulate matter suspended in the water column.
Prim Prod	Radionuclides stored in aquatic primary producers, including radionuclides in pelagic, microbenthic and macrobenthic primary producers.
RegoUp	Radionuclides in the upper oxic and biological active layer of aquatic sediments, including radionuclides in pore water and adsorbed on sediment particles.
$RegoUp_{org}$	Radionuclides incorporated into organic particulate matter in the upper aerobic and biological active layer of aquatic sediments.
RegoPG	Radionuclides in post-glacial aquatic sediments (clay gyttja) below the biological active layer, including radionuclides in pore water and adsorbed on sediment particles.
$RegoPG_{org}$	Radionuclides incorporated into organic particulate matter in post-glacial aquatic sediments (clay gyttja) below the biological active layer.
RegoGL	Radionuclides in glacial clay (typically overlaid by post-glacial deposits), including radionuclides in pore water and adsorbed on sediment particles.
RegoLow	Radionuclides in till (typically overlaid by glacial clay), including radionuclides in pore water and adsorbed on sediment particles.
Terrestrial (mire)	
PrimProd	Radionuclides stored in mire vegetation biomass, including both above and below ground biomass of bryophytes, vascular plants, dwarf shrubs and trees.
RegoUp	Radionuclides in the upper oxic and biological active layer of wetland peat (acrotelm peat), including radionuclides in pore water and adsorbed on peat.
$RegoUp_{org}$	Radionuclides incorporated into organic matter in the upper aerobic and biological active layer of peat (acrotelm peat).
RegoPeat	Radionuclides in deep, permanently anoxic, wetland peat (catotelm peat), including radionuclides in pore water and adsorbed on peat.
$RegoPeat_{org}$	Radionuclides incorporated into organic matter in the deep, permanently anoxic wetland peat (catotelm peat).
RegoPG	Radionuclides in post-glacial sediments (clay gyttja) overlaid by wetland peat, including radionuclides in pore water and adsorbed on sediment particles.
$RegoPG_{org}$	Radionuclides incorporated into particulate organic matter in post-glacial sediments (clay gyttja) overlaid by wetland peat.
RegoGL	Radionuclides in glacial clay buried under wetland peat and typically overlaid by post-glacial deposits. Inventory includes radionuclides in pore water and adsorbed on sediment particles.
RegoLow	Radionuclides in till, buried under wetland peat and typically overlaid by glacial clay. Inventory includes radionuclides in pore water and adsorbed on sediment particles.

To represent the radionuclide fluxes associated with sedimentation, radionuclide concentrations on suspended particulate matter are needed. Due to the temporal resolution of the model, it is considered reasonable to represent dissolved and adsorbed radionuclides with one compartment (Water), partitioning radionuclides within the inventory by assuming equilibrium. However, the radionuclide concentrations in refractory particulate organic matter are not necessarily in equilibrium with those in surface water. Therefore, a compartment representing radionuclides stored in particulate organic matter in the water column was added as a model compartment (PM_{org}).

For the modelling of radiocarbon (C-14), one compartment was not sufficient to represent storage (and subsequent release) of radionuclides in aquatic sediments. Compartments representing radionuclides stored in organic matter were identified as essential to describe the accumulation in aquatic sediments. The storage of carbon in sediments is a function of organic matter input and mineralisation. Mineralisation rates are highly dependent on oxygen, and in oxygen-depleted environments even decomposable (labile) organic matter will accumulate. This implied a need for a vertical stratification of the aquatic sediments into oxygenated top sediments and oxygen-depleted deep sediments. It was assumed that radionuclides in pore water are in equilibrium with radionuclides adsorbed on solids, and the two components (Regolith and Water in regolith) were described with one compartment and an equilibrium partition coefficient (K_d).

The oxygenated top sediments were represented by two compartments, one representing radionuclides adsorbed on solids/dissolved in pore water (RegoUp), and one representing radionuclides in organic matter ($RegoUp_{org}$). The sum of these two inventories reflects radionuclides in the biologically active aquatic sediment, wherein fauna can be exposed to ionising radiation.

Below the oxygenated layer, decomposition rates slow down and organic matter builds up in aquatic sediments. These regolith layers are recognised as marine or lacustrine gyttja, and the build-up of these sediments in Forsmark started after the last glaciation (i.e. they are post-glacial sediments). As with the oxygenated layer (see above), radionuclides stored in post-glacial sediments are represented with two compartments, i.e. one that represents radionuclides adsorbed on solids/dissolved in pore water (RegoPG) and one that represents radionuclides in organic matter ($RegoPG_{org}$).

The older sediments buried under post-glacial gyttja are depleted of organic matter and the amounts of radionuclides stored in organic matter in these layers were considered quantitatively insignificant. Older deposits at the site consist primarily of two classes, till and glacial clay. The ontogeny and physical properties are different for these two geological layers, and thus minerogenic old sediments were split into two compartments, glacial clay (RegoGL) and till (RegoLow). Both compartments represent radionuclides adsorbed on solids and radionuclides dissolved in pore water.

The last physical biosphere component identified in SKB (2013b) is the atmosphere. As part of the SR-PSU safety assessment, SKB has developed a new conceptual and numerical model of the atmosphere, which allows a separation between near-surface and higher layers (Saetre et al. 2013a). However, the dynamics in the atmosphere are fast (hours) compared to the dynamics in water (weeks/months) and regolith (years or more), and the exchanges with the upper atmospheric layers are much faster than the exchanges with surface water. Thus, the atmosphere was treated as a sink (or source) in the radionuclide transport model, and the concentrations of volatile radionuclides were calculated using a steady-state solution.

8.3.2 Terrestrial ecosystems

SKB recognises two major types of terrestrial ecosystems that are likely to be affected by radionuclides from a geological repository, namely mire ecosystems and agricultural ecosystems (Löfgren 2010). SKB has identified several biosphere components that should be considered in a safety assessment of a geological repository (SKB 2013b). Considerations and assumptions related to the modelling of the terrestrial ecosystems at Forsmark are summarised in the following. The main underlying references given in Saetre et al. (2013a) are the SR-Site terrestrial ecosystems (Löfgren 2010) and landscape modelling (Lindborg 2010) reports. Model compartments are illustrated in Figure 8-1 and Figure 8-2.

Site and literature data indicate that simulated dynamics and concentrations of radionuclide inventories in regolith layers are not likely to be affected by inclusion or exclusion of organism compartments, and consequently terrestrial herbivores (incl. humans and livestock), carnivores (incl. humans) and decomposers were not included as model compartments in the radionuclide transport model. For a few elements (e.g. non-metals like Br and Cl) the inventory in terrestrial primary producers makes up a substantial fraction of that in soils in natural terrestrial ecosystems (Löfgren 2010). Primary production is also the main source of organic carbon in wetland peat, and thus it was found appropriate to include terrestrial primary producers (PrimProd) as an explicit model compartment in the sub-model of the mire ecosystem.

With the modelling of radiocarbon (C-14) in mind, we identified a need for separate compartments reflecting storage (and release) of radionuclides in organic matter. The accumulation of carbon in peat is a function of organic matter input and mineralisation. Mire peat has strong vertical gradients with respect to oxygen content, hydraulic conductivity and organic matter quality, and thus a need for separate compartments in an oxygenated top layer and an oxygen-depleted deep layer of peat was identified. Radionuclides in pore water and radionuclides adsorbed on solids were assumed to be in equilibrium, and the two inventories were described with one compartment and an equilibrium partition coefficient (K_d).

The oxygenated surface peat was modelled using two compartments, one representing radionuclides adsorbed on solids/dissolved in pore water (RegoUp), and one representing radionuclides in organic matter ($RegoUp_{org}$). The sum of these two inventories reflects radionuclides in the biologically active peat, where roots take up elements and wetland-dwelling organisms can be exposed to ionising radiation. Below the oxygenated layer, decomposition rates slow down and organic matter accumulates in peat that may grow to several metres thickness below the groundwater table, given sufficient time. Also the radionuclides in deep peat are modelled with two compartments, one for radionuclides adsorbed on solids/dissolved in pore water (RegoPeat), and one for those in organic matter ($RegoPeat_{org}$).

Peat in terrestrial wetlands is formed on top of layers that were formed when the discharge area was covered by water (i.e. when the area was a sea basin or a lake). In order not to neglect radionuclides that have accumulated in earlier successional stages or those accumulated during transport through these layers, we recognised the need for representing radionuclides stored in organic matter of marine and lacustrine sediments ($RegoPG_{org}$) and radionuclides adsorbed on solids/dissolved in pore water of the same layer (RegoPG), and the underlying minerogenic layers of glacial clay (RegoGL) and till (RegoLow).

Agricultural ecosystems are simulated in order to calculate the potential exposure of future human inhabitants. Discharge of deep groundwater is unlikely to cause long-term accumulation of radionuclides in agricultural ecosystem developed from draining former mires or lakes, as organic soils cannot be sustainably cultivated for long periods of time (Lindborg 2010, Lindborg et al. 2013).

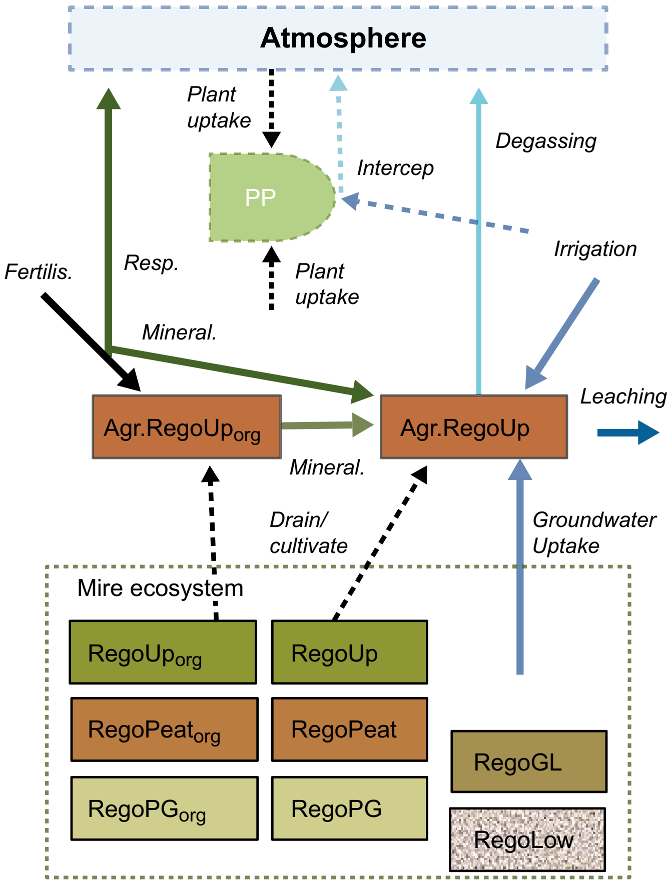


Figure 8-2. *A graphical representation of the radionuclide transport model used for agricultural ecosystems. Each box corresponds to a radionuclide inventory associated with a physical compartment. Solid arrows represent radionuclide fluxes between compartments and fluxes into and out of the system. Radionuclide fluxes are linked to diffusion of gas (light blue), to mass fluxes of water (dark blue) and solid matter (black), and to mineralization (green). Four sources of radionuclides are represented: 1) irrigation, 2) fertilisation, 3) draining and cultivation of a lake-mire system and 4) groundwater uptake. The activity concentration in crop is calculated assuming that the plant is in equilibrium with radionuclides in soil and the canopy atmosphere (plant uptake), and that radionuclides in irrigation water are intercepted by the canopy. Note that each land use variant uses a different set of source terms (see text and Saetre et al. 2013a).*

Instead, three stylised agricultural land use variants were used to calculate dose to future human inhabitants. These were: draining and cultivating a mire (over a human lifetime), irrigating and fertilising a garden plot (over a human lifetime), and long-term fertilisation of a cultivated clay soil due to infield-outland agriculture (see Saetre et al. 2013a, and Section 7.2). In the first variant, radionuclide accumulation in lake and mire regolith layers was included in the initial conditions for agricultural soil, and radionuclides entered the cultivated soil through groundwater uptake. In the other two variants, radionuclides entered cultivated soil from above. Thus, for dose calculations it was considered sufficient to represent the dynamics of radionuclides in the soil-plant system with two regolith compartments, representing radionuclides in the upper biological active soil layers of cultivated soil (see below, Figure 8-2).

Elemental pools in decomposers and consumers (herbivores and carnivores) are expected to be small in relation to the pools in the uppermost layers of cultivated soil. The turnover of soil animals and microbiota is typically very fast. Also the majority of plant biomass is expected to have a relatively fast turnover, as annual crops (cereals, root crops and vegetables) were considered. For simplicity, organism components were therefore not included as separate compartments in the agricultural ecosystem sub-models, and consequently radionuclide concentrations in crop, and livestock and dairy products were calculated assuming they were in equilibrium with soil and fodder concentrations, respectively. However, a few non-metals (including plant nutrients) and rare elements are known to bio-accumulate. Thus, we explicitly accounted for storage of radionuclides in plant biomass in the transport calculations, by considering a fraction of the total inventory to be immobilised (Saetre et al. 2013a).

The oxygenated and unsaturated layer of cultivated soil was represented by two compartments, one representing radionuclides adsorbed on solids, dissolved in pore water or bound in crop (RegoUp), and one representing radionuclides in soil organic matter ($RegoUp_{org}$). The sum of these inventories reflects radionuclides in the biologically active layer of cultivated soil, where roots take up elements and soil organisms can be exposed to ionising radiation.

The dynamics in the atmosphere are fast (occurring in hours), and the exchanges with upper atmospheric layers are much greater than the exchanges with the upper regolith layers. Thus, for modelling purposes the atmosphere was treated as a sink (and source in mire ecosystems), and the concentrations of volatile radionuclides in the canopy atmosphere (and layers above) were calculated using a steady-state solution.

8.4 Transport processes

8.4.1 Process identification

For the identification of processes important for transport and accumulation of radionuclides in natural and agricultural ecosystems in Forsmark, we first considered the conceptual model of the Forsmark landscape (Lindborg 2010, Lindborg et al. 2013), and the conceptual models presented for marine, freshwater and terrestrial ecosystems (Aquilonius 2010, Andersson 2010, Löfgren 2010). In all three types of ecosystems, fluxes of radionuclides were primarily associated with mass fluxes (of water, solid matter and gas), or with transitions between inorganic and organic forms of radionuclides (i.e. primary production and mineralisation of organic matter). The exchange of radionuclides between solid and liquid states was also highlighted as a key process for radionuclide transfer in all types of ecosystems.

In the next step it was assessed which of these processes may be of quantitative importance for the flux of radionuclides between the identified model compartments, accounting for the spatial configurations of the system components. That is, the attention was focused on fluxes between compartments that were in proximity of, or in physical contact with, each other. Finally, the identified processes were checked against the processes in the SKB FEP list (SKB 2013b). The identification and audit of processes affecting radionuclide transport at Forsmark are described in Chapter 7. Below follows a brief description of the processes that were represented by a flux of radionuclides in the transport model, and Table 8-2 gives an overview of the radionuclide fluxes that were represented in the model.

Table 8-2. Overview of radionuclide fluxes (processes) explicitly included in the radionuclide transport model (see Figure 8-1). The processes have been categorised with respect to the driving force of the flux, namely mass-flux of solid (MS), water (MW) or gas (MG), diffusion in water (DW) or in gas (DG), or incorporation into or release from organic matter due to photosynthesis (PP) or mineralisation (Min). "Y" indicates that the process is included as a dynamic flux between compartments in the aquatic, mire or agricultural sub-model. An asterisk indicates that the outcome of the process is accounted for, assuming that a steady state between dynamic fluxes has been reached.

Process	Related FEP in Chapter 7	Type	Radionuclide flux Aqua	Mire	Agri
Biological					
Bioturbation	Bioturbation	MS	Y		Y
Plant (root) uptake	Uptake, Primary production	PP	Y	Y	*
Litter respiration/release	Primaty production, Decomposition	Min	Y	Y	
Litter production	Excretion, Particle release/trapping	PP	Y	Y	
Regolith Mineralisation	Decomposition	Min	Y	Y	Y
Vegetation ingrowth^BTW	Primary production, Covering, Terrestrialisation	MS	Y	Y	
Water bound					
Advective horizontal^BTW	Convection	MW	Y	Y	
Advective vertical	Convection	MW	Y	Y	Y
Diffusion (vertical)	Convection		Y	Y	
Water uptake	Import	MW			Y
Solid liquid phase dissociation	Reactions, Sorption/desorption		*	*	*
Sediment dynamics					
Sedimentation	Deposition	MS	Y		
Resuspension	Resuspension	MS	Y		
Burial	Deposition, Resuspension, Decomposition	MS	Y	Y	
Gas transport					
Degassing	Phase transition, Convection	MG	Y	Y	Y
Gas uptake	Phase transition	MG	Y	Y	
Human behaviour					
Drain/cultivate^BTW, INIT	Stage of succession				Y
Fertilise^BTW	Anthropogenic release	MS			Y
Irrigate	Anthropogenic release	MW			Y
Radiological					
Radionuclide decay/ingrowth	Decay		Y	Y	Y

^BTW = Flux between ecosystems or biosphere objects.
^INIT = Affects initial inventory (rather than flux).

Bioturbation

Bioturbation refers to translocation of radionuclides by mixing of sediment and soil particles in aquatic and terrestrial regolith layers. Mixing of aquatic sediments by, for example, sediment-dwelling organisms, leads to improved oxygenation. When the depth of the upper sediment layer is reduced during episodes of resuspension, bioturbation causes the oxygen front to penetrate into underlying sediments, resulting in an apparent translocation of radionuclides from anoxic regolith layers to the upper, biologically active, sediment layer.

The combined effect of ploughing and soil-animal activity (e.g. earthworms burrowing) mixes cultivated soil. When drained mire and lacustrine sediments are cultivated, radionuclides from deeper regolith layers are redistributed and mixed with radionuclides in the upper soil horizon (Figure 8-2).

Plant uptake

Plant uptake is fixation of inorganic radiocarbon and other radionuclides into plant biomass, as a result of primary production. In aquatic ecosystems, plants take up dissolved radionuclides from the surrounding water. In terrestrial (mire and agricultural) ecosystems, plants take up radionuclides from the upper soil layers through root uptake, and from the canopy atmosphere through interception and leaf uptake (C-14 only).

Litter respiration/release

When organic matter is metabolised by decomposers and grazers, labile organic carbon is transformed to inorganic carbon. Litter respiration/release thus refers to the release of radionuclides from fast (within a year) decomposition of aquatic and wetland net primary production. Through this process radionuclides stored in plant biomass are released to the water column and to the upper peat layer in aquatic and mire ecosystems, respectively.

Litter production

Most of the biomass produced annually is metabolised by grazers and decomposers (see litter respiration above). However, a part of the biomass production is made up of refractory organic matter. This decomposes much more slowly, and consequently a fraction of the biomass production will contribute to the build-up of organic matter in the upper regolith layer. Thus, the process, litter production, represents the transfer of radionuclides stored in plant biomass to the upper regolith layers in aquatic and mire ecosystems, respectively.

Regolith mineralisation

When refractory organic matter is metabolised by decomposers, organic carbon is transformed to inorganic carbon. Regolith mineralisation refers to the release of radionuclides from slow decomposition of organic matter in soil and sediments. Through this process, radionuclides stored in organic regolith layers are released to the pore water of the corresponding regolith layer in aquatic, mire and agricultural ecosystems, respectively.

Vegetation ingrowth

Wetland vegetation will colonise shores and bottoms of the sea and lakes. The establishment of mosses, emergent and floating-leaved vegetation is associated with soft bottoms, where organic matter from refractory litter accumulates, ultimately forming a peat layer that will cover the aquatic sediments. The process, vegetation ingrowth, thus represents the translocation of radionuclides in aquatic regolith layers to the corresponding mire regolith layer, caused by peatland succession.

Advective horizontal

This process represents advective transport of radionuclides by lateral bulk movement of water. In the submerged period, horizontal transport of radionuclides by advection occurs through water exchange between adjacent sea basins. In the land period, it occurs through diffuse groundwater flow or by streams to recipients of surface water downstream (see Section 8.4.2).

Advective vertical

This process represents transport of radionuclides by vertical bulk movement of water and is considered to be the quantitatively most important mechanism for vertical transport of radionuclides between pore water in adjacent regolith layers and between aquatic sediments and the above water column (see Section 8.4.2).

Water uptake

During dry periods of the year diffusion and capillary rise cause an upward flow of groundwater to unsaturated soil layers. In areas with discharge of deep groundwater, water uptake will transport contaminated water from deep soil layers to the overlying cultivated and biologically active layer, where it can be taken up by fodder and food crops.

Diffusion (vertical)

Diffusion refers to the transport of radionuclides due to random movement of molecules in solution or gas. As the rate of diffusion is strongly dependent on distance, diffusion is only considered to be a quantitatively important at scales below one metre. Consequently, this process was only considered a relevant mechanism for vertical transport of radionuclides between adjacent regolith layers with large contact areas (> 100,000 m^2). Diffusion of radionuclides in gas is included in the process degassing, see below.

Solid liquid phase dissociation

In regolith layers, and in the water column, there will be an exchange of elements (including radionuclides) between the solid state (the soil/sediment matrix and suspended particulate matter), and the liquid state (pore water or the water column). The exchange of radionuclides between the solid and liquid state is considered to be fast (occurring in days) as compared to the model resolution (years), and thus this process is described by an equilibrium-partitioning coefficient (K_d), rather than by dynamic fluxes (see Saetre et al. 2013a and Tröjbom et al. 2013).

Sedimentation

Particles suspended in the water column will be pulled downwards by gravity, and ultimately settle on the top of the uppermost sediment layer in aquatic ecosystems. Thus, the process, sedimentation, refers to the flux of radionuclides associated with the surface structure of suspended particulate matter, or stored in suspended particulate organic matter, to the corresponding inventory in the upper aquatic sediments.

Burial

If the rate of sedimentation of particulate matter is larger than the rate of resuspension, or if the rate of production of litter is larger than the rate of mineralisation, there is a net accumulation of sediments, and the total thickness of the regolith layer will grow. As the depth of the upper biological active zone is limited by oxygen supply from above, the deeper layer of this zone will become anoxic as a consequence of burial. Radionuclides associated with buried sediments will consequently be translocated from the upper sediments to the oxygen-depleted sediment layers below.

Degassing

There will be an exchange of gas between the surfaces of open water and soil pore water, and the overlying atmosphere. Degassing refers to the radionuclide flux caused by the exchange of dissolved gas from the water column, or from the soil pore water, to the atmosphere, for aquatic and terrestrial ecosystems, respectively. For natural ecosystems degassing is limited by the phase transition, whereas for agricultural ecosystems it is limited by gas diffusion through air-filled soil pores.

Gas uptake

There will be an exchange of gas between the surfaces of open water and soil pore water, and the overlying atmosphere. Gas uptake refers to the radionuclide flux caused by the gross exchange of gas from the atmosphere (source) to gas dissolved in the water column (Water), or in the soil pore water of surface peat (RegoUp), for aquatic and mire ecosystems, respectively.

Drain/cultivate

Draining lakes and wetlands will lower the groundwater table, and organic regolith layers above the water table will subside due to compaction and decomposition. The process, drain/cultivate, thus refers to the transfer of radionuclides from wetland regolith layers to the unsaturated layer of cultivated soil in agricultural ecosystem. This transfer or radionuclides is handled as an initial condition for radionuclide inventories in the cultivated soil, and the process does not affect radionuclide inventories in the natural ecosystems.

Fertilise

The key principle behind the agrarian infield–outland system is to fertilise arable land with nutrients from meadows and pastures, by the use of animal manure as organic fertiliser. The process, fertilise, thus represents the input of radionuclides stored in mire vegetation to infield soil, originating from wetland hay used as animal fodder.

Irrigate

Radionuclides in water can be transferred to soil and vegetation through irrigation of arable land. Under the current climatic conditions, irrigation of soil for growing potatoes and vegetables in the open are plausible in the Forsmark area. Thus, irrigation refers to the input of radionuclides from irrigation water to cultivated soil on the scale of a houshold garden-plot.

Radionuclide decay/ingrowth

Radioactive decay is the process by which a nucleus of an unstable atom loses energy by emitting particles (e.g. alpha or beta) or gamma rays of ionising radiation. Radioactive decay is treated as a sink term in all model compartments. For decay that results in a radioactive progeny nuclide, the radioactive decay is matched by a source term representing ingrowth for the progeny.

8.4.2 Hydrology and advective transport

The hydrological input from water flow modelling and the handling of water fluxes when modelling advective transport in the radionuclide model deserve special attention due to their importance for model development and transport modelling. Specifically, radionuclides released from a geological repository may reach the surface ecosystems by the flow of deep groundwater, and the flux of water is a major process for transport of radionuclides within and between surface ecosystems.

Essentially, hydrological modelling contributes in three major ways to the biosphere modelling of radionuclide transport and exposure.

- Discharge areas for groundwater potentially carrying radionuclides from the SFR repository to the surface are identified by particle tracking in a “bedrock hydrogeology model”, which in SR-PSU is developed using DarcyTools (see Chapter 6 and Odén et al. 2014). These discharge areas are used as a basis for identification and delineation of biosphere objects used in the biosphere radionuclide transport modelling.
- A hydrological analysis in GIS, based on the DEM describing the present topography, is used to identify the streams in the landscape. The resulting stream network shows how the biosphere objects are connected in the landscape and is used to determine transport directions and fluxes, using additional data on catchment areas and runoff, between biosphere objects (see Chapter 6).
- The fluxes between the compartments in the biosphere radionuclide model (Figure 8-1) are calculated using a “surface hydrology model” developed with the MIKE SHE tool (see Chapter 3 and Werner et al. 2013a). The “surface hydrology model” simulates groundwater flow, surface water flow, and various hydrological processes related to vegetation and interactions with the atmosphere. It is therefore capable of providing input to the calculations of all types of hydrology-related transport in the radionuclide model.

For the purposes of the present description of the radionuclide model, some additional information is given below related to the third type of modelling, i.e. the calculation of fluxes between compartments. The MIKE SHE model is a distributed model consisting of cells that generally are small in the horizontal directions, relative to the size of compartments in the radionuclide model. Conversely, the vertical model discretisation is enhanced in the radionuclide model, in order to distinguish between layers with differing transport properties. This means that some of the calculation layers in the MIKE SHE model were subdivided and the associated fluxes distributed on the new layers after delivery of the water fluxes to the radionuclide modelling. The methodology and results of this procedure are described in Werner et al. (2013a).

The MIKE SHE model calculates water fluxes in a large model volume, of which the biosphere objects considered in the radionuclide transport modelling constitute only small parts. It follows that the quantification of fluxes to be used in the radionuclide model requires an extraction of flow modelling results for sub-volumes (the biosphere objects) of the larger hydrological model volume, and a "horizontal compartmentalisation" from cells to compartments within these sub-volumes, performed by means of water balance calculations (cf. below).

The hydrological modelling and calculation of water fluxes were done for the specific biosphere objects included in the biosphere model (Chapter 6). The fluxes between compartments are obtained by using the water balance tool in MIKE SHE, which allows the user to define volumes for which water balances (including fluxes and storage terms, if any) are to be calculated. Note that the biosphere objects are not bounded by water divides, which implies that there are water exchanges with surrounding parts of their catchment areas, in addition to the internal exchanges and those involving the vegetation and the atmosphere (evapotranspiration and precipitation).

For each biosphere object, water fluxes representing three future hydrological stages are calculated (Werner et al. 2013a): a sea stage at year 3000 AD, a lake stage (with growing mire) at year 5000 AD, and finally a fully terrestrial stage at year 11,000 AD. As described in Chapter 6, two landscape objects (121_2 and 157_2) never develop into lakes, and for these objects hydrological parameters from both 5000 and 11,000 AD, represent a terrestrial stage. As illustrated in Figure 8-1, the biosphere objects that go through a lake stage contain two regolith columns; one aquatic, below the lake; and one terrestrial, below the mire surrounding the lake. During the marine phase, only the aquatic column exists. During the lake and terrestrial phase both columns are active; when the mire expansion is completed only a stream remains in the object, and consequently the aquatic column represents sediments under this stream. The two landscape objects not having a lake stage are also missing a stream, which means that only the terrestrial column is applicable after the marine period.

The vertical flow of water between two compartments is calculated by multiplying the area of the respective column with the specific flux (flux per unit area). The representative flux between two aquatic compartments is taken from the marine stage during the marine period, and from the lake stage after lake isolation. For the terrestrial column the representative flux from the lake period is used when land first emerges after the marine period, and the flux from the fully terrestrial stage is used after the mire expansion is completed. In transition periods (i.e. during lake isolation, land emergence, and mire expansion), linear interpolation was used to estimate vertical flux rates from the parameters representing the start and the end of the transition period (see Saetre et al. 2013a for details).

There is a horizontal advective transport of radionuclides between the flooded area in the mire and the lake or stream due to surface runoff. In the other direction there is a transport of radionuclides from the lake or stream to the flooded area due to flooding. Since biosphere objects 121_2 and 157_2 neither become lakes nor have streams, surface runoff is assumed to occur as diffuse overland water flow through flooded areas to the downstream object. The combinations of water fluxes and activity concentrations that are used to calculate advective fluxes in these and the other biosphere objects are described in Saetre et al. (2013a).

8.5 Calculating future exposure

8.5.1 Humans

The doses to human inhabitants resulting from an expected release of radionuclides from existing and planned repositories for long-lived waste are assessed over many thousands of years. The assessment involves estimating activity concentrations of radionuclides in the environment (air, soil and water, see previous sections), and in plants and animals that may serve as foodstuffs for human inhabitants. Assumptions on properties and habits of the humans that will live in or utilise the biosphere objects are required to estimate external exposure and intake of contaminated food (exposure scenarios). The doses from intakes of radionuclides can then be computed using dose per unit intake coefficients that account for retention in the human body and exposure from progeny radionuclides.

Radionuclides in the environment may lead to both external and internal exposure. In this safety assessment, the total dose from exposure to radionuclides in the environment is the sum of exposure through ingestion of water, ingestion of food, external exposure and inhalation. The internal exposure from water ingestion is the product of the activity concentration in contaminated water and the amount of contaminated water consumed, and the corresponding dose is calculated by multiplication with the appropriate dose conversion factor for ingestion. Similarly, the internal exposure from food ingestion is the product of the activity concentration in contaminated food and the amount of contaminated food consumed, summed over all contaminated food items in the diet. The corresponding dose is calculated by multiplication with the dose conversion factor for ingestion.

Both radionuclides in gaseous form and radionuclides adsorbed to dust particles contribute to the activity concentration in air. This means that the internal exposure from inhalation of contaminated air depends on the activity concentration in air from particles and from radionuclides in gaseous form, the inhalation rate, and the time spent in contact with contaminated air. The dose from inhalation can then be calculated by multiplying exposure with an appropriate dose coefficient.

External exposure from the environment is calculated from the activity concentrations in environmental media and the time spent in contact with or close to the media. In this safety assessment, only exposure from the soil is considered, since this is the only medium expected to be associated with both high activity concentrations and long exposure times, as compared with direct irradiation from water or air. The exposure scenarios considered in the SR-PSU safety assessment are summarised in Chapter 7. A more detailed description, including the mathematical models, is given in Saetre et al. (2013a, b).

8.5.2 Non-human biota

The assessment of dose rates to non-human biota has been based on the ERICA methodology (Brown et al. 2008, Beresford et al. 2008). The method estimates absorbed dose rates from both external irradiation resulting from radionuclides in environmental media (soil, sediment, water) and internal irradiation from the incorporation of radionuclides within the organism. Geometrical data and habitat occupancies for the organisms considered, together with data on the decay properties of individual radionuclides, are used to calculate dose conversion coefficients (DCC). These coefficients are then used to calculate the absorbed dose rate for each radionuclide from the activity concentrations in environmental media or within the organism itself. Internal and external dose rates across all radionuclides of interest are then summed for each organism.

The SR-PSU application of the ERICA method in the analysis of non-human biota at Forsmark is described in Saetre et al. (2013a). In short, concentrations of radionuclides in relevant environmental media were calculated with the radionuclide transport model described above. The ERICA Tool was used to calculate DCCs for representative organisms, and dose rates to biota were calculated with ECOLEGO as an integrated module of the radionuclide model for the biosphere.

The ERICA assessment approach, as presented in Brown et al. (2008) and Beresford et al. (2008), and the background to dose assessments for non-human biota are described in Jaeschke et al. (2013). As stated there, one of the challenges in a site-specific assessment is to identify a small enough number of targets (organisms) to make the assessment manageable without reducing the information value of the assessment beyond credibility. Jaeschke et al. (2013) identified a number of representative species for the Forsmark area based on three criteria related to the regulations (SSM 2008a):

- organisms ecologically important for the relevant ecosystems,
- endangered, endemic, or genetically important species,
- species of commercial or cultural value (not including domestic/agricultural species).

The representative species were compared with the reference organisms of the ERICA Tool (Brown et al. 2008). The comparison showed that the reference organism concept was acceptable to use in most cases, but a few adjustments have been made in this safety assessment to better include site-specific characteristics of biota in the Forsmark area. This is further described in SKB (2014). In total, 41 organism types have been included in the SR-PSU safety assessment.

In SR-PSU, the environmental impact from radiation has been assessed by evaluating potential effects of a radionuclide release on individuals, based on the rationale that if there are no detrimental effects on individuals then negative consequences for populations and ecosystems are very unlikely. This assumption may not be universally valid, but the approach is consistent with international practice. Therefore, dose assessment results have been interpreted with respect to the ERICA screening value that has been derived on the basis of population-relevant individual effects data, i.e. effects relating to mortality, morbidity and reproduction endpoints (see **SR-PSU Main report**).

9 Data used in the biosphere assessment

9.1 Overview of parameterisation and parameters

The radionuclide model for the biosphere has, as far as possible, utilised the site-specific data both for describing parameters and populating parameter values. Compared to earlier SKB assesments, large amounts of site data are available for the SR-PSU biosphere assessment. Site data describes both important ecological and hydrological processes as well as providing site-specific concentrations of elements in organisms, regolith and waters, together with a high resolution digital elevation model, (DEM), and a detailed stratigraphic model of the regolith (see SKB 2008a, Tröjbom and Nordén 2010, Werner et al. 2013a, Strömgren and Brydsten 2013, Sohlenius et al. 2013a). This dataset is probably one of the most detailed collections of synchronised surface data ever produced in Sweden.

The radionuclide model for the biosphere presented in Chapter 8 relies on nearly 360 input parameters, of which one third represents radionuclide- or element-specific properties. For each parameter, a best estimate was derived from site or literature data, and the parameter uncertainty was described by a probability density function (PDF). The best estimates were used for deterministic calculations of human exposure and to assess potential radiological impacts on the environment (Chapter 10).

The parameters used in the radionuclide model reflect important processes related to transport and accumulation of, and exposure to, radionuclides at the site over time, thus including the effects of site development. In order to summarise the number and types of parameters used, the parameters are divided into ten categories in Table 9-1.

The present chapter summarises the report "Biosphere parameters used in radionuclide transport modelling and dose calculations in SR-PSU" (Grolander 2013), to which the reader is referred for detailed descriptions of parameters and parameterisation. Section 9.2 includes a description of the principles and methods used to select parameter values that represent the site and to determine PDFs that describe the natural variation and the uncertainties associated with the selected parameter values. Section 9.3 is devoted to a brief description of the parameters used in the radionuclide model for the biosphere in the context of the ten defined categories (Table 9-1). Alternative parameterisations for other calculation cases than the base case are also included in the parameter category descriptions when relevant.

Table 9-1. Categories of parameters listed together with examples of the parameters included in the category, data sources and references.

Type of parameter	Example	Source	Reference
Landscape geometries	Size of biosphere objects and catchment areas, sedimentation and resuspension rates	Site investigation, site modelling	Grolander (2013)
Regolith properties	Density and porosity of sediments and soil	Site investigation	Grolander (2013)
Hydrology and water exchange	Vertical and horizontal advective fluxes, marine water exchange	Site investigation, site modelling	Werner et al. (2013a)
Terrestrial ecosystem properties	Biomass, productivity, mineralisation rate	Site investigation, site modelling	Grolander (2013)
Aquatic ecosystem properties	Biomass, productivity, mineralisation rate	Site investigation, site modelling	Grolander (2013)
Distribution coefficients and diffusivity	Element-specific solid/liquid distribution coefficients (K_d) for regolith and particulate matter	Site investigation, literature	Tröjbom et al. (2013)
Concentration ratios	Element-specific concentration ratios between environmental media and organisms (CR)	Site investigation, literature	Tröjbom et al. (2013)
Human characteristics	Agricultural practices, food and water consumption	Literature	Grolander (2013)
Non-human biota	Occupation factors for biota	Literature	Grolander (2013)
Radionuclide-specific properties	Radionuclide half-life and does coefficients	Literature	Grolander (2013)

9.2 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 (summarised in Chapters 3-5). Data from this description have been the primary source of parameter values for the radionuclide model. Below is a brief description of the principles used to derive best estimate 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, data from the open literature were utilised.

For each parameter describing a property of, or process in biosphere objects, a best estimate was derived from site or literature data, and the parameter variation was described by a probability density function. The biosphere 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 were used in the simulations of transport, accumulation and exposure, should give representative descriptions (typical) of compartments or flows between compartments within a biosphere object, accounting for spatial variation within the compartments, and temporal variations during the year.

This means that when the variations in parameter values are quantified (for example, in terms of standard deviation, or maximum and minimum values), the measures of variation should reflect variation at the time scale of years and at a spatial scale of a biosphere object. Moreover, the parameter variation should reflect random variation of the typical value, not systematic variation in response to changes in environmental conditions or climate, which are not expected to occur at the spatial and temporal scale considered in the assessment. Consequently, typical values and natural variation were primarily determined from data collected at the Forsmark site, and separate probability density functions were assigned to different climate domains.

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

Most of the parameters are described by a best estimate (BE) 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 by a uniform distribution. For most of these parameters, the best estimate corresponded to the arithmetic mean of the minimum and maximum values.

9.3 Description of parameters

There are nearly 360 parameters used in the biosphere assessment. These parameters can be divided into ten categories: Landscape geometries, Regolith properties, Hydrology and water exchange, Terrestrial ecosystem properties, Aquatic ecosystem properties, Distribution coefficients (K_d), Concentration ratios (CR), Human characteristics, Non-human biota, and Radionuclide-specific properties. In Table 9-1 the categories are listed with examples and references.

K_d (Section 9.3.6) and CR (Section 9.3.7) are element-specific parameter groups and each of the 31 stable elements included in the assessment was given a unique parameter value for each K_d and CR parameter. For the radionuclide-specific parameters, a unique value was given for each of the modelled radionuclides. The parameters are described in more detail in Grolander (2013). Some of the parameters are also presented in specific reports; for example, the K_d and CR parameters are described in Tröjbom et al. (2013) and the hydrological parameters in Werner et al. (2013a).

9.3.1 Landscape geometries

The continuous temporal development of the landscape, due to shoreline displacement (Chapter 4), results in time-specific volumes and areas of objects and surrounding catchments, and determines the type of ecosystem (Chapter 5) at different time steps in the radionuclide model (i.e. terrestrial or aquatic). The geometric parameters describe geometric extensions (i.e. areas and depths) of the biosphere objects, and sediment depths, which change over time depending on sedimentation and resuspension rates. There are transition times for different ecosystem stages, e.g. the time of transition between marine and limnic stages and the time for ingrowth of peat in the aquatic stages, which set the time for when a lake becomes a mire. These parameters are derived using the regolith-lake development model (RLDM) for Forsmark (Brydsten and Strömgren 2013). A detailed description of these parameters is given in Grolander (2013). Some of the properties are also affected by the introduction of different calculation cases, e.g. permafrost and extended global warming (cf. below).

9.3.2 Regolith properties

Parameters describing densities and porosities of the regolith materials in the modelled compartments were derived using site data from several studies (Grolander 2013). Density and porosity parameters are based on measurements on different regolith types in the SKB site investigations at Forsmark and Laxemar-Simpevarp. Literature data from sites other than those investigated by SKB were used as supporting data.

In addition to regolith densities and porosities, parameters describing properties of agricultural soils were derived. The degree of compaction achieved when a wetland is transformed from its natural state into arable land was calculated as the ratio between the dry bulk density of undrained peat in wetlands and the dry density of peat from cultivated wetlands (see Section 5.3.2). The water content of soils that can be used for cultivation was assessed using both site-specific porosity estimations and literature data on saturations of peat and glacial clays. The properties of the regolith are assumed to be the same in all biosphere calculation cases.

9.3.3 Hydrology and water exchange

It is assumed that waterborne transport of radionuclides in the biosphere is proportional to the flux of water. This section provides a brief description of parameters representing water fluxes in marine basins, and between model compartments of biosphere objects for modelling marine, limnic and terrestrial stages.

A parameter quantifying inter-basin water exchanges, i.e. annual average water flows between neighbouring marine basins, was calculated by the flexible-mesh modelling tool MIKE 3 FM using site data from Forsmark (Karlsson et al. 2010, Werner et al. 2013a). Specifically, gross in- and outflows are used to calculate net flows and their directions across basin boundaries. The major factor influencing long-term changes of inter-basin water exchanges is long-term bathymetry development, which was determined from the DEM (Strömgren and Brydsten 2013) and long-term landscape development modelling (Brydsten and Strömgren 2013).

In addition to the water exchanges in marine basins, 27 parameters describing advective fluxes between model compartments of biosphere objects were calculated using the MIKE SHE modelling tool (Werner et al. 2013a), using site data from Forsmark and models of shoreline displacement and landscape development. Specifically, parameters representing such inter-compartment water fluxes at future time steps were calculated for marine (sea), limnic (lakes) and terrestrial stages. Surface parameters denote surface water fluxes between terrestrial and limnic compartments of biosphere objects, and fluxes out from biosphere objects.

Parameter values from MIKE SHE were delivered for the future time steps 3000 AD, 5000 AD, and 11,000 AD, using locally measured meteorological data representing a normal year for present, temperate climate conditions. For the time step 5000 AD, parameter values were also delivered for a wet and warm climate, representing a future climate potentially affected by global warming. In the year 3000 AD, all seven biosphere objects considered in the modelling are submerged by the sea, i.e. relevant parameters are those representing fluxes for the marine stages. In 5000 AD, no biosphere object is submerged; five biosphere objects contain both limnic and terrestrial systems, whereas two objects are terrestrial systems only. Therefore, fluxes are calculated for terrestrial and limnic stages at this time step. In the year 11,000 AD, there are no lakes within the model area, and hence only terrestrial parameters were delivered for this time step.

The parameters and their usage in radionuclide-transport modelling are further described in the biosphere parameter report (Grolander 2013). Details on the MIKE SHE modelling are found in the hydrology report (Werner et al. 2013a).

9.3.4 Terrestrial ecosystem properties

Terrestrial ecosystems include both wetlands and agricultural land. Wetlands were parameterised with data representing an open wetland at Forsmark. At a coastal location such as Forsmark, mire formation and the following succession will span over a number of different mire types, with different vegetation communities, e.g. reed, brown mosses, *Sphagnum* mosses and, at some times, the presence of trees. The different successional stages of the wetland will differ in properties such as vegetation, biomass, Net Primary Production (NPP) and peat accumulation. This was reflected in the statistics describing the parameter, e.g. minimum and maximum values. The parameterisation of agricultural land represents cultivation and utilisation of a drained wetland. Unless otherwise stated in the text below, these parameters are fully described in Grolander (2013).

Fluxes of carbon between atmosphere and the terrestrial part of the ecosystem include release to the atmosphere from peat (upper regolith in mires), release to the atmosphere from decomposing biota and uptake from the atmosphere by plants. These fluxes were calculated using the piston velocity, uptake of carbon by plants (based on biomass and NPP), carbon concentration in air and the height of the atmospheric layer from which CO_2 is taken up by primary producers. C-14 export from the ecosystems were calculated based on wind velocity, the height of the atmospheric layer from which CO_2 is taken up by vegetation, and the vertical turbulent flux between the different atmospheric layers.

The production in terrestrial ecosystems that can be sustainably harvested was parameterised in the radionuclide model in order to evaluate exposure to humans from the terrestrial food web. The production of berries, mushrooms and game meat was parameterised for wetlands, and domestic animals, cereals, tubers and vegetables were parameterised for agricultural land (Grolander 2013).

Some characteristics of agricultural products are important for the exposure estimates in the radionuclide model, e.g. leaf area index, carbon concentrations in milk and meat and densities of milk and meat. Based on literature data, parameter values for dust concentrations in the air above agricultural land and wetlands, ingestion rates of food, water and soil by milk-producing cattle and meat cattle were included in the radionuclide model.

The parameters for the terrestrial ecosystem are partly changed depending on the calculation case, e.g. for different climate cases. Irrigation is not considered relevant in most of the calculation cases, due to the use of drained peatlands where water is easy accessible (SKB 2014). However, irrigation is included as an additional calculation case using a garden plot.

9.3.5 Aquatic ecosystem properties

Aquatic ecosystems include both limnic and marine systems. Ecosystem properties affect transport of radionuclides and uptake of radionuclides into biota, and the subsequent exposure of biota as well as of humans through consumption of aquatic biota. Parameters of biomass and production of aquatic primary producers, together with mineralisation rates of organic matter in water and regolith, are used to model the transport of radionuclides from inorganic forms in water to organic forms stored in the sediments.

The concentrations of inorganic carbon and particulate matter are important for estimating transport and sorption properties of radionuclides in water. Other aquatic ecosystem parameters are also used to model the exchange of C-14 across the water-air interface. The amount of edible food produced within the aquatic objects (fish and crayfish) is parameterised in order to evaluate exposure to humans from the aquatic food web. For most biosphere calculation cases, the aquatic ecosystem properties are assumed to be identical. However, for calculations involving permafrost systems the amount of edible food produced in aquatic ecosystems is altered since the productivity of aquatic biota in lakes is lower under periglacial conditions than under temperate conditions.

The aquatic parameters are, to a large degree, based on site data and understanding of the aquatic ecosystems at Forsmark, which is described in Aquilonius (2010) and Andersson (2010). The description of aquatic parameters used in SR-PSU is given in Grolander (2013).

9.3.6 Distribution coefficients and diffusivity

Distribution coefficients, K_d, were used to calculate the sorption of elements onto soils and particulate matter. The K_d model assumes a linear relationship between element concentration sorbed onto the solid phase and element concentration in the dissolved phase. The K_d values are both element-specific and site-specific, since they depend on both the properties of the elements and the biogeochemical environment in the regolith or water compartment. In this safety assessment, K_d values have been derived for 31 elements in 10 regolith compartments, and for particulate matter in limnic and marine systems.

The K_d values were based on a large set of site data collected both in Forsmark and Laxemar-Simpevarp (Sheppard et al. 2009, 2011, Engdahl et al. 2008, Kumblad and Bradshaw 2008). These data were collected to represent the modelled soil types and make it possible to assign element- and site-specific K_d values representative of the modelled environment. In addition to the site data, literature data were used as supporting information.

Despite the large site-specific dataset, data were missing or not sufficient for parameterisation in some cases. In these cases, element or parameter analogues were assigned or literature data were used. The parameterisation methods used and the data selected are presented in detail in Tröjbom et al. (2013). To represent the mass flux of radionuclides driven by concentration gradients, diffusivities are used; these are presented in Grolander (2013). Alternative K_d values or diffusivity parameters are not provided, i.e. the same K_d values and diffusivity parameters are used for all calculation cases in the biosphere assessment.

9.3.7 Concentration ratios

Concentration ratios, CR, were used to calculate uptake of radionuclides in biota. CR assumes a linear relationship between concentrations in biota and in surrounding media (soil or water). The CR values are element specific, site-specific and biota type specific. CR values were assigned to 20 biota types for the calculation of environmental concentrations in biota and doses to humans. In addition to these, CR values were assigned to 41 biota types for calculation of doses to the biota itself in the dose assessment for non-human biota. These CR values were assigned to the 31 elements included in the safety assessment, using a large site and literature dataset.

Site data were used when possible, but in many cases site data were missing. In these cases, parameter and/or element analogues were used for parameterisation. In cases where no site data or suitable analogues were available, literature data were used for the parameterisation. The parameterisation methods used and the data selected are presented in detail in Tröjbom et al. (2013). Alternative CR values are not provided; the same CR values are used for all calculation cases in the biosphere assessment.

9.3.8 Human characteristics

Parameters related to the characteristics of humans are based upon literature values. This category comprises basic parameters such as yearly demands for water and energy, inhalation rate and parameters related to land use and the most exposed groups.

Parameters that describe the fractions of the yearly energy demand that are fulfilled by consumption of different food items, fraction of arable land used for cultivation of cereals, potato and fodder, exposure time, and number of individuals in the exposed group, have been derived using historical records and official Swedish statistics (Grolander 2013, Saetre et al. 2013b). The parameters used to characterise humans and their behaviour are not altered in the different climate cases.

9.3.9 Non-human biota

For calculations of external doses to non-human biota, the parameter "occupation factor" was used. The parameter describes which habitat(s) each organism type utilises. The possible occupancies in aquatic ecosystems are in or on sediment and in or on water, whereas occupancy in terrestrial ecosystems include in or on soil and in air. In this assessment, the default values in the ERICA Tool were used for reference organisms (Grolander 2013), assuming that each organism type only occupies one habitat. For representative (site-specific) species, the occupation factors were based on data presented in Jaeschke et al. (2013).

The dose conversion coefficients for non-human biota described in Section 9.3.10 can be used to estimate the non-weighted absorbed dose rate from media and organism activity concentrations. However, radiation effects depend not only on non-weighted absorbed dose, but also on the type of radiation. For example, for a given non-weighted absorbed dose rate, alpha radiation may result in a more significant effect than beta or gamma radiation. Therefore, the weighted total dose rates (in $\mu Gy\ h^{-1}$) were estimated through the application of weighting factors for alpha, low-energy beta and high-energy beta-gamma radiation, together with dose conversion coefficients, as described in Brown et al. (2008). The factors used are presented in Grolander (2013).

For most radionuclides, estimates of radionuclide uptake in biota were made using concentration ratios (see Section 9.3.7). The exception is uptake of C-14 and tritium for which uptake was modelled differently due to the nature of these two elements for which stable isotopes are very abundant in the environment. The modelling of tritium and C-14 is described in Saetre et al. (2013a) and parameters used are described in Grolander (2013).

None of these parameters were altered in the different calculation cases. The set of organism types included as targets for the safety assessment was slightly altered in the periglacial case, whereas the same organisms were used in the base case and the extended global warming case (see Section 7.4).

9.3.10 Radionuclide specific properties

Radionuclide-specific dose coefficients were used for converting the activity levels in environmental media (in Bq) to doses to humans (in Sv). Three different kinds of radionuclide-specific coefficients were used: dose coefficients for external exposure from radionuclides in or on the ground ($Sv\ h^{-1}$ per $Bq\ m^3$), dose coefficients for ingestion ($Sv\ Bq^{-1}$), and dose coefficients for inhalation ($Sv\ Bq^{-1}$). The doses obtained with these coefficients are the effective committed doses to members of the public that are classified as adults. The selected dose coefficients and motivations are presented in Grolander (2013).

The dose coefficient for external exposure used in the assessment is defined as the dose rate to which an individual is exposed from a unit volumetric concentration of the radionuclide in regolith. The values used for external exposure (taken from Eckerman and Ryman (1993)) are based on the case of homogeneous distribution of the radionuclides in a soil layer of infinite depth and infinite lateral extent (Eckerman and Leggett 1996).

The dose coefficients for ingestion used in this assessment (taken from ICRP (1996) are independent of the ingestion pathway, i.e. via food or water. The only exception is C-14, for which different dose coefficients are used for ingestion via food and via water, because carbon is present in different chemical forms in water and food and C-14 in food is more bioavailable (Leggett 2004).

The inhalation coefficients used in this assessment (taken from ICRP 1996) were specified for different kinds of absorption in the lungs: fast (F), moderate (M) and slow (S). The highest value for each isotope across different classes of absorption was pessimistically chosen. For C-14 the value for C-14 dioxide was used.

The internal dose coefficients used in this assessment (taken from ICRP 1996) take into account the dose due to ingrowth of radioactive progeny radionuclides within the body following an intake of unit activity of the parent nuclide. The dose coefficients do not take into account the contribution to the dose owing to activity of progeny products that might be present in the environment. In radionuclide transport modelling in SR-PSU, the radionuclides in radioactive decay chains are either modelled explicitly or taken into account by combining dose coefficients in order to reflect the growth of radioactive progeny in the environment.

Dose estimates to non-human biota were calculated using organism-, radionuclide- and radiation type-specific dose conversion coefficients (DCC, µGy h^{-1} per Bq kg^{-1} fresh weight) according to the methods in Ulanovsky and Pröhl (2006) and Ulanovsky et al. (2008). Eight different kinds of DCCs were used: for internal exposure from alpha, high-energy beta/gamma, and low-energy beta, and for external exposure from high-energy beta/gamma in aquatic ecosystems, low-energy beta in aquatic ecosystems, high-energy beta/gamma radiation in air in terrestrial ecosystems, high-energy beta/gamma in soil in terrestrial ecosystems, and high-energy beta/gamma on soil in terrestrial ecosystems. The same radionuclide-specific parameters values are used for all calculation cases.

10 Analysis of unit release results

In SR-PSU the risk for humans and non-human biota is estimated from radionuclide concentrations in environmental media that are the calculation endpoints from a chain of transport models. The model chain covers transport from the repository (near-field model), through the geosphere (far-field model) and in the biosphere, and time-dependent radionuclide concentrations are calculated (see Section 2.2.3). Results from the analysis of the full transport model-chain, i.e. annual doses (Sv y^{-1}) and dose rates for non-human biota (µGy h^{-1}), are presented in the **Radionuclide transport report** and summarised in the **SR-PSU Main report**. The annual dose includes the annual committed effective dose from internal exposure plus the annual effective dose from external exposure.

This chapter presents results from transport modelling with constant unit releases into the biosphere. The aim and method of analysing unit release results are described in Section 10.1. The maximum annual doses to humans and the maximum dose rates to non-human biota derived from a unit release rate of each of 55 radionuclides are described in Sections 10.2 and 10.3. Section 10.4 compares the calculated maximum annual landscape dose conversion factors (LDFs, cf. Section 10.1) with corresponding dose conversion factors from SAR-08 (the previous SFR safety assessment, SKB 2008b) and SR-Site (the latest safety assessment of a KBS-3 spent fuel repository, SKB 2010, 2011).

In the following Section 10.5, a detailed analysis of the transport and accumulation of four radionuclides (C-14, Cl-36, Mo-93 and Ni-59) is presented. Most of the analyses described in the remainder of the chapter are also focused on these four radionuclides. In Section 10.6 these radionuclides are used to examine the effects of climate on unit release rate results for humans and non-human biota. The next two sections deal with how model endpoints are affected by assumptions on the distribution of the release to the biosphere objects (Section 10.7), and the delineation of the biosphere object (Section 10.8). Section 10.9 examines how maximum LDFs and dose rates are affected by parameter uncertainties and what parameters cause the most uncertainty in predicted annual doses and dose rates, whereas Section 10.10 describes an analysis of residual exposure pathways.

10.1 Purpose and methodology

The purpose of this chapter is to examine how predicted maximum annual doses and dose rates depend on transport simulations in the surface systems, and to show how predicted environmental concentrations are affected by landscape development, climatic conditions, and properties of the biosphere objects. To do this we analyse the response in the surface systems independently from releases simulated by the near-field and far-field transport models (which are described in the **Radionuclide transport report**). Instead we treat deep groundwater as a source of radionuclides and feed the surface systems with a constant release of one becquerel per year of each of the studied radionuclides, which here is referred to as "unit release rate" or, for simplicity, often just "unit release".

The analysis of unit release rate results is useful from the perspective of understanding the primary drivers of simulated transport and accumulation in a developing landscape. For example, with a unit release rate, the effects of retention in regolith layers and organic matter are not confounded with the dynamics of radionuclides reaching the biosphere, which also reflect release and transport in the repository and the geosphere. Moreover, with a constant release rate, radionuclide concentrations in the biosphere frequently approach stationary conditions in the assessed time frames, and if not, transient responses can be contrasted with clearly defined steady-state concentrations. The unit release rate approach also allows a direct comparison with simulation results derived in previous SKB safety assessments (so-called landscape dose conversion factors, cf. below).

Process understanding that is derived from this hypothetical release of radionuclides can be generalised to other release scenarios. However, quantitative relationships between release and exposure, and conclusions on what biosphere conditions and land use may result in high exposure, do not necessarily translate well to the less stylised release scenarios. This is particularly true for transient releases of radionuclides, where the timing of the release may be a key factor for potential exposure and dose.

An annual dose or dose rate derived from a unit release rate in a landscape is referred to as a *landscape dose conversion factor* (LDF), and it represents an upper limit for the dose/dose rates that can be expected given a constant release rate of radionuclides to the surface systems over a defined assessment period. The fact that the endpoints from a constant release rate are dose conversion factors is evident from their units: Sv y^{-1} per Bq y^{-1} and µGy h^{-1} per Bq y^{-1}. Nevertheless, in this chapter we frequently refer to these endpoints as doses or dose rates. This terminology should be understood as a shorthand notation for annual dose or dose rate *given* a unit release rate, and should not be confused with results from the full calculation chain.

As the primary purpose of the results presented in this chapter is to build understanding of simulated transport and accumulation of radionuclides in the biosphere, best estimates of parameters (rather than probability density functions) have been used to represent biosphere properties in the simulations. Although there are many sources of parameter uncertainties, we consider the chosen set of parameters to be the most precise description available of the Forsmark site, and as such to be fit for its purpose. However, Monte-Carlo simulations using sampled parameter values are used for comparison with the dose factors used in SAR-08 (Section 10.4) and to assess model uncertainty and sensitivity (Section 10.9). Moreover, in this chapter we do not consider the ingrowth of progeny radionuclides except for the dose contribution of very short-lived radionuclides that are included in dose coefficients (i.e. are treated as being in secular equilibrium). The inclusion of progeny nuclides in the calculation chain is described in the **Radionuclide transport report**.

10.2 Human exposure – overview

Landscape dose conversion factors (LDF) for a simulation period of 18,000 years were calculated for a unit release rate of 55 radionuclides, using the global warming biosphere calculation case (BCC1, see Chapter 7). As expected, the highest doses were typically found in biosphere object 157_2, where radionuclides in deep groundwater first reached the biosphere (discharge areas are described in Chapter 6 and Section 7.4.1). The only exception to this pattern was seen for Mo-93 that primarily accumulated in peat, and where draining and cultivating the deep peat layers in the downstream lake basin (157_1) yielded the highest dose (Table 10-1). The maximum LDF in all other biosphere objects was lower than in 157_1 and 157_2 (data not shown).

For long-lived radionuclides (half-life longer than 1,000 years) the major exposure routes were ingestion of food (C-14, Ca-41, Cl-36, Cs-135, Mo-93, Ni-59, Pd-107, Se-79, Sn-126, Tc-99, and Zr-93) or ingestion of water from a drilled well (Am-243, Cm-245, Cm-246, Ho-166m, Np-237, Pa-231, Pu-239, Pu-240, Pu-242, Ra-226, Th-229, Th-230 and Th-232) or from a dug well (I-129) extracting water from the till (RegoLow) (Table 10-1). Nb-94 and uranium isotopes were exceptions to the main patterns. Nb-94 emits high gamma-energy and has a low bioavailability, and thus external radiation from soil was the dominant exposure route.

The primary exposure pathway for uranium (U-238, U-235 and U-236) was burning of peat, and inhalation was as important as exposure through ingestion. For all radionuclides except I-129, the land use variant of draining and cultivating a lake-mire system (drained-mire farmers, DM) or irrigating and fertilising a kitchen garden (garden-plot households, GP) always led to higher annual doses than other land use variants. This was expected as these land use variants account for both long-term accumulation of radionuclides (in soil or bio-fuel) and exposure to deep groundwater by consumption of well water and irrigation (GP only).

Exposure calculations depend on several element- and radionuclide-specific parameters, including sorption coefficients (K_d), plant uptake parameters (CR), and dose coefficients. Long-lived radionuclides for which ingestion of water dominated exposure (e.g. Np-237, Pa-231, Th and Pu isotopes) had consistently higher sorption in the till layer, than radionuclides dominated by food ingestion (e.g. C-14, Pd-107, Ni-59, Se-79 and U isotopes). That is, K_d for till (RegoLow) was above 10 m^3 $kgDW^{-1}$ for the first group whereas it was typically below 1 m^3 $kgDW^{-1}$ for the second group (data not shown; "DW" stands for dry weight). Thus, retardation in the deepest regolith layer (till/RegoLow) appears to be a key factor for the relative importance of the two ingestion routes for radionuclides with a long half-life.

Table 10-1. Maximum landscape dose conversion factors, LDF (Sv y^{-1} per Bq y^{-1}), calculated in deterministic simulation using best-estimate parameters for four exposed populations, each associated with a unique land use variant: DM = drained-mire farmers, HG = hunter-gatherers, GP = garden-plot households and IO = infield-outland farmers. "Exposure route" refers to the exposure pathways for the most exposed population with the highest LDF. Radionuclides are sorted according to decreasing half-life. For a few of the radionuclides a different human population was most exposed in the probabilistic simulations. These are identified in footnotes in the table.

Radionuclide	Half-life (years)	Exposed population	Biosphere object	Max. dose (Sv y^{-1}/Bq y^{-1})	Exposure route (% of total dose)			
					Ingestion of food	Ingestion of water	Inhalation	External
Th-232	1.4E+10	DM	157_2	2.6E–12	25.4	74.5	0.1	0.0
U-238	4.5E+09	GP[1]	157_2	5.4E–12	38.9	24.1*	36.1	0.9
U-235	7.0E+08	GP[1]	157_2	5.7E–12	36.6	22.6*	36.8	4.0
U-236	2.3E+07	GP[1]	157_2	5.5E–12	37.7	23.3*	39.1	0.0
I-129	1.6E+07	IO	157_2	8.0E–12	11.9	88.1*	0.0	0.0
Pd-107	6.5E+06	DM	157_2	1.9E–14	97.0	3.0*	0.0	0.0
Cs-135	2.3E+06	DM[2]	157_2	2.0E–13	91.2	8.8	0.0	0.0
Np-237	2.1E+06	DM	157_2	1.3E–12	24.4	75.3	0.1	0.3
Zr-93	1.5E+06	DM	157_2	1.8E–13	94.7	5.3	0.0	0.0
Pu-242	3.7E+05	DM	157_2	2.8E–12	25.9	74.0	0.1	0.0
Se-79	3.3E+05	DM	157_2	3.0E–13	75.0	25.0*	0.0	0.0
Cl-36	3.0E+05	DM	157_2	7.5E–13	96.8	3.2*	0.0	0.0
U-234	2.5E+05	GP[1]	157_2	5.7E–12	37.1	23.0*	39.9	0.0
Tc-99	2.1E+05	DM	157_2	1.7E–13	96.7	3.3	0.0	0.0
U-233	1.6E+05	GP	157_2	5.9E–12	37.3	23.3*	39.4	0.0
Ca-41	1.0E+05	DM[2]	157_2	6.2E–14	92.9	7.1*	0.0	0.0
Sn-126	1.0E+05	DM	157_2	2.0E–13	47.4	21.6	0.0	31.1
Ni-59	7.6E+04	DM	157_2	2.9E–14	97.0	3.0*	0.0	0.0
Th-230	7.5E+04	DM	157_2	2.4E–12	23.5	76.5	0.1	0.0
Pa-231	3.3E+04	DM	157_2	8.4E–12	28.0	72.0	0.0	0.0
Pu-239	2.4E+04	DM	157_2	2.7E–12	20.5	79.4	0.1	0.0
Nb-94	2.0E+04	DM	157_2	3.8E–14	10.0	38.4	0.0	51.6
Cm-245	8.5E+03	DM	157_2	2.2E–12	16.6	83.3	0.1	0.0
Am-243	7.4E+03	DM	157_2	2.0E–12	15.2	84.7	0.1	0.1
Th-229	7.3E+03	DM	157_2	5.9E–12	10.9	89.0	0.0	0.0
Pu-240	6.6E+03	DM	157_2	2.4E–12	10.3	89.6	0.1	0.0
C-14[4]	5.7E+03	DM	157_2	7.9E–15	90.4	9.6*	0.0	0.0
Cm-246	4.7E+03	DM	157_2	2.0E–12	9.7	90.3	0.0	0.0
Mo-93	4.0E+03	DM[3]	157_1	5.5E–12	99.5	0.5*	0.0	0.0
Ra-226	1.6E+03	DM	157_2	4.3E–12	43.1	56.5	0.0	0.4
Ho-166m	1.2E+03	DM	157_2	2.1E–14	1.2	83.4	0.0	15.3
Ag-108m	438	HG	157_2	5.4E–14	1.6	0.1	0.0	98.3
Am-241	432	GP[3]	157_2	1.7E–12	1.0	99.0	0.0	0.0
Am-242m	141	GP	157_2	1.6E–12	1.0	99.0	0.0	0.0
Ni-63	100	DM	157_2	1.7E–15	26.5	73.5	0.0	0.0
Sm-151	90	GP	157_2	8.5E–16	1.0	99.0	0.0	0.0
Pu-238	88	GP	157_2	2.0E–12	1.0	99.0	0.0	0.0
U-232	69	DM	157_2	3.0E–12	5.8	94.2	0.0	0.0
Cs-137	30	DM	157_2	1.3E–13	13.0	87.0	0.0	0.0
Cm-243	29	GP	157_2	1.3E–12	1.0	99.0	0.0	0.0
Sr-90	29	DM	157_2	2.8E–13	5.2	94.8	0.0	0.0
Pb-210	22	GP	157_2	6.1E–12	3.4	96.6	0.0	0.0
Ac-227	22	GP	157_2	1.0E–11	1.0	99.0	0.0	0.0
Cm-244	18	GP	157_2	1.0E–12	1.0	99.0	0.0	0.0
Nb-93m	16	GP	157_2	1.0E–15	1.0	99.0	0.0	0.0
Pu-241	14	GP	157_2	4.2E–14	1.0	99.0	0.0	0.0
Cd-113m	14	GP	157_2	2.2E–13	9.0	91.0	0.0	0.0
Eu-152	14	GP	157_2	1.2E–14	0.9	96.1	0.0	2.9
H-3	12	GP	157_2	1.2E–15	1.0	99.0*	0.0	0.0
Ba-133	11	GP	157_2	1.3E–14	1.9	97.5	0.0	0.6
Ra-228	5.8	DM	157_2	6.0E–12	1.2	98.8	0.0	0.0
Co-60	5.3	GP	157_2	3.0E–14	1.3	97.2	0.0	1.5
Th-228	1.9	GP	157_2	1.2E–12	1.0	99.0	0.0	0.0
Cm-242	0.45	GP	157_2	1.0E–13	1.0	99.0	0.0	0.0
Po-210	0.38	GP	157_2	1.0E–11	1.0	99.0	0.0	0.0

Most exposed population changed in probabilistic simulations to
[1]DM in 157_1, [2] IO in 157_2, [3] DM in 157_2.

[4] Three different C-14 sources in the inventory of the SFR repository were used in the SR-PSU assessment: inorganic, organic and induced radiocarbon (**SR-PSU Main report**). As they were treated in the same way in the biosphere model, the LDF was the same for all three.

*Radionuclides that have a higher concentration in the dug well than in the drilled well.

For all but one short-lived radionuclide (half-life shorter than 1,000 years) the dominating exposure route was ingestion of water from a dug well (H-3) or a drilled well (other radionuclides) (Table 10-1). Moreover, for a majority of these short-lived radionuclides the ingestion of water contributed to more than 99% of the total LDF. As exposure from drinking water from a drilled well was included in the two land use variants drained-mire farmer and garden-plot household, they had very similar maximum LDFs for this set of radionuclides (i.e. the difference between the two was typically less than a few percent). Only for a few of the short-lived radionuclides did other exposure pathways (e.g. ingestion of food) affect the LDF, and for most of them the combined contribution of other exposure routes was still limited to less than 10%. The one exception to this pattern was Ag-108m. This radionuclide primarily accumulated in surface peat and had comparatively high dose coefficient for external exposure, which resulted in a high external exposure (99% of the LDF, Table 10-1).

10.3 Exposure of non-human biota – overview

Similar to the calculations for human exposure (Section 10.2), the biosphere calculation case for global warming (BCC1, Chapter 7) was used to assess the impact on non-human biota. The maximum total dose rates to a set of organisms in each of the three simulated ecosystems (marine, freshwater and terrestrial) are presented for each radionuclide in Table 10-2. Exposure of non-human biota is distinguished as internal or external. The internal dose contribution from each radionuclide (Table 10-2) has been analysed below with the intention of investigating their relative impact.

It is worth mentioning that these results are for a unit release rate of each of the safety relevant radionuclides. This means that the results do not allow conclusions to be drawn on the relative impact of these radionuclides under the conditions of a simulated transient release from the repository, since the rates and time patterns of release will be different for each radionuclide. Dose rates for NHB obtained for the different release curves in the SR-PSU calculation cases are instead discussed in the **SR-PSU Main report** and in the **Radionuclide transport report**.

The present unit release rate assessment indicated that the highest dose rates are expected in the terrestrial and freshwater environments, reflecting the findings of previous assessments (Torudd 2010, Jaeschke et al. 2013) as well as the general SR-PSU results. In nearly all cases, exposure from a radionuclide was either entirely internal or external, and for most of the radionuclides it was ~ 100% internal. On average ~ 80–90% of total dose rates were caused by internal exposure, considering all cases of exposure from radionuclides in all ecosystems. Radionuclides with dominating external exposure in all three ecosystems were Ag-108m, Ho-166m, Nb-94 and Sn-126. For a few radionuclides (Ba-133, Cl-36, Co-60, Cs-137, Eu-152, Mo-93 and Ra-228) the dominating exposure pathway (external or internal exposure) varied, indicating relative differences in biotic uptake between different ecosystems.

"Key organisms" were distinguished, in this report, as those which appeared with the highest frequency of radionuclide-specific maximum dose rates caused by unit release of that radionuclide. Such organisms may have the highest concentration ratio for certain radionuclides and/or may live in a particular habitat where the highest exposures occur. A key organism in this respect may not necessarily be the most exposed (or the most sensitive) organism in an ecosystem, as some radionuclides may contribute significantly to dose, whereas others give, relatively, an almost negligible exposure. However, a distinction of key organisms serves as a useful indication and may provide some additional insight into which organisms are disproportionately exposed.

In the terrestrial environment, the key organisms were Detritivorous invertebrates, Lichen and bryophytes, Soil invertebrates and Gastropods. In the marine environment, the key organisms were Zooplankton, Polychaetes, Phytoplankton and Crustaceans. In the freshwater environment, the key organisms were Zooplankton, Vascular plant, Bivalve mollusc and Microphytobenthos. These organisms are typically less radiosensitive than higher plants and vertebrates. The organisms highlighted in the unit release assessment broadly agree with those with highest exposures in previous assessments (Torudd 2010, Jaeschke et al. 2013).

Table 10-2. Maximum dose rates (µGy h^{-1} per Bq y^{-1}) for marine, freshwater and terrestrial biota for the deterministic unit release rate simulation. For each radionuclide, the most exposed organism is shown. The relative contribution of internal exposure to the total dose rate is presented as well as the biosphere object in which the maximum dose rate occurred. Radionuclides are presented in alphabetic order; only radionuclides with a half-life longer than one year are shown. Amp = Amphibian, Bent fish = Benthic fish, Bent moll = Benthic mollusc, Biv moll = Bivalve mollusc, Crust = Crustacean, Detr inv = Detritivorous invertebrate, Fl ins = Flying insect, Gast = Gastropod, Lich = Lichen and bryophytes, Macro = Macroalgae, Microph = Microphytobenthos, Phytopl = Phytoplankton, Polych = Polychaete worm, Soil inv = Soil invertebrate, Vasc pl = Vascular plant, Zoopl = Zooplankton.

Radionuclide	Marine biota				Freshwater biota				Terrestrial biota			
	Object	Organism	Max dose rate	Internal (%)	Object	Organism	Max dose rate	Internal (%)	Object	Organism	Max dose rate	Internal (%)
Ac-227	157_2	Zoopl	4.8E–19	100	157_2	Zoopl	7.9E-18	100	157_2	Detr inv	3.0E–18	100
Ag-108m	157_2	Polych	3.0E–11	2	157_2	Biv moll	3.8E-11	20	157_2	Soil inv	3.1E–10	5
Am-241	157_1	Zoopl	3.9E–13	100	157_2	Zoopl	4.6E-11	100	157_2	Gast	2.6E–12	100
Am-242m	157_2	Zoopl	3.6E–16	100	157_2	Zoopl	9.7E-15	100	157_2	Gast	6.5E–16	95
Am-243	157_1	Zoopl	3.2E–12	100	157_2	Zoopl	1.7E-08	100	157_2	Gast	9.9E–10	99
Ba-133	157_2	Polych	3.5E–16	0	157_2	Biv moll	5.4E-16	91	157_2	Detr inv	4.2E–16	2
C-14-ind*	157_2	Bird	8.1E–12	100	157_2	Bird	3.2E-11	100	157_2	Bird	2.1E–12	100
C-14-inorg*	157_2	Bird	8.1E–12	100	157_2	Bird	3.2E-11	100	157_2	Bird	2.1E–12	100
C-14-org*	157_2	Bird	8.1E–12	100	157_2	Bird	3.2E-11	100	157_2	Bird	2.1E–12	100
Ca-41	157_1	Crust	1.5E–12	100	157_2	Amp	1.7E-11	100	157_2	Amp	1.2E–11	100
Cd-113m	157_2	Crust	7.2E–17	100	157_2	Biv moll	2.8E-16	100	157_2	Fl ins	5.8E–16	100
Cl-36	157_2	Macro	3.1E–12	0	157_2	Crust	2.7E-11	44	157_2	Tree	2.3E–08	100
Cm-242	157_2	Zoopl	2.4E–18	100	116	Zoopl	6.4E-20	100	157_2	Detr inv	4.4E–20	100
Cm-243	157_2	Zoopl	2.0E–16	100	157_2	Zoopl	2.3E-15	100	157_2	Detr inv	1.0E–16	99
Cm-244	157_2	Zoopl	2.3E–16	100	157_2	Zoopl	2.7E-16	100	157_2	Detr inv	1.2E–17	100
Cm-245	157_1	Zoopl	3.3E–12	100	157_2	Zoopl	2.0E-08	100	157_2	Soil inv	8.9E–10	99
Cm-246	157_1	Zoopl	3.0E–12	100	157_2	Zoopl	1.0E-08	100	157_2	Soil inv	4.6E–10	100
Co-60	157_2	Bent mol	1.4E–18	0	157_2	Biv moll	1.3E-19	63	157_2	Soil inv	4.3E–19	0
Cs-135	157_1	Vasc pl	1.1E–16	100	157_2	Bent fish	7.4E-13	100	157_2	Amp	9.1E–14	100
Cs-137	157_2	Polych	4.1E–18	0	157_2	Mammal	6.2E-19	100	157_2	Detr inv	3.5E–19	2
Eu-152	157_2	Zoopl	7.5E–18	100	157_2	Biv moll	8.7E-20	54	157_2	Soil inv	3.7E–19	0
H-3	157_1	Vasc pl	2.7E–15	100	157_2	Vasc pl	3.2E-14	100	157_2	Amp	3.7E–14	100
Ho-166m	157_2	Polych	3.9E–13	0	157_2	Crust	1.6E-12	2	157_2	Detr inv	1.4E–11	0
I-129	157_1	Zoopl	4.2E–11	100	157_2	Zoopl	3.6E-10	100	157_2	Bird egg	1.6E–08	100
Mo-93	157_2	Polych	2.1E–12	1	157_2	Crust	1.9E-11	25	157_2	Soil inv	1.0E–10	75
Nb-93m	157_2	Zoopl	8.1E–21	100	157_1	Vasc pl	9.1E-21	100	157_2	Bird egg	4.5E–22	100
Nb-94	157_2	Polych	4.6E–14	0	157_1	Crust	1.5E-11	1	157_2	Detr inv	3.7E–11	0
Ni-59	157_1	Crust	1.2E–13	100	157_2	Zoopl	4.7E-11	100	157_2	Soil inv	1.9E–12	80
Ni-63	157_1	Crust	7.3E–16	100	157_2	Zoopl	6.9E-15	100	157_2	Soil inv	2.1E–16	100
Np-237	157_1	Zoopl	1.1E–12	100	157_2	Zoopl	2.1E-08	100	157_2	Detr inv	1.2E–09	100
Pa-231	157_1	Zoopl	3.4E–12	100	157_2	Zoopl	3.7E-08	100	157_2	Detr inv	1.4E–08	100
Pb-210	157_2	Zoopl	1.1E–18	100	157_2	Zoopl	1.3E-19	100	157_2	Detr inv	9.6E–20	99
Pd-107	157_1	Crust	1.2E–13	100	157_2	Zoopl	5.4E-11	100	157_2	Soil inv	1.7E–12	100
Po-210	157_1	Zoopl	2.2E–22	100	157_1	Phytopl	3.9E-19	100	157_2	Lich	4.8E–22	100
Pu-238	157_2	Phytopl	3.5E–14	100	157_2	Vasc pl	1.9E-13	100	157_2	Gast	6.4E–15	100
Pu-239	157_1	Phytopl	1.7E–11	100	157_2	Vasc pl	2.8E-08	100	157_2	Gast	9.5E–10	100
Pu-240	157_1	Phytopl	1.5E–11	100	157_2	Vasc pl	1.2E-08	100	157_2	Gast	4.1E–10	100
Pu-241	157_2	Phytopl	2.9E–20	100	157_2	Vasc pl	2.0E-20	100	157_2	Gast	6.9E–22	100
Pu-242	157_1	Phytopl	1.7E–11	100	157_2	Vasc pl	3.6E-08	100	157_2	Gast	1.2E–09	100
Ra-226	157_1	Phytopl	7.3E–11	100	157_2	Biv moll	3.9E-08	100	157_2	Soil inv	2.6E–09	93
Ra-228	157_2	Polych	5.0E–18	0	157_1	Biv moll	5.7E-18	99	157_2	Soil inv	2.2E–18	5
Se-79	157_1	Zoopl	1.2E–10	100	157_2	Zoopl	4.3E-09	100	157_2	Detr inv	2.7E–10	100
Sm-151	157_2	Zoopl	4.7E–18	100	157_2	Zoopl	6.0E-17	100	157_2	Gast	5.7E–18	100
Sn-126	157_2	Polych	9.5E–13	0	157_2	Crust	9.9E-11	3	157_2	Detr inv	7.0E–10	0
Sr-90	157_1	Crust	9.5E–13	100	157_2	Biv moll	7.8E-13	99	157_2	Amp	1.1E–12	100
Tc-99	157_1	Vasc pl	3.0E–13	100	157_2	Bent fish	4.7E-13	100	157_2	Bird egg	1.9E–10	100
Th-228	157_2	Phytopl	1.1E–18	100	116	Zoopl	4.1E-18	100	157_2	Lich	2.6E–22	100
Th-229	157_1	Vasc pl	8.5E–13	100	157_2	Zoopl	1.0E-09	100	157_2	Lich	7.6E–12	98
Th-230	157_1	Macro	9.4E–13	100	157_2	Zoopl	2.5E-09	100	157_2	Lich	1.9E–11	100
Th-232	157_1	Macro	8.1E–13	100	157_2	Zoopl	2.4E-09	100	157_2	Lich	1.8E–11	100
U-232	157_1	Bent mol	1.8E–12	100	157_2	Microph	2.2E-11	100	157_2	Lich	3.5E–11	100
U-233	157_1	Bent mol	1.2E–09	100	157_2	Microph	2.7E-08	100	157_2	Lich	4.3E–08	100
U-234	157_1	Polych	1.2E–09	100	157_2	Phytopl	2.7E-08	100	157_2	Lich	4.4E–08	100
U-235	157_1	Polych	1.1E–09	100	157_2	Vasc pl	2.6E-08	99	157_2	Lich	4.0E–08	100
U-236	157_1	Bent mol	1.1E–09	100	157_2	Microph	2.6E-08	100	157_2	Lich	4.1E–08	100
U-238	157_1	Polych	1.0E–09	100	157_2	Microph	2.4E-08	100	157_2	Lich	3.8E–08	100
Zr-93	157_1	Vasc pl	2.1E–14	100	157_2	Zoopl	7.4E-11	100	157_2	Lich	1.1E–12	100

* Three different C-14 sources in the SFR repository were used in the SR-PSU assessment, namely inorganic, organic and induced radiocarbon (**SR-PSU Main report**). However, as they were treated in the same way in the biosphere model, they had identical dose rates.

In the unit release rate simulations, the radionuclides reach the biosphere via groundwater discharge in biosphere object 157_2. As described in Chapter 6 and Section 7.4.1, this object is connected to a number of others, i.e. during the submerged period as connected sea basins and during the land period via surface water flow to downstream freshwater or mire objects. As is shown in Table 10-2, maximum dose rates are always found in object 157_2 or object 157_1. In terrestrial environments, maximum dose rates are always found in object 157_2 and also for freshwater ecosystems the highest abundance of peak dose rates are found there. The biosphere object 157_2 has no limnic successional stage; it evolves from a marine bay directly into a wetland. However, since it cannot be ruled out that small ponds (limnic ecosystems) would be present in the object during the early wetland period, exposure of limnic species has cautiously been considered. Most peak dose rates for the marine environment occur in biosphere object 157_1; these peak dose rates occur after object 157_2 has become land.

Calculated dose rates in terrestrial ecosystems are directly related to concentrations in soil whereas exposure in aquatic ecosystems can be related to either concentration in water (internal exposure) or in sediment (external exposure). Environmental concentrations depend on sorption properties, biological uptake and radionuclide half-life. A general remark is that for radionuclides with dominating external exposure, the peak dose rate is nearly always found in object 157_2. A detailed analysis is performed for four selected radionuclides in Section 10.4 below.

10.4 Comparisons with previous safety assessments

Although the overall biosphere assessment methodology has not changed since the previous assessment of the SFR repository (SAR-08, SKB 2008b), the radionuclide model of the biosphere has been refined, and the use of site data and site modelling results has successively increased (see Section 2.5). This section compares annual doses, given a unit release rate, calculated with the present SR-PSU model with the corresponding values reported in the latest assessment of the deep repository for high-level nuclear waste (SR-Site, SKB 2011) and in the previous assessment of SFR (SAR-08). However, before LDF values are compared (Sections 10.4.2 and 10.4.3) a brief summary of key differences between the assessments is presented as a background. This presentation of background information is focused on three areas: the biosphere objects, the numerical models and the parameter values.

10.4.1 Biosphere objects, model development and parameter values

In SAR-08, a chain of linked biosphere objects (i.e. areas affected by radionuclides from the repository) were identified, but only the first object was analysed in the assessment. This object was a future lake-mire system (Bergström et al. 2008), later referred to as object 116. In SR-Site, several potential discharge areas were linked through surface streams in the landscape and assessed in parallel (including object 116). However, the most upstream area (object 121_3) in one chain of objects yielded the highest LDFs for most radionuclides (Avila et al. 2010). In the present SR-PSU assessment, biosphere objects were also linked through the flow of surface water. However, groundwater from the repository primarily discharged into one object (157_2), and radionuclides reached downstream objects (including object 116) with surface water. All of the objects in the chain were assessed, and object 157_2 yielded the maximum LDF for the majority of radionuclides (Table 10-1).

In SAR-08, ecosystem-specific dose conversion factors were calculated from dynamic simulations of natural ecosystems that did not change over time. Each ecosystem was simulated separately, and to account for accumulation in earlier successional stages the simulations were run for extended periods of time (i.e. 20,000 years). In SR-Site, this approach was replaced by explicitly modelling the transitions between ecosystems (i.e. lake isolation and terrestrialisation, see Chapter 8), and biosphere objects were modelled continuously over an interglacial (9000 BC to 9500 AD). A similar approach was used in SR-PSU, running simulations from present day conditions to 20,000 AD. In all assessments, agricultural systems were assessed in a more stylised manner. Agricultural soil concentrations were in SAR-08 assumed to be similar to those in peat. In SR-Site and SR-PSU, the initial inventories in drained agricultural soils were estimated from radionuclide concentrations in the mire ecosystem, and soil concentrations were modelled dynamically after drainage.

The model complexity, in terms of included compartments and radionuclide fluxes, increased considerably from SAR-08 to SR-Site, especially with respect to the mire ecosystem. Moreover, the regolith layer resting on the bedrock was included in the SR-Site model, and radionuclides from the geosphere (bedrock) were discharged into the till layer, rather than into surface water or surface peat. The basic model structure in SR-PSU was the same as in SR-Site, but compartments representing storage of radionuclides in organic matter (and fluxes corresponding to mineralisation) were added to get a better representation of the fate of radiocarbon (Chapter 8). In all three assessments, ecosystem productivity affected consumption of food from the biosphere object. However, in SR-PSU the diet was explicitly related to several different historical land use practices and food intake by hunters and gatherers was constrained by protein toxicity.

Compared to previous assessments, SR-Site utilised data collected at the site to a higher degree. Modelling of near-surface hydrology and the landscape development underpinned parameters describing the biosphere object. In SAR-08, element-specific parameters describing adsorption (K_d) and biological uptake (CR) were based on literature data, whereas site data were introduced and combined with literature data in SR-Site. In the SR-PSU biosphere assessment, a similar approach was used for deriving parameters reflecting surface hydrology and geometric properties of biosphere objects. Moreover, additional element-specific site data were collected and assessed (Sheppard et al. 2011), and data from Forsmark was given a greater weight than in previous assessments.

10.4.2 Comparison of LDF values in SR-PSU and SR-Site

In the SR-Site safety assessment, unit release rate simulations, in which 1 Bq y^{-1} was released to the surface ecosystems, were used to calculate annual doses, using best estimates as parameter values (Avila et al. 2010). In general, LDF values from SR-Site were similar to those reported for SR-PSU (Figure 10-1, Appendix 4), and for about half of the radionuclides the difference in LDF values was within a factor of two. Moreover, for most radionuclides the dominating exposure pathway (e.g. ingestion of food or water) and the time period yielding the maximum LDF (submerged, or early or late land period) were similar in both assessments. This was not surprising since the most important biosphere objects were similar in the two assessments, i.e. relatively small sea basins developing into mire ecosystems, as were the structures of the radionuclide models.

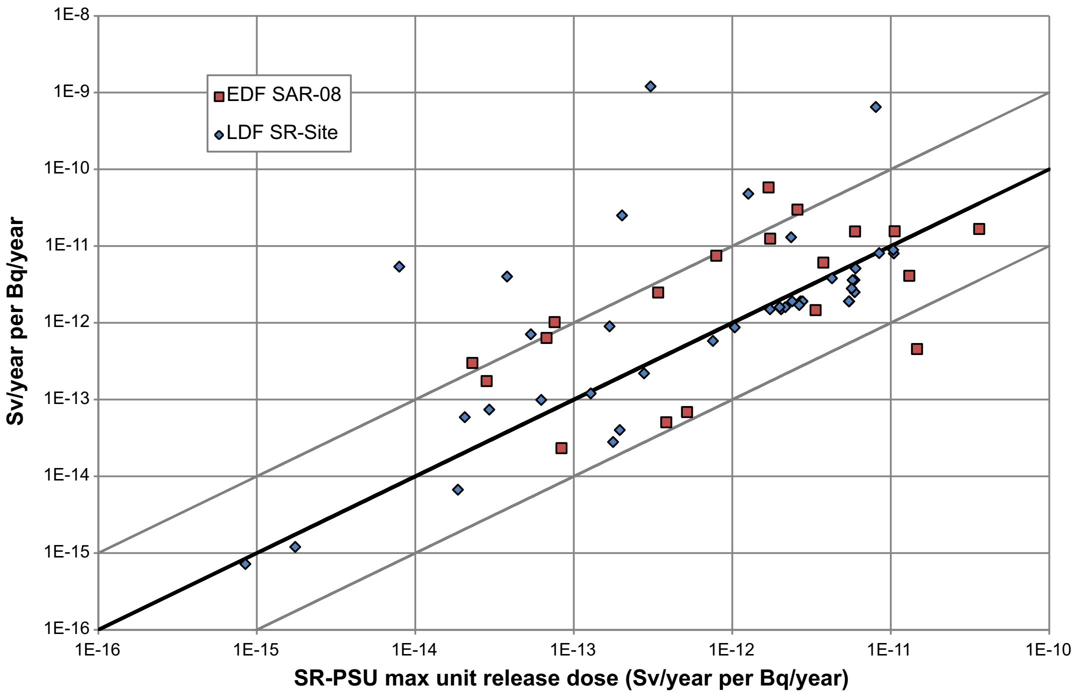


Figure 10-1. *Maximum LDFs (Sv y^{-1} per Bq y^{-1}) from the previous radionuclide models used in safety assessments SAR-08 (red squares) and SR-Site (blue diamonds) versus the corresponding LDF from SR-PSU (x-axis). Note that SR-PSU LDFs were calculated to match those of the previous safety assessments, either as mean values from probabilistic simulations (SAR-08) or from best estimates of parameter values (SR-Site).*

There was a tendency for slightly higher LDFs in SR-PSU results as compared to the earlier assessment, and more than two thirds of the LDFs were higher in SR-PSU. However, seven of the radionuclides had an LDF that was more than one order of magnitude smaller in SR-PSU than in SR-Site. Given the overall good agreement between the two assessments, and the general trend of higher LDFs in SR-PSU it is reasonable to attribute LDF deviations of more than one order of magnitude to differences in radionuclide (or element) specific properties, or to differences in the processes of importance for a specific radionuclide only.

Increased sorption of radionuclides in the lower regolith was the most important factor explaining lower LDFs in SR-PSU compared to SR-Site. That is, higher K_d-values in till for Se-79, Nb-94, Sn-126, Np-237 and Ag-108m increased the accumulation in the lower regolith and retarded transport to surface regolith layers, leading to lower exposure. This shift in parameter values was due to the improved description of sorption properties under reducing conditions in deep till, owing to SR-PSU site investigations (Sheppard et al. 2011). For Se-79 and I-129 plant uptake in crop also had a significant effect on the difference in LDF values. That is, CR-values for crops were considerably lower for these two radionuclides in SR-PSU as compared to SR-Site, and this change was also due to improved descriptions of equilibrium conditions in agricultural soils relevant for Forsmark (Sheppard et al. 2011).

In SR-PSU, the representation of several processes describing transport and accumulation of carbon were improved. For example, accumulation (and decomposition) of organic matter in aquatic sediments and deep peat was included in the model, and the representation of degassing was updated. However, the primary exposure route for C-14 in SR-Site was ingestion of fish during the transition from a sea bay to a lake. Thus, the above mentioned model updates could not explain the significantly lower LDF for C-14 in SR-PSU. Instead, the main explanation for the difference was that conservative estimates for water exchange at the beginning of lake isolation (in SR-Site) had been replaced by more reasonable assumptions of intermediate water exchange during the transition from a bay to a lake. Moreover, constraints on the amount of contaminated fish that could reasonably be consumed by the most exposed group lowered the LDF of C-14 by approximately one order of magnitude.

10.4.3 Comparison of LDF values in SR-PSU and SAR-08

In SAR-08 the dose conversion factors were derived from Monte-Carlo simulations on data sets drawn from parameter distributions (Bergström et al. 2008). To allow for unbiased comparisons, the same approach was used to derive LDFs for SR-PSU (see Section 10.9 for details). Dose conversion factors for short-lived radionuclides (e.g. Am-242m, Co-60, Cs-137, H-3, Ni-63 and Sr-90) were not calculated for all ecosystems in SAR-08, and thus these radionuclides were not included in the comparison. Moreover, to be consistent with the risk estimation in SAR-08, the LDFs for the well were multiplied by the probability assigned to drilling a well in the plume downstream of the repository ($p = 0.1$, SKB 2008b).

In general the LDF values calculated with the SR-PSU model (and parameters) did not correspond as well to LDFs reported in SAR-08 as to values reported in SR-Site (Figure 10-1, Appendix 4). This was expected, given the developments in numerical models, parameters and the biosphere objects used in the three assessments. There was a fair correspondence between SR-PSU and SAR-08 calculations with respect to the dominating exposure route (ingestion of water, ingestion of food or external radiation), but the LDF values typically deviated by more than a factor of eight between the two assessments. For three radionuclides (Ag-108m, C-14 and Nb-94) the highest exposure resulted from hunting and gathering in both SR-PSU and SAR-08 calculations, but otherwise the ecosystems yielding the highest exposures did not match.

There was a clear tendency for sorbing radionuclides to have lower LDF values in SR-PSU calculations than reported in SAR-08 (e.g. Ho-166m, Am-241, Cs-135, Ag-108m and Np-237). This pattern was primarily due to a lack of retardation of radionuclides in the deep regolith layer, as all released radionuclides reached the surface in SAR-08. The shift from literature based parameter values to estimates representing conditions in Forsmark also caused some of the more significant deviations. For example, site-specific estimates of sorption (K_d) in peat with respect to Mo-93 and Tc-99 were considerably higher than the literature values used in SAR-08, resulting in significantly higher LDFs from the SR-PSU calculations.

As the local catchment areas of the biosphere objects used in SAR-08 were large compared to those of the upstream lake-mire biosphere objects used in SR-PSU, dilution in surface water and surface regolith was expected to cause systematically lower concentrations of non-sorbing radionuclides in SAR-08. However, the effect of dilution in surface sediments was overshadowed by developments in the numerical model introduced after the SAR-08 assessment. For example, a larger dilution of C-14 in the lake object 116 was offset by discharging all radiocarbon directly into the water, ignoring degassing in upstream wetlands and protein toxicity from a one-sided diet.

10.5 Analysis of transport and exposure in the biosphere

10.5.1 Methodology and selection of radionuclides

In this section we examine simulated transport and accumulation of selected radionuclides in the surface ecosystems through a detailed analysis of a unit release rate, i.e. a constant release of 1 Bq per year from the bedrock to the lowest regolith layer of the biosphere. Results were derived by running the biosphere base calculation case (BCC1) for c. 18,000 years after repository closure (i.e. until 20,000 AD, see Section 7.4.1 for details). This calculation case assumes a climate and landscape development that corresponds to global warming, which means that the climate will be similar to that of today (temperate conditions) during the entire simulation period. For the analysis we selected four relatively long-lived radionuclides (half-life longer than 4,000 years), each with its unique set of properties.

The first radionuclide to be studied was radiocarbon (C-14). C-14 is unusual in many ways; it does not significantly adsorb to soil particles or suspended material, it is highly volatile and will degas when in contact with the atmosphere, and long-term accumulation occurs through plant fixation of primarily atmospheric carbon and subsequent storage of organic matter in deep peat. The second radionuclide was chlorine-36 (Cl-36). This radionuclide has weak sorption properties, and as chlorine is a plant nutrient it has significant concentrations in plant biomass. In these two respects Cl-36 is similar to C-14, but Cl-36 was treated as non-volatile. Moreover, although Cl-36 accumulates in living plants, it is primarily stored in inorganic form in organisms, which leads to a relatively fast release upon plant senescence and decomposition.

The third radionuclide, Mo-93, has highly variable sorption properties. While molybdenum is relatively mobile in inorganic regolith layers, it adsorbs much more strongly to sediments that are rich in organic matter, including peat and post-glacial clay gyttja. Thus, it tends to be poorly retained in deep soil layers, but accumulates in sediments that may expose humans and non-human biota. Moreover, it is redox sensitive. The last radionuclide, Ni-59, is long-lived with a half-life of 76,000 years. It is immobile, especially in deep regolith layers. Thus, while it is unlikely to cause exposure of organisms in surface ecosystems (in time spans of thousands of years), it has great potential for accumulation in glacial clay. This means that humans that drain and cultivate a mire after long-term accumulation could be exposed to this radionuclide.

The detailed results of each of these four radionuclides are presented below. First, the distribution of the total inventory (or activity) over biosphere compartments in the radionuclide model is examined. Then, the temporal patterns of environmental concentrations in regolith compartments, and surface water are studied. As inorganic carbon occurs in gaseous phase at normal air temperature, concentrations of C-14 in the canopy atmosphere are also examined. Patterns in radionuclide accumulation (inventories and concentrations) are related to environmental properties and drivers such as vertical and horizontal water fluxes, regolith depths, degassing rates, and radionuclide-specific properties (e.g. degree of sorption and plant uptake). Annual doses and dose rates are presented and related to the environmental media that caused the exposure. Doses from inhalation of radionuclides present on dust particles are calculated from concentrations in air for all radionuclides (Table 10-1, Saetre et al. 2013a). However, as these air concentrations are simply a scaling of the environmental concentrations in the upper regolith layer they are not further discussed in this chapter.

10.5.2 Detailed interpretation of unit release results for C-14

Accumulated inventory in model compartments

C-14 is a highly mobile radionuclide ($K_d = 0$ is applied in the modelling), and the total radionuclide inventory in object 157_2 approached a steady-state relatively fast in both the submerged and the land (limnic and terrestrial) periods for a unit release (Figure 10-2). Less than 10% of the activity released during the submerged period was retained in the object (accounting for radioactive decay), whereas the corresponding number was less than one in a thousand during the land period (see the gap between the red dotted and the black solid lines in Figure 10-2). The accumulated inventory in marine sediments was inherited by terrestrial regolith layers. However, at equilibrium the total inventory in the land period was less than a third of that in the submerged period. This partly reflected a larger vertical flux of water through the regolith layers during this phase. For example, the vertical flux of water through till (which holds the largest inventory) was 0.02 and 0.17 m y^{-1} during the submerged and the land periods, respectively.

During the submerged period, RegoLow was the dominant inventory in 157_2 (~ 90% of the total activity), and small additional amounts were found in the overlying sediments, with RegoGL and RegoPG each contributing ca. 5% (Figure 10-2). The distribution of the inventory reflects the combined effect of regolith thickness, porosity and (upward) groundwater flux. During the land period, the inventory was dominated by the same compartments. However, the contribution of radionuclide in organic form was more important, with RegoUp_org and RegoPeat_org contributing almost 30% to the total inventory, in spite of their limited thickness.

Biosphere object 157_1 received radionuclides with the surface water from object 157_2. However, during the early submerged period, the majority of C-14 released to the primary object was exchanged with other basins than 157_1, and thus did not reach this downstream object directly. During the land

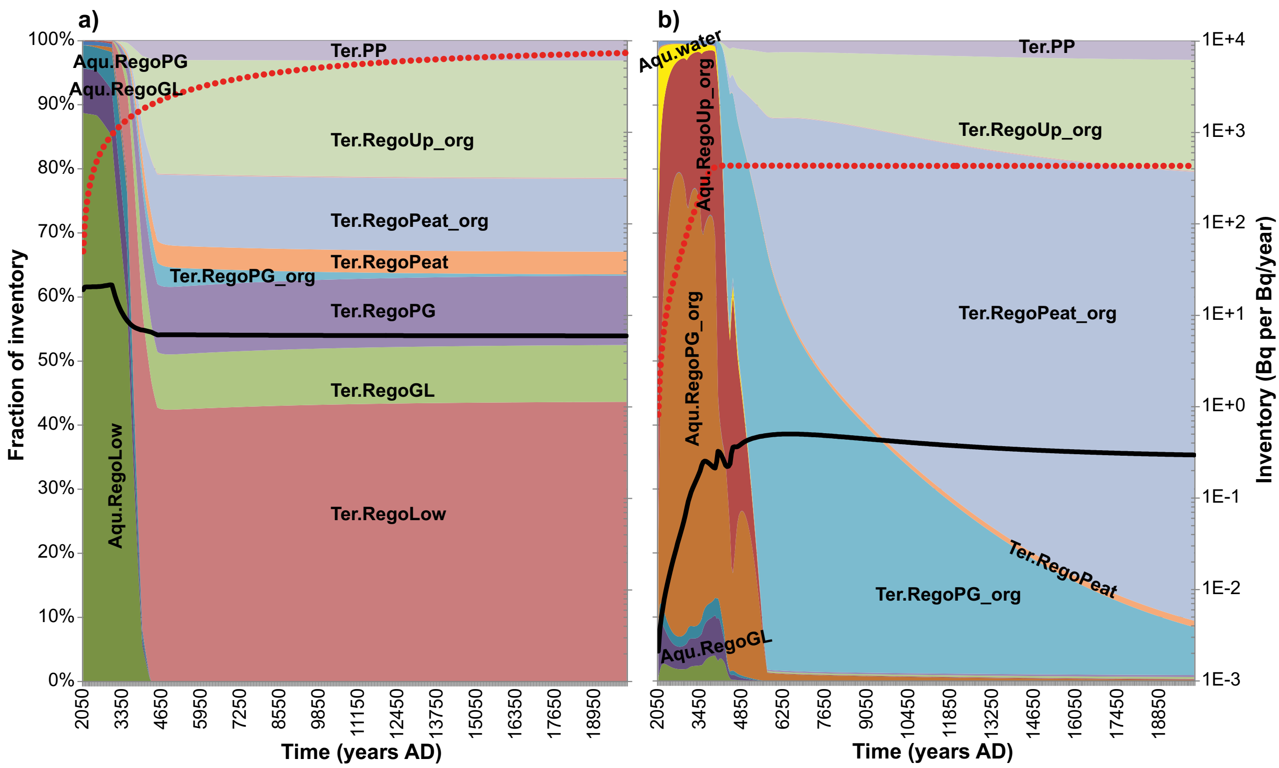


__Figure 10-2.__ Distribution of the total inventory of C-14 among ecosystem compartments, illustrated by the coloured areas (referring to the linear left axis of each figure), and the inventory/release (right axis of each figure), presented as functions of time for two biosphere objects. a) Biosphere object 157_2, which received a constant input of radionuclides (1 Bq y^{-1}) via groundwater from the bedrock. b) Downstream biosphere object 157_1, which received radionuclides by surface water from object 157_2. The lines represent the total inventory of C-14 in the object (black line) and the cumulative activity release to the object (accounting for radioactive decay; red dotted line) on the logarithmic right axes.

period, the major export pathway from the wetland in 157_2 was degassing and only a small fraction of released C-14 reached the downstream object with surface water. Consequently, it is not surprising that the inventory was one order of magnitude lower in the downstream object 157_1 than that in 157_2 (Figure 10-2).

In contrast to object 157_2, the largest part of the inventory in 157_1 was found in organic sediment layers during the submerged period. The fractions in aquatic sediments were growing relatively fast, reflecting that the rate of carbon fixation was fast compared to the export through horizontal water movement and gas exchange. During the land period, the distribution of the inventory in object 157_1 was more similar to that of 157_2, as plant uptake at the surface was an important pathway for C-14 accumulation in both objects. However, due to the geometry of the objects, a much deeper peat layer developed in the lake basin of object 157_1 than in 157_2 (depth of 1.4 m vs. 0.1 m), and organic matter in this peat layer dominated the total inventory in 157_1 (Figure 10-2b). As radionuclides did not enter the object from the bedrock, the fraction of inventory in the deep regolith layers was also very small in the land period (in contrast to the conditions in object 157_2).

Activity concentration in sediments and soils

Having reached steady-state conditions, the activity concentration of C-14 in the deeper regolith layers of 157_2 was roughly proportional to soil porosity and inversely proportional to the soil density and the groundwater flux rates through the layer (Figure 10-3). As with the inventory, the highest concentrations were observed during the submerged period, and activity concentrations decreased in the land period, due to an increase in vertical groundwater flux. In biosphere object 157_2, the vertical gradient in flux-rates was relatively small during both the marine and the land period, and thus differences in concentration between inorganic regolith layers were primarily driven by physical sediment properties (i.e. density and porosity). The dynamics in C-14 concentration in the upper aquatic sediments reflected that of the water column, as the primary production was the main pathway for carbon accumulation in the organic sediments. The peak was reached in the small bay, before the coastline passed and the sea bottom emerged out of the sea.

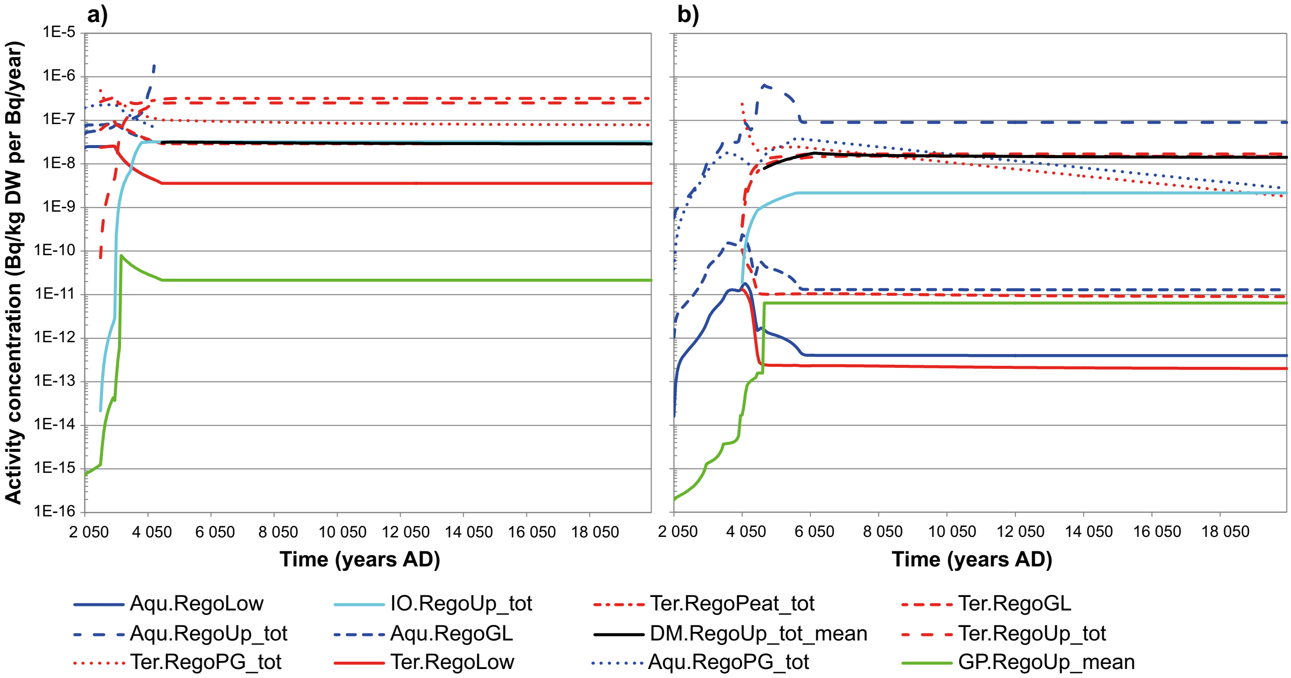


Figure 10-3. *Activity concentrations for unit release (Bq kgDW^{-1} per Bq y^{-1}) of C-14 in regolith layers in two biosphere objects. a) Biosphere object 157_2 received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. b) Downstream biosphere object 157_1 received radionuclides with surface water from 157_2. Dark blue lines represent concentrations in regolith layers in the aquatic part of the model. Abbreviations of regolith layers are explained in Table 8-1; prefixes represent ecosystems or land use variants. For simplicity, total concentrations are shown for regolith layers with both an organic and an inorganic radionuclide inventory (indicated by "tot").*

The activity concentration in agricultural soil was primarily a function of the concentration in the upper regolith horizons that can be cultivated (peat, post-glacial clay gyttja and glacial clay; the drained-mire farmer land use variant), the concentration in vegetation used for fertilisation (the infield-outland farmer and the garden-plot household variants) and the concentration in water used for irrigation of vegetables (the garden-plot household variant). The highest concentration of C-14 resulted from cultivation of the drained mire object and horticultural cultivation fertilised by sea-weeds, followed by long-term fertilisation of wetland hay (Figure 10-3). The initial inorganic C-14 inventory in drained regolith layers was generally high, but activity concentrations in the drained-mire farmer variant were similar to the infield-outland farmer variant in 157_2 where cultivated soil was fertilised with hay. Irrigation with well water or fertilisation with ash (garden-plot households) resulted in significantly lower concentrations in soil, compared with the other land use variants for both biosphere objects (Figure 10-3).

Radionuclide concentrations in all regolith layers in 157_1 were one to four orders of magnitude lower than in 157_2. This was primarily due to additional degassing of C-14 in surface peat of the downstream object, and dilution via groundwater in deeper regolith layers. The two exceptions to this pattern were the concentration in soil resulting from draining and cultivating the mire at a late succession stage (drained-mire farmer), and the garden-plot household variant. For these land use variants, the concentration difference between the objects was less than one order of magnitude. This was due to a larger long-term accumulation of carbon in the lake basin of 157_1, and a relatively small difference in the C-14 concentration of irrigation water (see below).

Activity concentration in water

During the early development of the Forsmark landscape (the marine period), the exchange of water between neighbouring sea basins was large. The exchange of water between connected basins was bidirectional and fluxes of water changed with time. Major changes in concentrations of radionuclides in water occurred when flow paths changed due to the shoreline displacement (Figure 10-4). The loss of C-14 to the atmosphere by degassing was small compared to transfers by water exchange between adjacent basins. During this period, the highest concentration of C-14 was always found in the object receiving the discharge of radionuclides from the repository directly via groundwater (157_2), and the concentration differences between 157_2 and the other objects were relatively small (within an order of magnitude). Moreover, partial isolation of a basin receiving radionuclides by exchange of water from connected basins led to a decline in water concentration, and complete isolation led to a continuous concentration decline (e.g. object 160 at 3200 AD, object 121_1 at 3800 AD, and object 159 at 4100 AD). Simultaneously as the biosphere objects were isolated, the concentrations in non-isolated sea objects increased, as these then received a larger proportion of the released activity.

When biosphere object 157_2 emerged out of the sea (~ 4300 AD), radionuclides discharged into 157_2 only reached downstream objects 157_1 and 116. The C-14 concentration in water of these objects was determined by the release of radionuclides to the object, the degassing rate, and the horizontal flux of surface water. In the mire ecosystem of 157_2, C-14 losses by degassing were much larger than the horizontal transport with surface water, and thus less than 2% of the C-14 flux reached the downstream object. In this object (157_1) the concentration peaked after isolation, (due to relatively small fluxes of surface water). With time, the surrounding mire vegetation expanded into the lake, and groundwater had to pass through mire peat. Thus, the concentration in surface water dropped as C-14 was lost through degassing to a larger extent and less of the radionuclide reached the lake/stream in the object.

Future human settlers may use water in the form of surface water (after lake isolation) and/or well water (when the biosphere object is one metre or more above sea level) for drinking, for watering livestock, and for irrigation of small-scale horticulture. In biosphere object 157_2, the activity concentration of C-14 was highest in the dug well (Figure 10-4), and thus, drinking and irrigation water for all exposed populations of permanent inhabitants living in or using resources from the object was collected from the dug well (except hunter-gatherers that use surface water only). The dug well in the primary object extracted water from the first regolith layer (till), and provide groundwater with an activity concentration that is similar to that of the pore water of this soil layer (Werner et al. 2013a). Thus at steady-state the concentration in water from a dug well in 157_2 is reciprocal to the vertical groundwater flux in till.

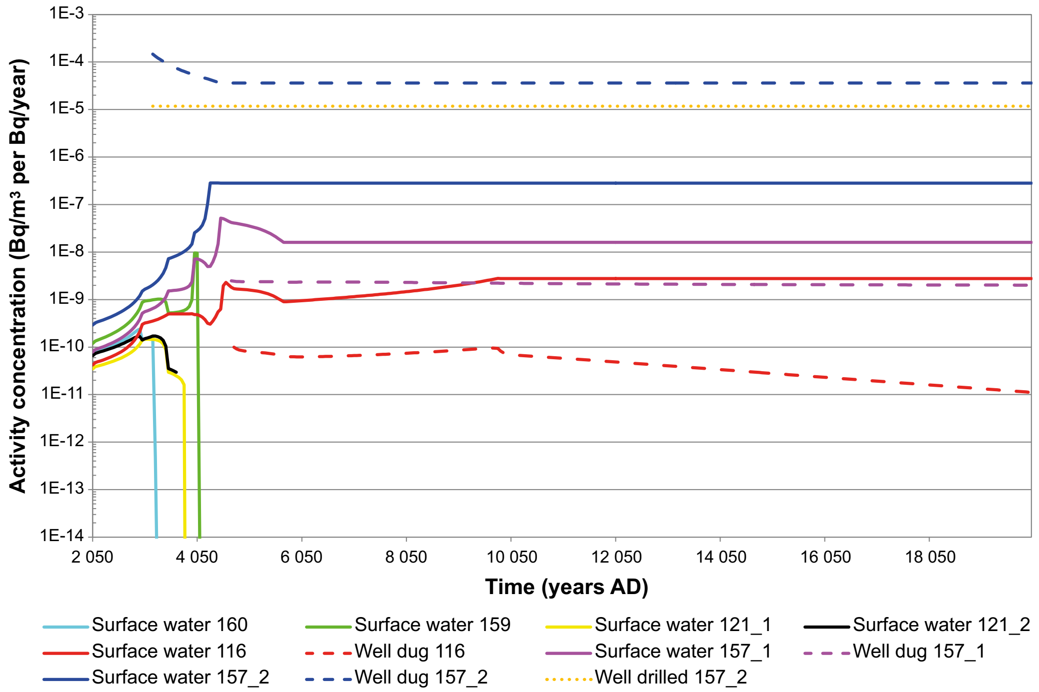


Figure 10-4. *Activity concentrations for unit release (Bq m^{-3} per Bq y^{-1}) of C-14 in surface water of seven biosphere objects. Solid lines represent concentrations in sea basins during the submerged period and concentrations in surface water on land (lakes, streams or other surface water) during the land period. Biosphere object 157_2 received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. In the land period, objects 157_1 and 116 are located downstream from 157_2. Note that there is no external source of radionuclides to the other biosphere objects (121_1, 121_2, 159 and 160) during the land period.*

For C-14, the concentration in water from a dug well in biosphere object 157_2 was three times as high as that from a drilled well, and two order of magnitude higher than that of surface water in the object. Horizontal fluxes of groundwater diluted deep groundwater in surface peat, about one order of magnitude (see Cl-36). However, the main cause for the large drop in concentration in surface water was the effective degassing in surface peat. Permanent residents in the downstream object who are at a sufficient level of technology (i.e. a garden-plot household or farmers draining a mire) could use water from a drilled well.

Activity concentration in canopy air

Inorganic carbon occurs in gaseous phase at normal air temperature, and the fixation of gaseous carbon (i.e. CO_2) is a primary pathway for both ingestion of terrestrial C-14 and accumulation of C-14 in soil organic matter. In the biosphere radionuclide model, the activity concentration of gaseous carbon in canopy air is a function of the release of C-14 to the atmosphere and vertical and horizontal dilution with ambient air (see Section 8.3 and Saetre et al. 2013a). In the model, C-14 is released to the atmosphere as a function of degassing from surface peat (mire ecosystem), from cultivated soil (agricultural ecosystems) and from leaf-intercepted water (garden plot). In soils fertilised with organic matter, there is also a release of C-14 from the decomposition of labile organic carbon (infield-outland and garden plot fertilised with seaweeds).

The concentration of gaseous C-14 and the specific activity in the canopy atmosphere was two orders of magnitude larger in the mire ecosystem than in the infield-outland cereal field in object 157_2 (Figure 10-5a, Table 10-3). This difference was primarily due to the low input rate of C-14 with organic fertilisers to the infield soil. The difference in atmospheric concentration of C-14 between the mire ecosystem, the drained and cultivated mire (cereals, tuber or fodder), and the garden plot was however within a factor of four. The variation in C-14 concentration between these land use variants was due to the combined effect of differences in the input term of C-14 to the canopy atmosphere and the rate of dilution, which primarily depended on plant canopy structure.

The canopy atmospheric concentration in the natural ecosystem (and the infield-outland farmer land use variant) was approximately 15 times lower in the downstream object 157_1 as compared to that in 157_2 (Figure 10-5). This difference corresponded well to the difference in C-14 concentration in pore water of surface peat in the two objects (data not shown). For the drained-mire farmer variant the difference was even larger. Irrigation water was the main source of radionuclides in the garden-plot household variant when well water was available. Thus, the concentration difference in the canopy atmosphere was limited to an order of magnitude between the two objects in this land use variant, reflecting the difference in C-14 concentration in water extracted from a dug well (in object 157_2) and a well drilled into the bedrock (used in object 157_1).

Table 10-3. The specific activity (SA) of C-14 resulting from a unit release rate to biosphere object 157_2. The SA in the plant canopy atmosphere is listed for the mire ecosystem (~ 15·10^4 m^2) and three types of cultivated land: an infield-outland cereal field (~ 5·10^4 m^2), a household kitchen garden (~ 150 m^2), and arable land resulting from draining a mire (~ 6·10^4 m^2). The importance of turbulent air movement for dilution in the canopy atmosphere is expressed as the ratio of the transfer rate in the vertical direction and the total atmospheric transfer rate (vertical and horizontal). The specific activity in soil pore water and the fraction of C-14 plant fixation originating from root (rather than canopy) uptake are added for reference.

Land use variant	To atmosphere Bq m^{-2} y^{-1}	SA canopy Bq kgC^{-1}	Turbulent dilution	SA soil Bq kgC^{-1}	Root Uptake
Mire	6.5E–06	1.5E–07	97%	2.0E–05	74%
Infield-outland	1.2E–07	4.8E–09	89%	2.4E–08	9%
Garden-plot*					
vegetable	3.4E–06	4.6E–08	70%	2.1E–06	49%
tuber	3.4E–06	4.4E–08	61%	2.1E–06	50%
Drained-mire					
tuber	1.7E–06	4.2E–08	96%	2.1E–06	51%
fodder	1.7E–06	9.0E–08	94%	2.1E–06	33%
cereal	1.7E–06	6.6E–08	90%	2.1E–06	40%

* Irrigation water is the primary source of C-14.

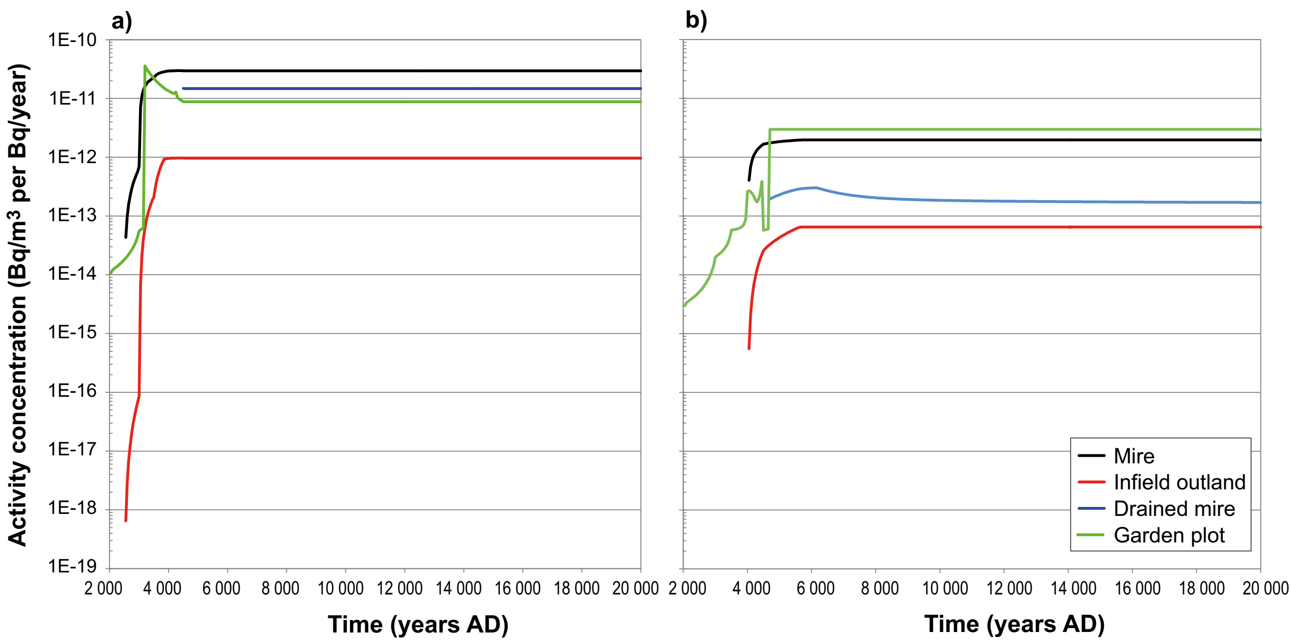


Figure 10-5. *Activity concentrations for unit release rate (Bq m^{-3} per Bq y^{-1}) of C-14 in canopy atmosphere in two biosphere objects. a) Biosphere object 157_2 received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. b) Downstream object 157_1 received radionuclides with surface water from 157_2.*

Dose to humans for unit release

Ingestion of food was the dominant exposure route of C-14 for all four land use variants (hunter-gatherers, infield-outland farmers, drained-mire farmers and garden-plot households). The radionuclide concentration in food items was proportional to the specific C-14 activity in water for aquatic food items. Similarly, the activity concentrations in foraged and cultivated terrestrial food items were proportional to the specific activity of the canopy atmosphere (C-14) and of the pore water (see Saetre et al. 2013a for details).

During the submerged period, several sea basins contributed to the dose for a unit release (i.e. 157_1, 157_2, 159 and 116), and the production of aquatic food covered the full protein demand of a hunter-gatherer community (Figure 10-6). The concentration of C-14 in surface water (Figure 10-4) and the availability (i.e. the production) of aquatic food were particularly important sources of temporal variation in the LDF during both the submerged and the land periods. As both of these factors were affected by threshold events, driven by the landscape development, the change in the LDF was occasionally fast. For example, the diminishing water body in object 157_2 caused the LDF to drop sharply before year 4000 AD, when the water depth fell below the threshold for sustainable fish production (1 m).

A second drop in the C-14 concentrations of water and aquatic food occurred when the biosphere object emerged out of the sea (after 4000 AD), and a significant part of the C-14 was exported to the atmosphere through mire degassing. However, as the exchange of water between basin 157_1 and the outer basins declined, the radionuclide concentration in water increased and peaked at the time for lake isolation (4500 AD). As mire vegetation expanded into the lake basin, an increasing fraction of the C-14 from the upstream mire was degassed before it reached the lake water. At 5700 AD mire vegetation covered the entire basin of lake 157_1, and the remaining stream was too shallow to support fish production for human consumption. Consequently, the LDF dropped sharply. This pattern was repeated when the downstream lake 116 was covered by mire vegetation (c. 9700 AD).

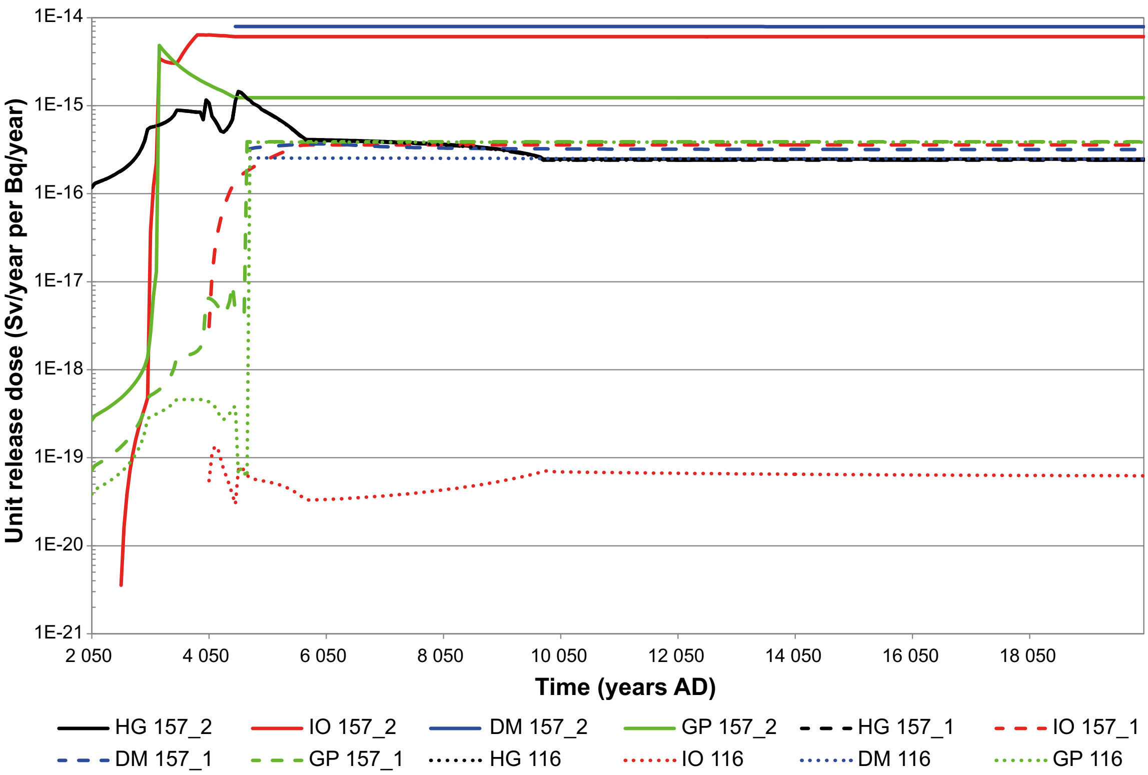


Figure 10-6. *The dose for unit release rate of C-14 to human inhabitants living in and/or using natural resources from the biosphere objects. Solid lines represent dose resulting from exposure in biosphere object 157_2, which received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. Dashed and dotted lines represent dose resulting from exposure in downstream objects 157_1 and 116, respectively. Colours indicate different land use variants: hunter-gatherers (HG), drained-mire farmers (DM), infield-outland farmers (IO), and garden-plot households (GP).*

Foraging mires in the landscape resulted in low exposure, in spite of relatively high C-14 concentrations in the canopy atmosphere and in the pore water of surface peat. This was because the production of natural food items in biosphere object 157_2, where discharge of radionuclides from the repository via groundwater may occur, could only support a small fraction of the energy demand of a band of hunters and gatherers. Since degassing was efficient during the land period, only small amounts of C-14 reached the downstream objects 157_1 and 116.

During the land period, biosphere object 157_2 could fully support farmers, who used the object for cultivation or for harvesting wetland hay. Draining and cultivating biosphere object 157_2 resulted in the highest dose from a constant unit release. This was expected as this land use variant was associated with relatively high C-14 concentrations in soil pore water (equal to those in surface water for this object) and the canopy atmosphere (Figure 10-4a, Figure 10-5a). The infield-outland farmers also received a relatively high dose from a unit release. However, for this variant, exposure was primarily caused by ingestion of meat and milk, produced by using wetland hay from the mire as winter fodder.

The exposure resulting from irrigation, and fertilisation with seaweeds (submerged period) or with wood/peat ash (land period), was examined for the garden-plot households. The dose for unit release from fertilisation with seaweeds increased with time as a function of concentrations in water. However, irrigation with water from a dug well gave significantly higher exposure. This land use variant was associated with relatively high C-14 concentrations in both pore water and the canopy atmosphere (Figure 10-5), but as produce from the garden plot only covered a fraction of the total food intake in this land use variant, the exposure from ingestion was less than that in the other two cultivation variants.

The exposure from drinking water was highest in the land use variant utilising a dug well, and the contribution from this pathway ranged from 10% (drained-mire farmers) to 60% (garden-plot households) of the total dose from a unit release. As the C-14 concentration in surface water was two orders of magnitude lower than in well water (Figure 10-4), exposure from drinking surface water was limited, and typically drinking water contributed with a few percent of the dose for unit release to hunter-gatherers.

Dose rate to non-human biota for unit release

Spatial variations in dose rates for any organism group are expected to roughly follow that of the environmental media (cf. Section 10.3). For C-14, maximum dose rates for unit release resulted from exposure in object 157_2 (Figure 10-7). The highest maximum dose rate was seen in the freshwater ecosystem followed by the marine ecosystem. Maximum dose rates in freshwater and marine ecosystems in object 157_1 were of the same magnitude as in the marine and the terrestrial ecosystems in 157_2. Exposure in all ecosystems of object 116 was much lower than in corresponding ecosystems of 157_1 and 157_2 (Figure 10-7).

The dose rates for unit release of C-14 to the most highly exposed freshwater organisms were caused by internal exposure. Since carbon uptake was modelled as a function of the specific C-14 activity in water, the dynamics of internal (and total) dose rates followed that of concentrations in surface water in 157_2 (Figure 10-4). Moreover, differences between organism groups reflected differences in organism carbon content (Figure 10-8). The exception to this pattern was Phytoplankton, which received much lower dose rates than other organism groups due to the fact that internal radiation has a limited impact on organisms of very small size.

For the most exposed terrestrial and marine organisms, the dynamics of the total dose rates followed those in the surface peat layer (RegoUp, Figure 10-3) and the surface water (Figure 10-4), respectively. External exposure was of importance for a limited number of organism types: freshwater and marine Phytoplankton (99% and 70% of total dose rate, respectively) in both biosphere objects, and marine Benthic molluscs, Macroalgae, Vascular plants and Polychaetes (15–20% of total dose rates) in object 157_2.

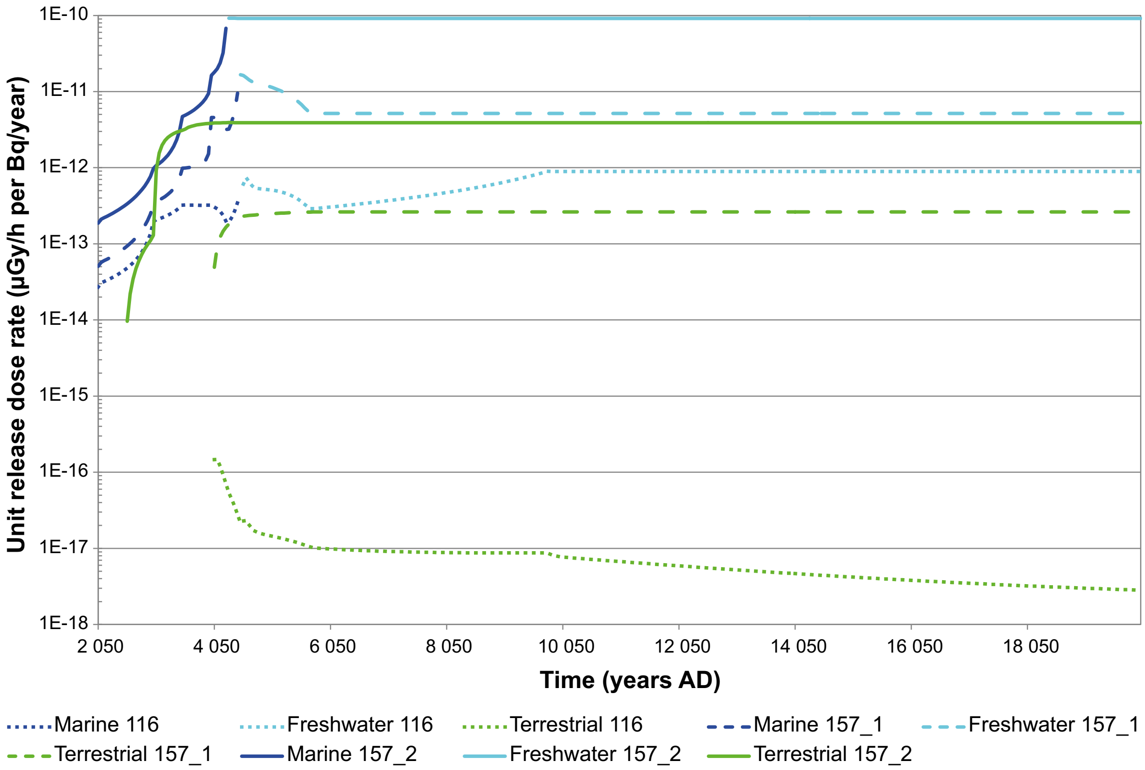


Figure 10-7. *Dose rates for unit release caused by C-14 to non-human biota inhabiting the future Forsmark landscape. The lines represent maximum dose rates for unit release across all examined organism groups within each ecosystem and biosphere object. Solid lines represent dose rates resulting from exposure in biosphere object 157_2, receiving a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. Dashed and dotted lines represent dose rates resulting from exposure in downstream objects 157_1 and 116, respectively. Colours indicate marine, freshwater (lake and stream), and terrestrial (mire) ecosystems.*

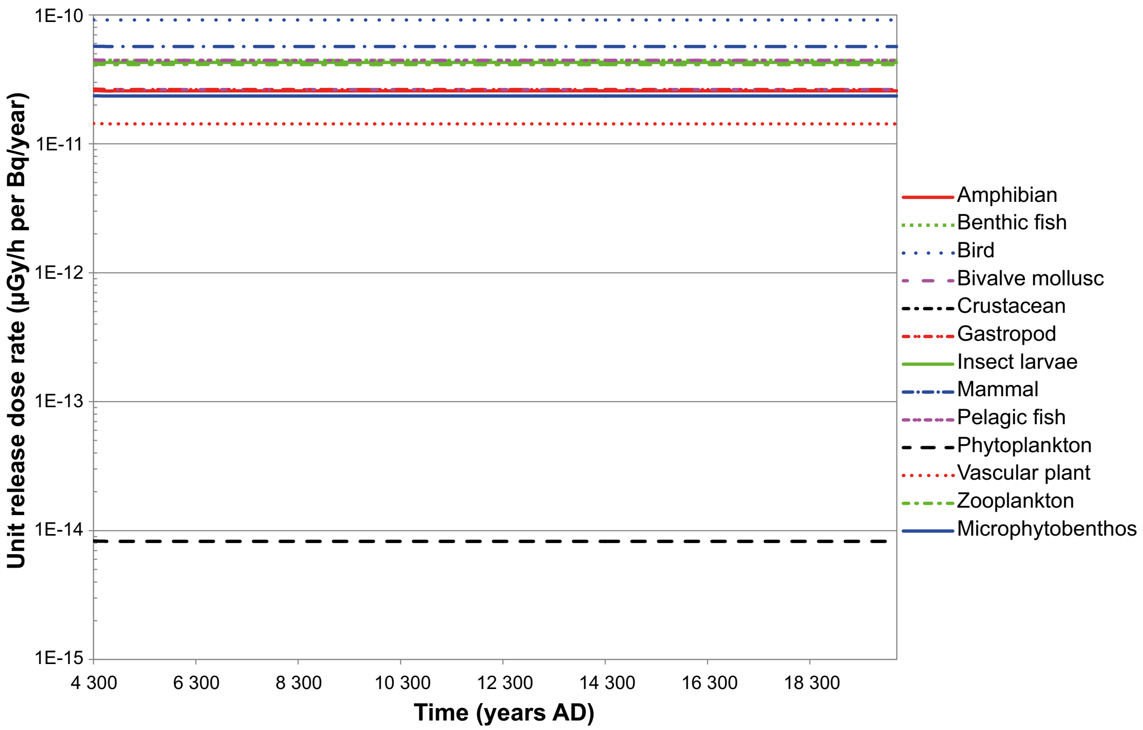


Figure 10-8. *Total dose rates for unit release for organisms living in the freshwater ecosystem in biosphere object 157_2.*

10.5.3 Detailed interpretation of unit release results for Cl-36

Accumulated inventory in model compartments

Cl-36 is a long-lived (301,000 years half-life) and mobile radionuclide (K_d < 0.02 m^3 $kgDW^{-1}$ was used in the modelling) and thus the total radionuclide inventory in 157_2 reached a steady state relatively quickly in both the submerged and the land period (Figure 10-9a). The inventories at equilibrium in inorganic regolith compartments (e.g. RegoLow and RegoGL) were substantially lower during the land period than during the submerged period, reflecting larger vertical flux rates of water through the sediment layers; for example, the vertical flux of water up through RegoLow was 0.02 and 0.17 m y^{-1} during the submerged and the land periods, respectively.

During the submerged period the inventory in 157_2 was dominated by RegoLow (> 90%), and small additional amounts were found in the overlying sediments (with RegoGL bearing c. 5% and RegoPG c. 1% of the inventory) (Figure 10-9a). The distribution of the inventory primarily reflected the combined effect of regolith depth, regolith density and upward groundwater flux. The distribution pattern between regolith layers was similar in the land period. However, plant uptake and litter production caused Cl-36 to accumulate in litter, and thus c. 8% of the radionuclide inventory was stored in organic matter of deep and surface peat (RegoPeat_org and RegoUp_org) at the end of the simulation period.

Biosphere object 157_1 received radionuclides with the surface water from object 157_2. The total inventory in 157_1 increased continuously during the submerged period, and it did not reach a steady state before lake isolation (Figure 10-9b). However, during the land period the total radionuclide inventory was approaching steady state. In contrast to object 157_2, the largest part of the inventory in 157_1 was found in the water during the submerged period, and the fractions in aquatic sediments were growing relatively slowly, reflecting that export of radionuclides with horizontal water movement was much larger than the downward transport of radionuclides to the sediments (associated with groundwater flux and sedimentation).

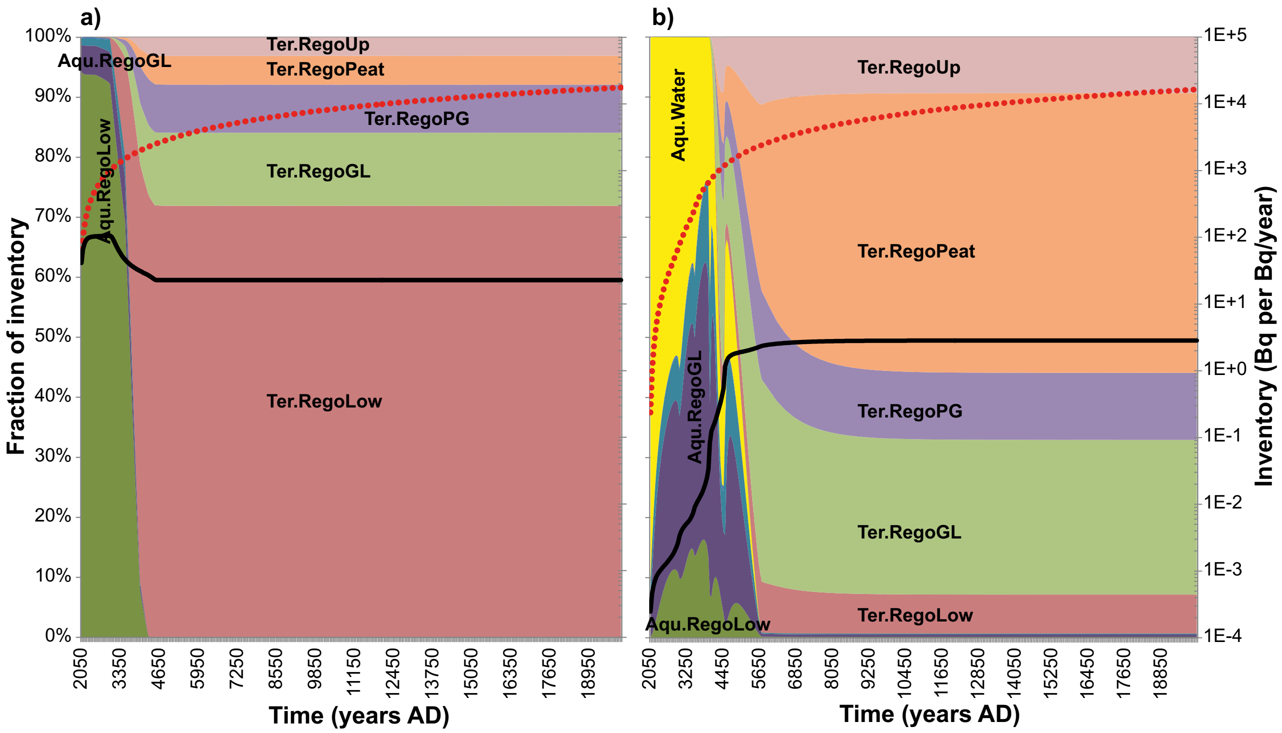


Figure 10-9. Distribution of the total inventory of Cl-36 among ecosystem compartments, illustrated by the coloured areas (referring to the linear left axis of each figure), and the inventory/release (right axis of each figure), presented as functions of time for two biosphere objects. a) Biosphere object 157_2, which received a constant input of radionuclides (1 Bq y^{-1}) via groundwater from the bedrock. b) Downstream biosphere object 157_1, which received radionuclides by surface water from object 157_2. The lines represent the total inventory of Cl-36 in the object (black line) and the cumulative activity release to the object (accounting for radioactive decay; red dotted line) on the logarithmic right axes.

During the land period the distribution of the inventory in 157_1 was more similar to that of 157_2, as the primary pathway for accumulation in this period was driven by plant uptake at the surface. However, due to the geometry of the objects, a much deeper peat layer developed in the lake basin of 157_1 than in 157_2 and this peat layer dominated the total inventory in 157_1 (Figure 10-9b). As radionuclides did not enter the object from the bedrock, the fraction of inventory in the deep regolith layers was also very limited in the land period (in contrast to the conditions in object 157_2).

Activity concentration in sediments and soils

As conditions approached steady-state, the concentration in sediment of Cl-36 in the deeper regolith layers was roughly proportional to the K_d of the regolith layer and inversely proportional to groundwater flux rates through the layer (Figure 10-10). As with the inventory, the decrease in concentration from the submerged to the land period in these layers was driven by an increased upward movement of groundwater during the land period. However, the vertical gradient of flux-rates was relatively small during both the submerged and the land period, and thus differences in concentration between deep regolith layers that were low, or moderate, in organic matter content, till (RegoLow), glacial clay (RegoGL) and post-glacial clay gyttja (RegoPG_tot), were primarily driven by differences in K_d (the K_d in till, glacial clay, and post-glacial clay gyttja were 0.0005, 0.005, and 0.008 m^3 $kgDW^{-1}$, respectively). The activity concentration in deeper regolith layers was consistently lower in 157_1 than in 157_2, primarily reflecting that radionuclides reaching the downstream object were diluted with surface water fluxes before they were transported downwards to deeper regolith layers (Figure10-10).

Since adsorption of chloride was low, the activity concentration of Cl-36 in the regolith layers of object 157_2 was roughly proportional to the soil porosity and inversely proportional to the soil density and the groundwater flux rates through the layer. Thus, the deep peat layer in object 157_2 had the highest radionuclide concentrations of all regolith layers, and the activity concentrations in surface and deep peat were also relatively high in the downstream object (Figure 10-10).

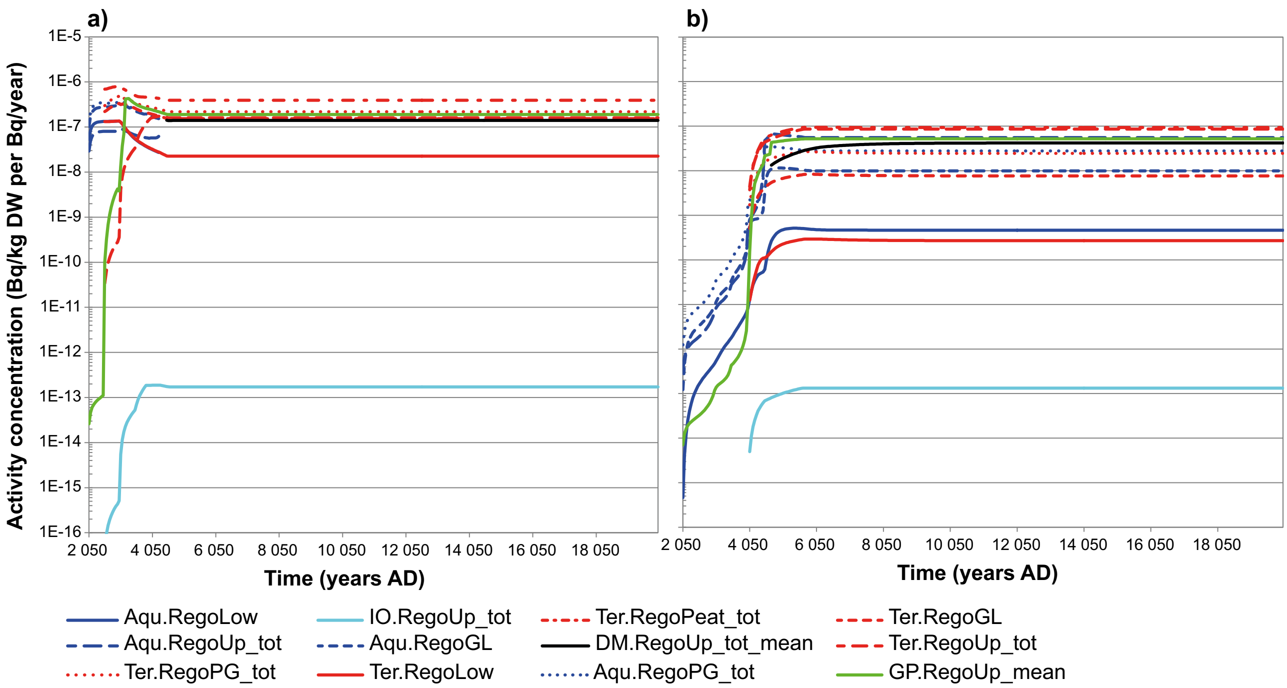


Figure 10-10. Activity concentrations for unit release (Bq $kgDW^{-1}$ per Bq y^{-1}) of Cl-36 in regolith layers in two biosphere objects. a) Biosphere object (157_2) received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. b) Downstream biosphere object 157_1 received radionuclides with surface water from 157_2. Abbreviations of regolith layers are explained in Table 8-1; prefixes represent ecosystems or land use variants. For simplicity, total concentrations are shown for regolith layers with both an organic and an inorganic radionuclide inventory (indicated by "tot").

Activity concentrations of Cl-36 in all model compartments were consistently lower in object 157_1 than in object 157_2 (Figure 10-10). In surface peat, the difference was only a factor of two between the objects, reflecting a larger dilution with runoff water in the downstream object. As the transport pathway of radionuclides was reversed in object 157_1, the concentration difference between objects 157_1 and 157_2 increased from top to bottom in the regolith layers. Thus, the concentration of Cl-36 was one and two orders of magnitude higher in 157_2 than in 157_1 in clay gyttja/glacial clay and till, respectively, at the end of the simulation period.

The activity concentration in agricultural soil was a function of the concentration in the upper regolith horizon that can be cultivated (the drained-mire farmer variant), the concentration in fertilisers originating from seaweeds, biofuel ash or mire hay (the garden-plot or infield-outland variants), and the concentration in water used for irrigation of the garden plot. The highest concentration of Cl-36 resulted from cultivating a garden plot (Figure 10-10), and the main source of radionuclides was fertilisation with biofuel ash (wood). However, concentrations in drained and cultivated soils in objects 157_2 and 157_1 were only a factor of two and four lower than in the garden plot, respectively.

Activity concentration in water

Activity concentrations of Cl-36 in surface water are shown in Figure 10-11. During the submerged period (until 3000 AD) the exchange of water between neighbouring sea basins was large (see previous section on C-14) and the highest concentration was always found in the biosphere object receiving the groundwater discharge of radionuclides. Peaks and drops in concentrations during this period primarily reflected the effect of the degree of isolation on the water exchange, and shifts in the radionuclide concentration in the basin of 157_2 were also seen in the downstream basins (Figure 10-11).

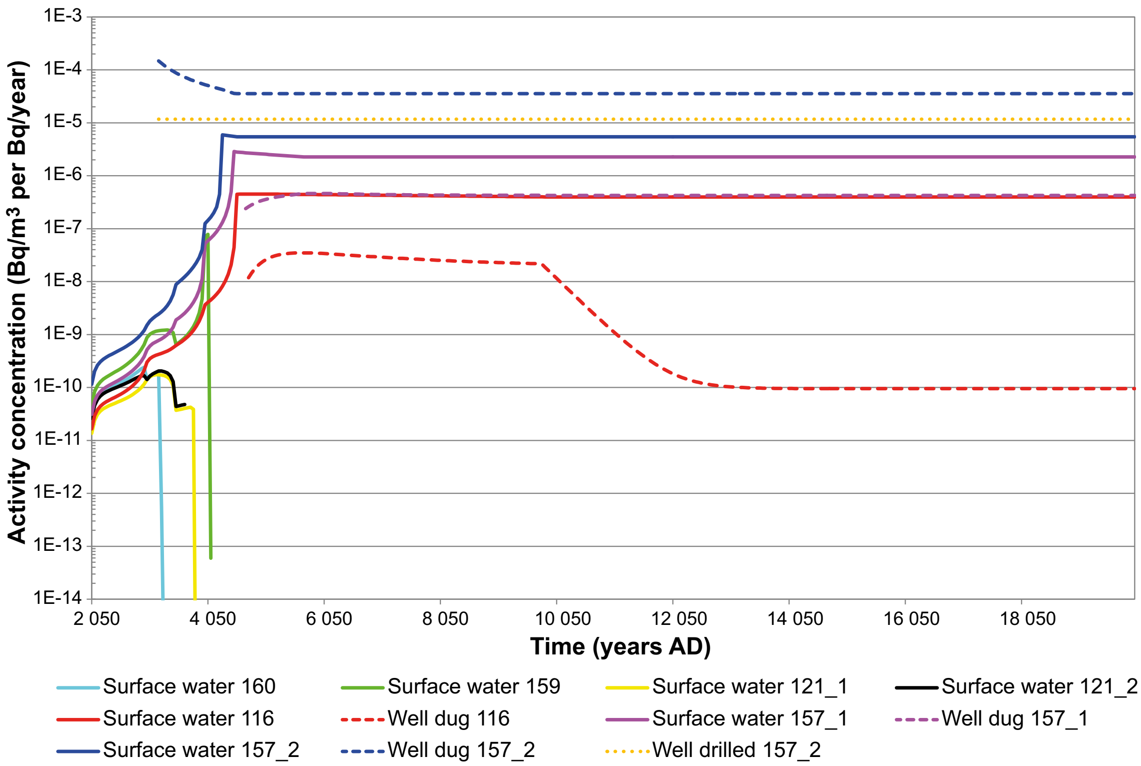


Figure 10-11. *Activity concentrations for unit release rate (Bq m^{-3} per Bq y^{-1}) of Cl-36 in surface water of seven biosphere objects. Solid lines represent concentrations in sea basins during the submerged period and concentrations in surface water on land (lakes, streams or other surface water) during the land period. Biosphere object 157_2 received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. In the land period, objects 157_1 and 116 are located downstream from 157_2. Note that there is no external source of radionuclides to the other biosphere objects (121_1, 121_2, 159 and 160) during the land period.*

Once the biosphere objects had emerged out of the sea, radionuclide-containing groundwater only reached 157_2, from which it was transported further to downstream objects 157_1 and 116. As the flux of surface water was small during the land period, the activity concentration peaked during this period. The Cl-36 concentration at steady state in water was approximately reciprocal to the horizontal flux of surface water through the biosphere object.

In biosphere object 157_2, the activity concentration of Cl-36 was highest in the dug well (Figure 10-11), and thus, drinking and irrigation water for all exposed populations of permanent inhabitants living in or using resources from the object was collected from the dug well (except hunter-gatherers that use surface water only). The concentration in water from a dug well in biosphere object 157_2 was three times as high as that from a drilled well, and six times higher than that of surface water in the object. For the downstream objects 157_1 and 116, the concentration in the dug well was lower than in surface water, and permanent residents in the downstream objects (with a sufficient level of technology) used water from a drilled well (which had the highest concentration).

Dose to humans for unit release

Doses to future human inhabitants living in and/or using natural resources from the biosphere objects (Figure 10-12) are a result of ingestion of radionuclides with food or water, from inhalation of radionuclides and external exposure (i.e. radiation from the ground). For Cl-36, ingestion via food was the dominant exposure route for all four land use variants (hunter-gatherers, infield-outland farmers, drained-mire farmers, and garden-plot households), whereas external exposure was negligible.

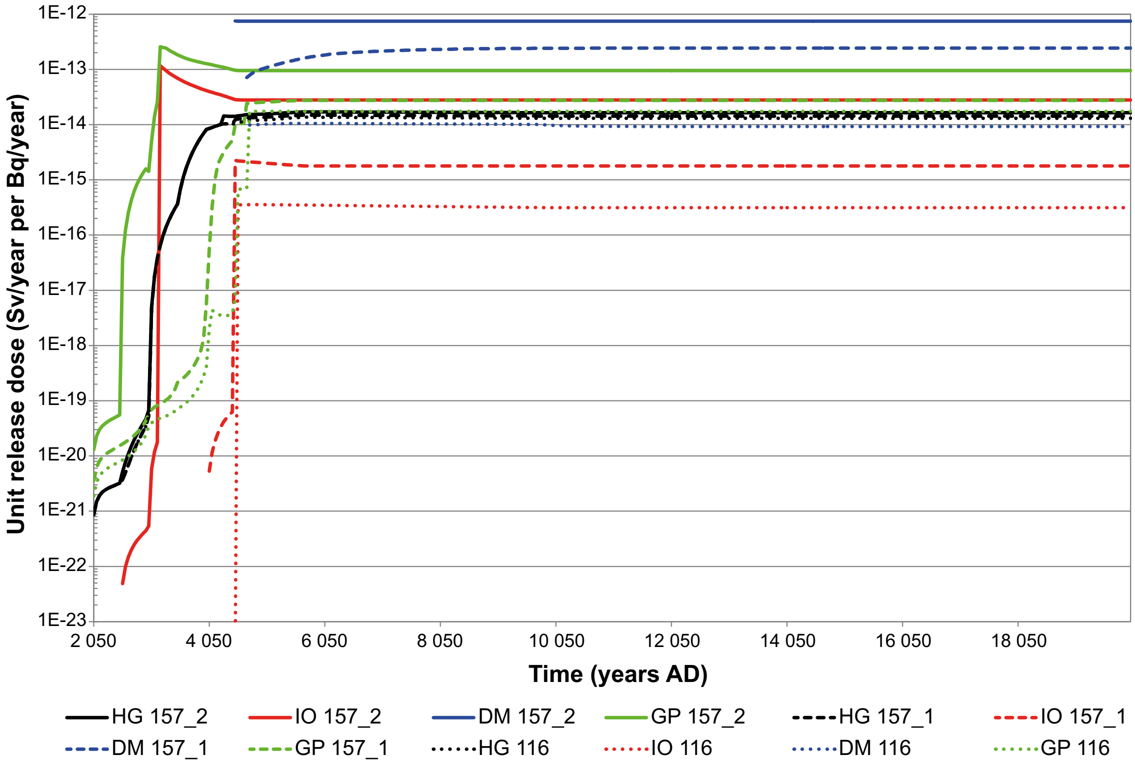


Figure 10-12. *The dose for unit release rate of Cl-36 to human inhabitants living in and/or using natural resources from the biosphere objects. Solid lines represent dose resulting from exposure in biosphere object 157_2, which received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. Dashed and dotted lines represent dose resulting from exposure in downstream objects 157_1 and 116, respectively. Colours indicate different land use variants: hunter-gatherers (HG), drained-mire farmers (DM), infield-outland farmers (IO), and garden-plot households (GP).*

The radionuclide concentration for unit release in food items was proportional to that in water (aquatic food items), in the pore water of surface peat in the mire (terrestrial food items, dairy products and meat), and in cultivated soil (crops, vegetables, dairy products and meat). The soil concentrations in the garden plot of 157_2 was similar to that of surface peat in the object (Figure 10-10), and higher than in other land use variants involving cultivation. However, drained-mire farmers received the highest dose (Figure 10-12). This was because food cultivated on the garden plot (potatoes and vegetables) only contributed to a fraction of the food consumed by the exposed group (~ 8% of total energy demand), whereas farmers draining the mire was self-sufficient with respect to all food consumed. Despite very low soil concentrations, the dose in the infield-outland land use variant was less than one order of magnitude lower than that from the garden-plot. This was due to exposure from the livestock feeding on mire hay.

Foraging the landscape (including all objects with radionuclides from the repository) resulted in a relatively low dose for unit release, in spite of relatively high Cl-36 concentrations in the upper peat layer (RegoUp_tot, Figure 10-10). This was because the production of natural food items in these areas could only support a small fraction of the energy demand of a band of hunters and gatherers, and consequently the diet was dominated by food without radionuclides originating from the repository. In the safety assessment, the contributions of the areas of all biosphere objects containing radionuclides originating from the repository were summed to yield an annual dose for hunter-gatherers.

The exposure from drinking water was highest in the land use variant utilising a dug well, and the contribution from this pathway ranged from three percent (drained-mire farmers) to more than 80% (infield-outland farmers) of the total dose from a unit release. Exposure from drinking surface water was limited, and drinking water contributed one percent of the dose for unit release to hunter-gatherers.

Dose rate to non-human biota for unit release

Exposure of plants and animals living in the biosphere objects resulted from external exposure (i.e. radiation from water, sediment or soil) and from internal exposure (i.e. from radionuclide uptake) (Figure 10-14). Both external and internal exposures directly depend on the activity concentrations of the radionuclides in the environmental medium, and thus temporal and spatial variation in dose rates for any organism group is expected to roughly follow that of the environmental media. For Cl-36, the highest dose rates resulted from exposure in mire ecosystems in object 157_1 and 157_2 (Figure 10-13). Dose rates from exposure in aquatic ecosystems (or in the mire ecosystem of downstream object 116) were more than three orders of magnitude lower (Figure 10-13; Figures 10-14a–c).

Due to the relatively low uptake of Cl-36 in most aquatic organisms (low CR) external exposure from sediment was of most importance for the freshwater and marine organisms. This was pronounced in marine ecosystems in object 157_2 where all examined organisms except Pelagic fish, Birds and Mammals had a contribution from external exposure of 19% or more. For most of the examined organism types, external exposure made up ~ 100% of the total exposure at some time point of the simulated time period. For the submerged period, the dose rate curves in object 157_2 follow two patterns (Figure 10-14a): those of pelagic organisms mimicked the dynamics of the concentration in water (Figure 10-11), whereas those of benthic organisms followed the dynamics of concentrations in sediment (Figure 10-10). The contribution from external exposure was less in object 157_1 than that in 157_2 with the highest contributions in Phytoplankton and Polychaetes (100% and 47% of total dose rate, respectively). Phytoplankton is discussed further below.

In freshwater ecosystems, all benthic organisms in object 157_2 received significant external exposure except Benthic fish (< 1% of total dose rate). The contribution was of less importance than in object 157_2, indicating lower concentrations in sediment. External exposure totally dominated the dose rates for Phytoplankton (100% of total dose rate in both objects) and Microphytobenthos (97% and 63% in object 157_2 and 157_1, respectively). The large importance of external exposure in the Phytoplankton was somewhat surprising, but was due to its very small size. A large part of the released energy from the internal beta radiation will escape outside the organism without contributing to internal dose. Also, dose rates for external exposure to high-energy β and γ decrease with increasing size due to self-shielding. The same was also true for Microphytobenthos, for which the same organism size was used. As this organism was benthic it received external exposure from the sediment, which had higher concentrations than in water. In reality, the size of Phytoplankton and Zooplankton overlap to some degree, but the sizes used in this safety assessment differed (SKB 2014), which led to higher Zooplankton exposure (Figure 10-14b).

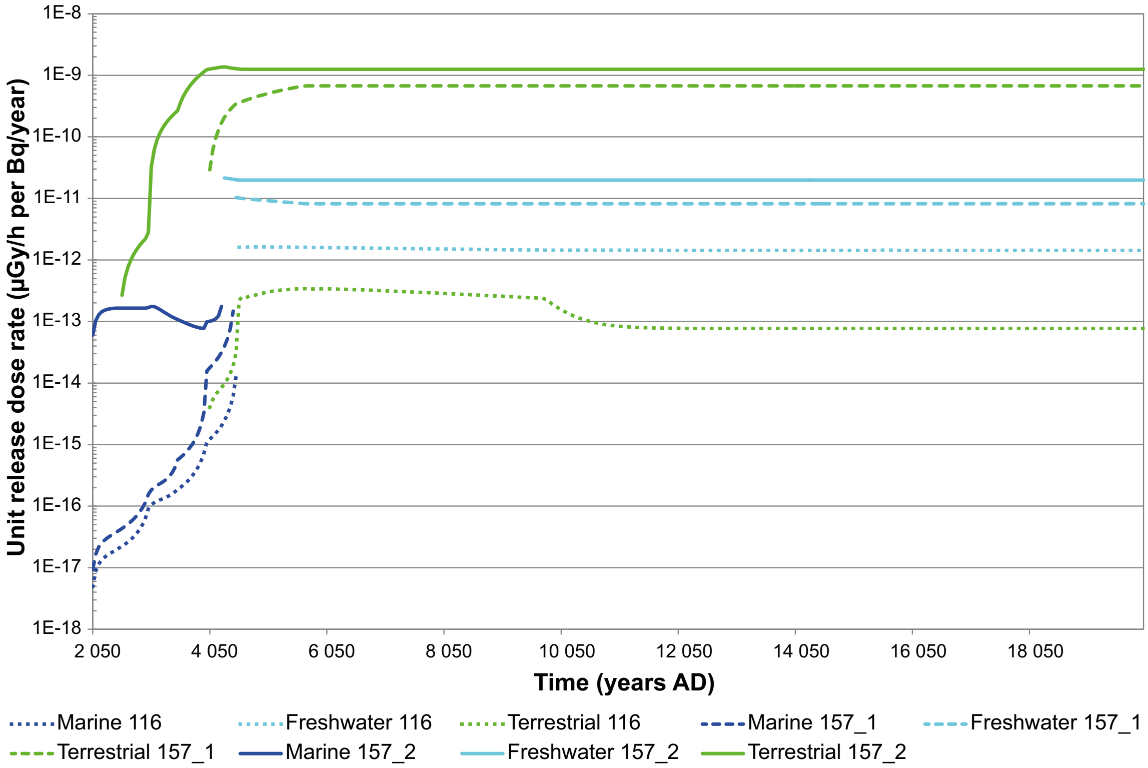


Figure 10-13. Dose rates for unit release caused by Cl-36 to plants and animals inhabiting the future Forsmark landscape. The lines represent maximum dose rates across all examined organism groups within each ecosystem and biosphere object. Solid lines represent dose rates resulting from exposure in biosphere object 157_2 receiving a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. Dashed and dotted lines represent dose rates resulting from exposure in downstream objects 157_1 and 116, respectively. Colours indicate marine, freshwater (lake and stream), and terrestrial (mire) ecosystems.

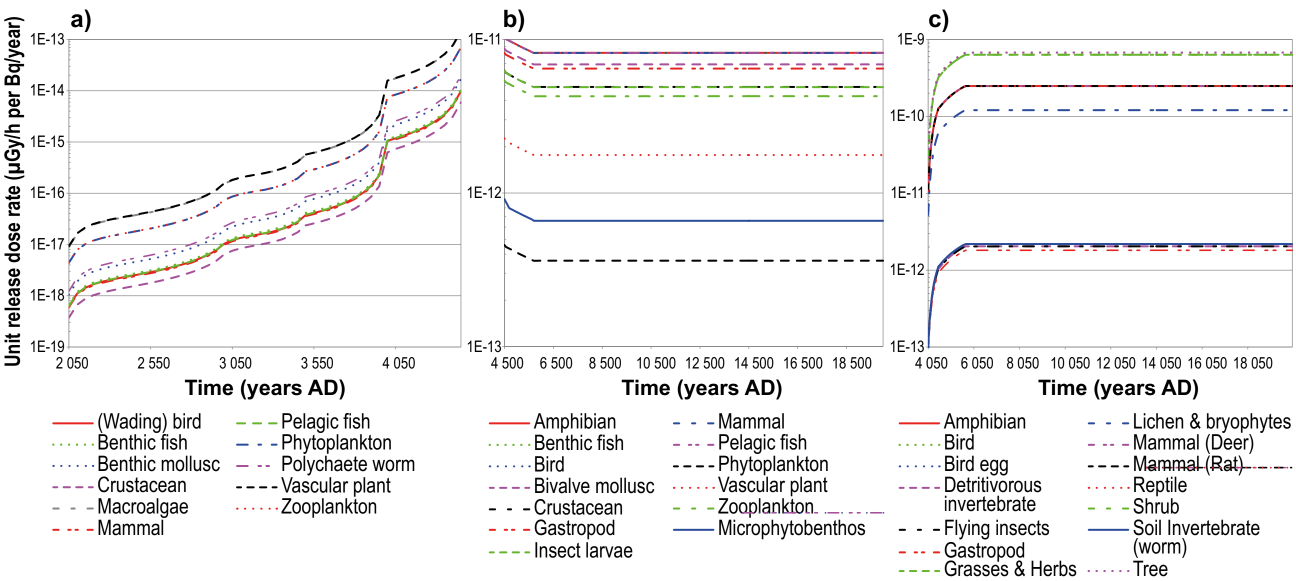


Figure 10-14. Dose rates for unit release for organisms living in, a) marine, b) freshwater and c) terrestrial (mire) ecosystems in biosphere object 157_2. Note the different scales on the vertical axes.

The dose rates for unit release of Cl-36 to the most highly exposed mire organisms were caused by internal exposure. Thus the dynamics of the total dose follow that of concentrations in the oxygenated peat layer (RegoUp, Figure 10-10), and the relative difference between organism groups reflected differences in steady-state concentration ratios between organisms and the environment (Figure10-14c). The CR of Grasses and herbs and Trees were 2.7 times higher than those of vertebrates such as Amphibians, Reptiles, Birds and Mammals.

10.5.4 Detailed interpretation of unit release results for Mo-93

Accumulated inventory in model compartments

Mo-93 is a relatively immobile radionuclide with a large variation in sorption to different sediments. K_d ranges between 0.02 m^3 $kgDW^{-1}$ in till and 11 m^3 $kgDW^{-1}$ in particulate matter in the freshwater column. The total inventory did not reach steady-state during the short submerged period, but approached steady-state after a couple of thousand years in the land period (Figure 10-15).

During the submerged period, radionuclides accumulated primarily in RegoLow (90–100%) in 157_2, and later also in overlying sediments (RegoGL up to 7% and RegoPG up to 11%) (Figure 10-15). The distribution of the inventory reflected the combined effects of release direction (radionuclides reaching RegoLow first), depth, density, and sorption of the different regolith layers (RegoLow, RegoGL and RegoPG). The release direction was important because the system did not reach steady-state within the considered time frame. (It would take approximately 3,700 years for a molybdenum species, being transported with the moving groundwater, to pass through the thick layer of till). During the land period the marine inventory distribution was quickly evened out. The main part of the inventory was found in RegoLow and RegoPG (~ 40% in each). The increased accumulation in RegoPG during the land period reflected the combined effect of RegoLow being saturated with radionuclides and relatively high sorption properties of RegoPG (K_d was 3.4 m^3 $kgDW^{-1}$).

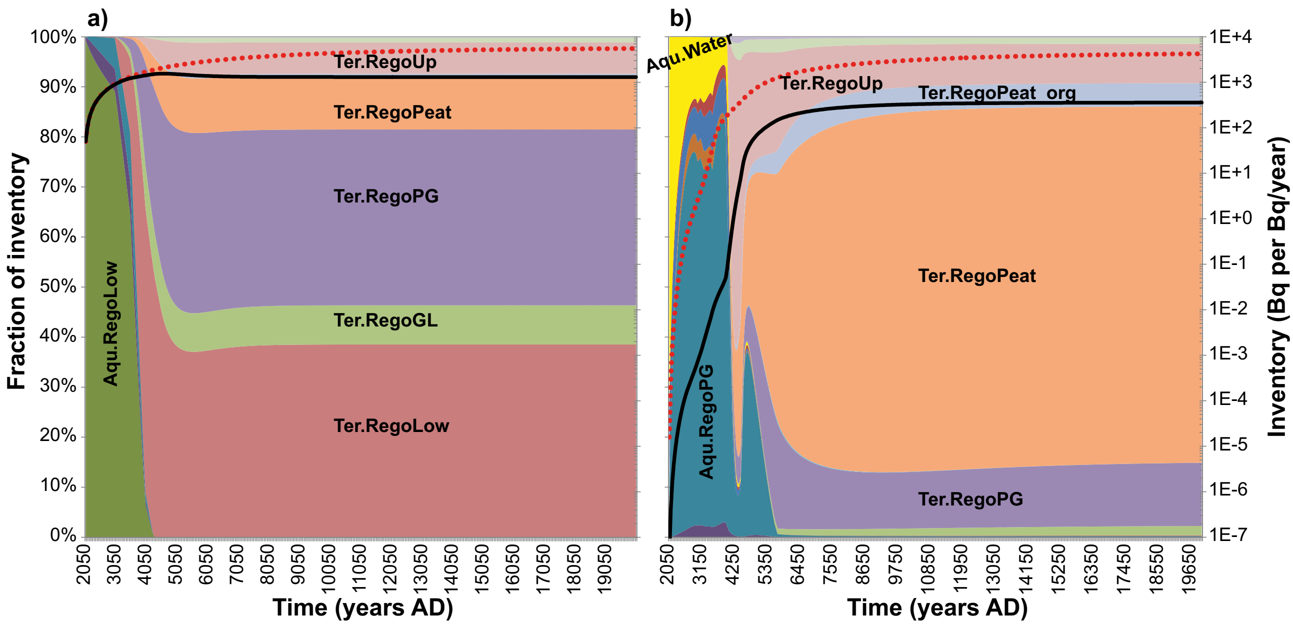


Figure 10-15. *Distribution of the total inventory of Mo-93 among ecosystem compartments, illustrated by the coloured areas (referring to the linear left axis of each figure), and the inventory/release (right axis of each figure), presented as functions of time for two biosphere objects. a) Biosphere object 157_2, which received a constant input of radionuclides (1 Bq y^{-1}) via groundwater from the bedrock. b) Downstream biosphere object 157_1, which received radionuclides by surface water from object 157_2. The lines represent the total inventory of Mo-93 in the object (black line) and the cumulative activity release to the object (accounting for radioactive decay; red dotted line) on the logarithmic right axes.*

Biosphere object 157_1 received radionuclides with the surface water from object 157_2. The total inventory in 157_1 increased continuously during the submerged period, and it did not reach steady state before lake isolation. During the land period, the total radionuclide inventory was approaching steady state, though when the simulation period ended (at year 20,000 AD) there was still some accumulation occurring. Due to the slow vertical water fluxes and sorption in deeper sediments in biosphere object 157_2, very small amounts of radionuclides reached biosphere object 157_1 during the submerged period. The largest inventories during this period were in water (initially 70%), the upper regolith (~ 10–20%) and post-glacial clay gyttja (~ 80% after the first 100 years). The fraction in aquatic sediments increased rapidly, partly due to the high K_d of particulate matter that resulted in a high flux of Mo-93 from the water to the upper regolith by sedimentation.

During the land period, the distribution pattern in 157_1 reflected that radionuclides reached the object with surface water. Thus radionuclides accumulated in top sediments before dispersing to deeper layers with groundwater movement. As the deep peat layer was thick (1.4 m) and had a high K_d (~ 3.9 m^3 $kgDW^{-1}$), the main part of the Mo-93 activity in object 157_2 was adsorbed in RegoPeat (70%). The rest of the inventory was found adsorbed in RegoUp (8%) and RegoPG (13%), or stored in organic matter in deep peat (RegoPeat_org, 5%).

Activity concentration in sediments and soils

The activity concentration of Mo-93 in marine sediments of object 157_2 increased continuously during the submerged period and thus never reached steady state (Figure 10-16a). Since vertical water fluxes through the marine sediments were similar in each of the regolith layers, sorption coefficients played a major role in the rate of accumulation in each layer. In the early stage of the submerged period high sorption in post-glacial clay gyttja was an effective barrier for accumulation in upper regolith.

As the biosphere object 157_2 emerged from the sea vertical hydrological fluxes increased. This resulted in decreased sediment concentrations (especially in deeper layers), and steady-state concentrations were reached in some thousands of years. At steady state, the concentration was highest in clay-gyttja (RegoPG) and peat (RegoPeat), which had similar hydrological flux rates and sorption coefficients. The concentration in the upper peat layer (Ter.RegoUp) was half of that in deep peat, reflecting the increase in water flux due to surface water runoff (1.2 compared to 0.7 m y^{-1}). The relatively low concentrations in glacial clay, and the even lower concentration in till, were mainly caused by high densities and low sorption in these regolith layers, as compared to overlying regolith layers. The densities of glacial clay and lower regolith were 670 and 2,100 kgDW m^{-3}, respectively, compared to about 100 kgDW m^{-3} in clay gyttja and peat layers, whereas K_d values in glacial clay and lower regolith were 0.2 and 0.02 m^3 $kgDW^{-1}$, compared to about 4 m^3 $kgDW^{-1}$ in the clay gyttja and peat layers.

The activity concentration in all model compartments was consistently lower in 157_1 than in 157_2 (Figure 10-16b). In surface peat, the difference was only a factor of two between the objects, reflecting a larger dilution with runoff water in the downstream object. As the transport pathway of radionuclides was reversed in 157_1, the concentration difference between 157_1 and 157_2 increased from top to bottom in the regolith layers. Thus the concentration of radionuclides was two and three orders of magnitude larger in 157_2 than in 157_1 in glacial clay and till, respectively, at the end of the simulation period.

The activity concentration in agricultural soil was a function of the concentration in the upper regolith horizon that can be cultivated (the drained-mire farmer variant), the concentration in fertilisers originating from seaweeds, biofuel ash or mire hay (the garden-plot or infield-outland variants), and the concentration in water used for irrigation of the garden plot. The highest concentration of Mo-93 resulted from cultivating a garden plot in object 157_2, and the main source of radionuclides was fertilisation with biofuel ash (from peat). However, concentrations in the garden plot in 157_1 and the drained and cultivated soils in 157_1 and 157_2 were less than a factor of three lower, and the thick peat layer in object 157_1 caused the concentration in the drained and cultivated soil in 157_1 to exceed that in the upstream object.

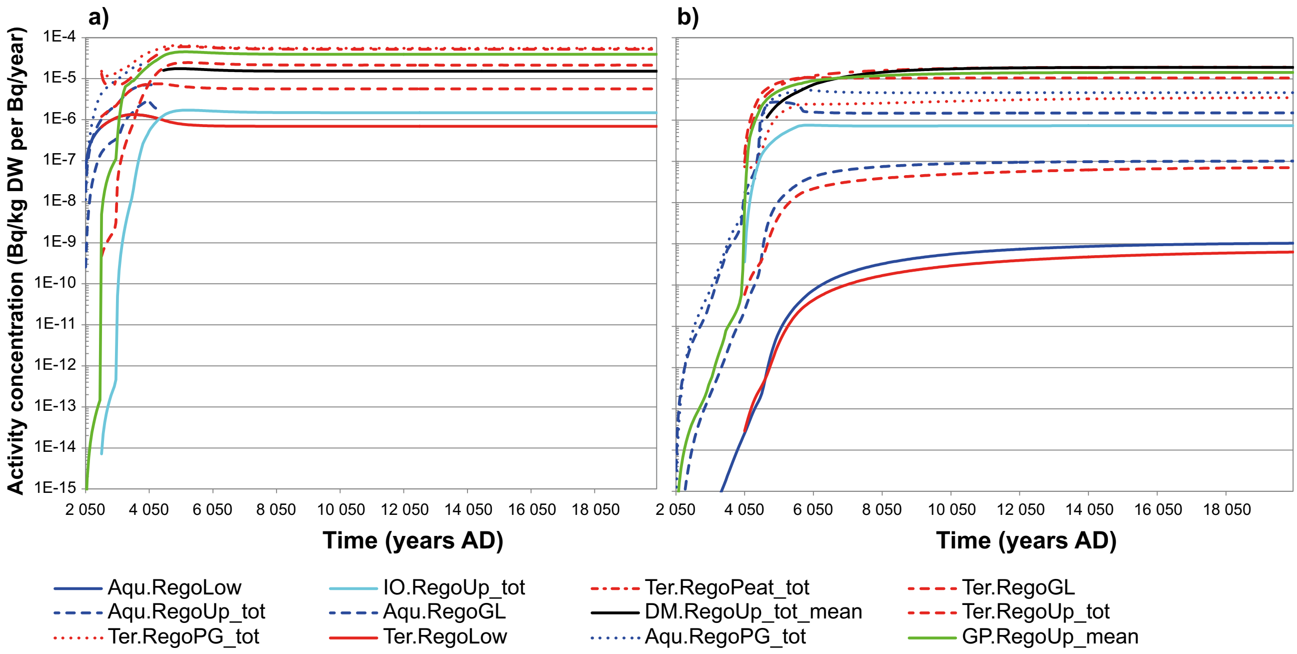


Figure 10-16. *Activity concentrations for unit release rate (Bq kgDW^{-1} per Bq y^{-1}) of Mo-93 in regolith layers in two biosphere objects. a) Biosphere object 157_2, which received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. b) Downstream biosphere object 157_1 received radionuclides with surface water from 157_2. Abbreviations of regolith layers are explained in Table 8-1; prefixes represent ecosystems or land use variants. For simplicity, total concentrations are shown for regolith layers with both an organic and an inorganic radionuclide inventory (indicated by "tot").*

Activity concentration in water

Activity concentrations of Mo-93 in surface water are shown in Figure 10-17. During the submerged period (until 3000 AD) the exchange of water between neighbouring sea basins was large (see previous section on C-14) and the highest concentration was always found in the biosphere object receiving the groundwater discharge of radionuclides. Peaks and drops in concentrations during this period primarily reflected the degree of isolation on the water exchange, and shifts in the radionuclide concentration in the basin of 157_2 were also seen in the downstream basins (Figure 10-17).

When the biosphere objects had emerged out of the sea, radionuclide-containing water was only reaching 157_2 and downstream objects 157_1 and 116. As the flux of surface water was small during the land period compared to water exchange between sea basins, the activity concentration peaked during this period (Figure 10-17). Given a constant unit release rate, the Mo-93 concentration in water at steady state was approximately the inverse of the horizontal flux of surface water through the biosphere object.

In biosphere object 157_2, the activity concentration of Mo-93 was highest in the dug well (Figure 10-17), and thus, drinking and irrigation water for all exposed populations of permanent inhabitants living in or using resources from the object was collected from the dug well (except hunter-gatherers that use surface water only). The concentration in water from a dug well in biosphere object 157_2 was three times as high as that from a drilled well, and almost eight times higher than that of surface water in the object. For the downstream objects 157_1 and 116 the concentration in the dug well was lower than in surface water, and permanent residents in downstream object (with a sufficient level of technology) used water from a drilled well (which had the highest concentration).

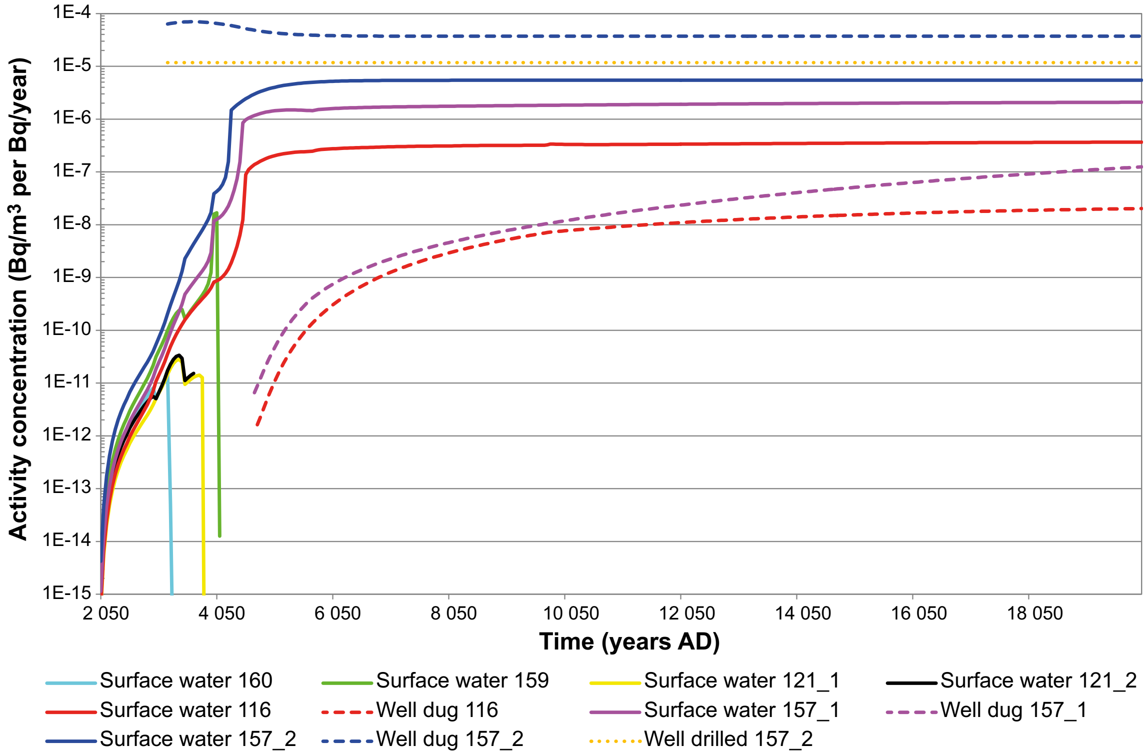


Figure 10-17. *Activity concentrations for unit release rate (Bq m^{-3} per Bq y^{-1}) of Mo-93 in surface water of seven biosphere objects. Solid lines represent concentrations in sea basins during the submerged period and concentrations in surface water on land (lakes, streams or other surface water) during the land period. Biosphere object 157_2 received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. In the land period, objects 157_1 and 116 are located downstream from 157_2. Note that there is no external source of radionuclides to the other biosphere objects (121_1, 121_2, 159 and 160) during the land period.*

Dose to humans for unit release

Dose to future human inhabitants, living in and/or using natural resources from the biosphere objects (Figure 10-18), results from external exposure (i.e. radiation from the ground), from inhalation of radionuclides and from ingestion of radionuclides with food or water. For Mo-93, ingestion was the dominant exposure route for all four land use variants (hunter-gatherers, infield-outland farmers, drained-mire farmers, and garden-plot households).

The radionuclide concentration in food items was proportional to that in water (aquatic food items), in the upper peat layer of the mire (terrestrial food items, dairy products and meat), and in cultivated soil (crops, vegetables, dairy products and meat). Similar to Cl-36, the soil concentration of Mo-93 in the garden-plot variant was just below that in surface peat of object 157_2 (Figure 10-16), and higher than in other land use variants involving cultivation. However, drained-mire farmers received the highest doses in both 157_1 and 157_2 (Figure 10-18). This was because farmers draining the mire were self-sufficient with respect to food production. Foraging the landscape (including all objects with radionuclides from the repository) resulted in a relatively low dose for unit release, in spite of relatively high Mo-93 concentrations in the upper peat layer (RegoUp_tot, Figure 10-16), due to the limited production of natural food in the biosphere objects (see Cl-36).

The exposure from drinking water was highest in the land use variant utilising a dug well, and the contribution from this pathway ranged from less than two percent (drained-mire farmers) to 14% (infield-outland farmers) of the total dose from a unit release. Although exposure from drinking surface water was limited as compared to consumption of well water (Figure 10-17), drinking water contributed 37% of the dose for unit release to hunters and gatherers living in object 157_2.

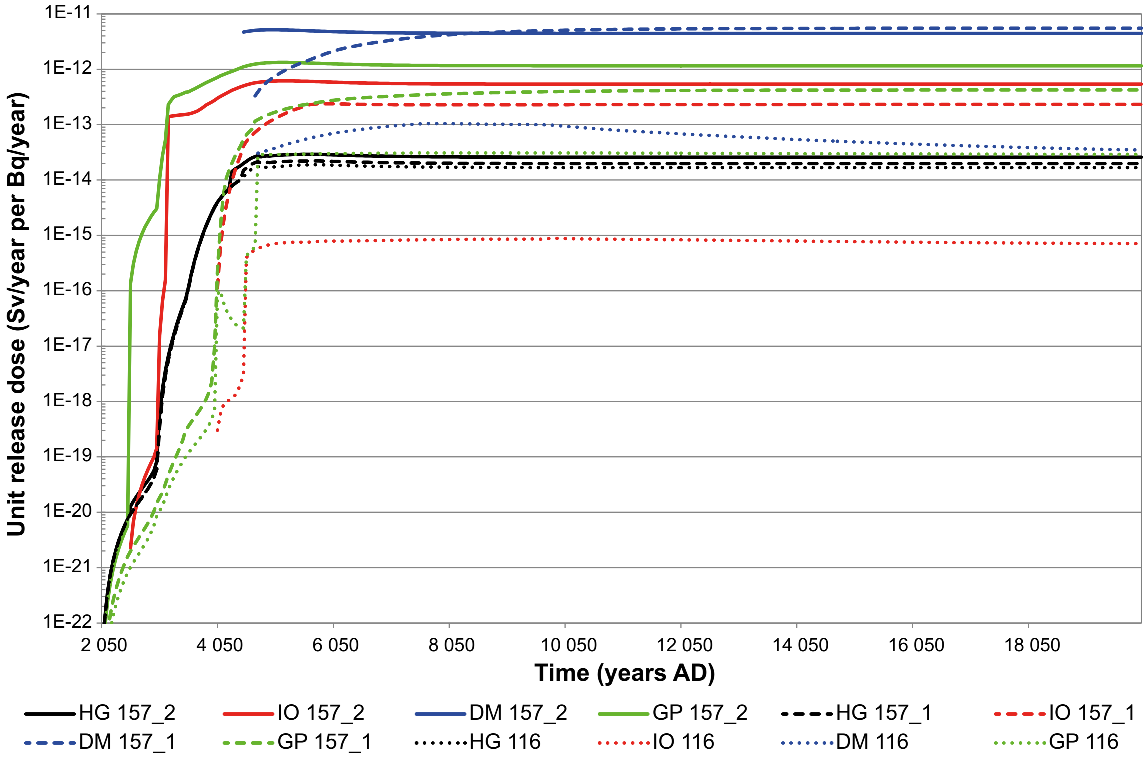


Figure 10-18. *The dose for unit release rate of Mo-93 to human inhabitants living in and/or using natural resources from the biosphere objects. Solid lines represent dose resulting from exposure in biosphere object 157_2, which received a constant release of radionuclides (1 Bq* y^{-1}*) via groundwater from the repository. Dashed and dotted lines represent dose resulting from exposure in downstream objects 157_1 and 116, respectively. Colours indicate different land use variant: hunter-gatherers (HG), drained-mire farmers (DM), infield-outland farmers (IO), and garden-plot households (GP).*

Dose rate to non-human biota for unit release

As stated in Section 10.3, temporal and spatial variations in dose rates for any organism group are expected to roughly follow that of the environmental media. For Mo-93, maximum dose rates for unit release resulted from exposure in mire ecosystems in object 157_2 and 157_1. Dose rates from exposure in freshwater ecosystems in those objects were approximately one order of magnitude lower and exposure in marine ecosystems (and in all ecosystems of downstream object 116) were even lower (Figure 10-19).

The most exposed mire organisms were those living in soil (most exposed organism: Soil invertebrate (worm)), compared with those living on soil, or in air (Figure 10-20). Since both exposure routes were dependent on the concentration in the upper soil layer, the dynamics of the total dose follows that in the oxygenated peat layer (RegoUp, Figure 10-16). The same CR value was used for the four most exposed organism types (Soil invertebrate (worm), Detritivorous invertebrate, Gastropod, Flying insect), so their relative order of exposure was due to differences in external exposure from their position in or on soil. The external exposure was of minor importance, less than 5% of total dose rate, for Gastropods and Flying insects. External exposure contributed significantly to total exposure for all other organism types; the highest contribution was seen for small, soil-dwelling mammals (83%).

The exposure from Mo-93 in aquatic ecosystems was dependent on habitat: pelagic organisms received dose rates largely from internal exposure, which was a function of concentration in surface water (Figure 10-17), whereas external exposure contributed more to the total dose rate for benthic organisms. The dynamics of the latter mainly followed that of the concentrations in sediment (Figure 10-16). In freshwater ecosystems, the most exposed organism types differed between object 157_1 and 157_2 due to differences in relative concentrations between water and sediment. Since the concentration in water was relatively high compared to that of upper sediment in object 157_1, internal exposure dominated the total dose rates. The relative order among the exposed organisms mirrored their uptake of Mo-93 (most exposed organism types had highest CR). The same pattern was also seen in the marine ecosystems where the most exposed organisms in object 157_2 were benthic, with external exposure dominant, whereas internal exposure dominated in object 157_1, correlating exposure with Mo-93 uptake (CR).

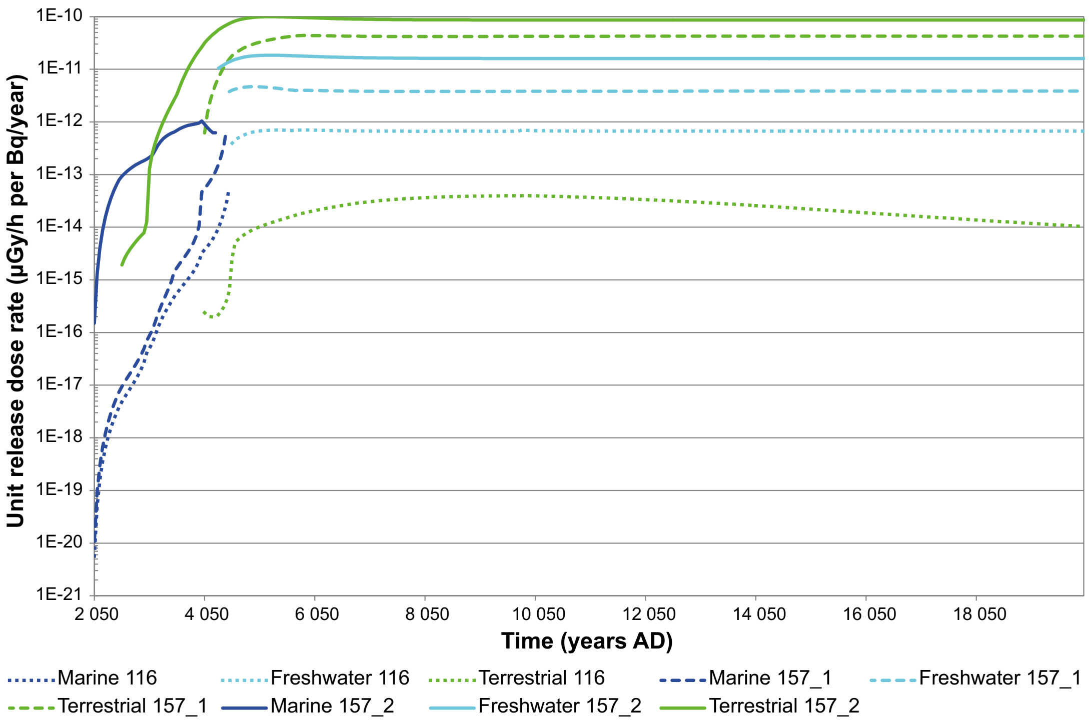


__Figure 10-19.__ Dose rates for unit release caused by Mo-93 to non-human biota inhabiting the future Forsmark landscape. The lines represent maximum dose rates across all examined organism groups within each ecosystem and biosphere object. Solid lines represent dose rates resulting from exposure in biosphere object 157_2, which received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. Dashed and dotted lines represent dose rates resulting from exposure in downstream objects 157_1 and 116, respectively. Colours indicate marine, freshwater (lake and stream), and terrestrial (mire) ecosystems.

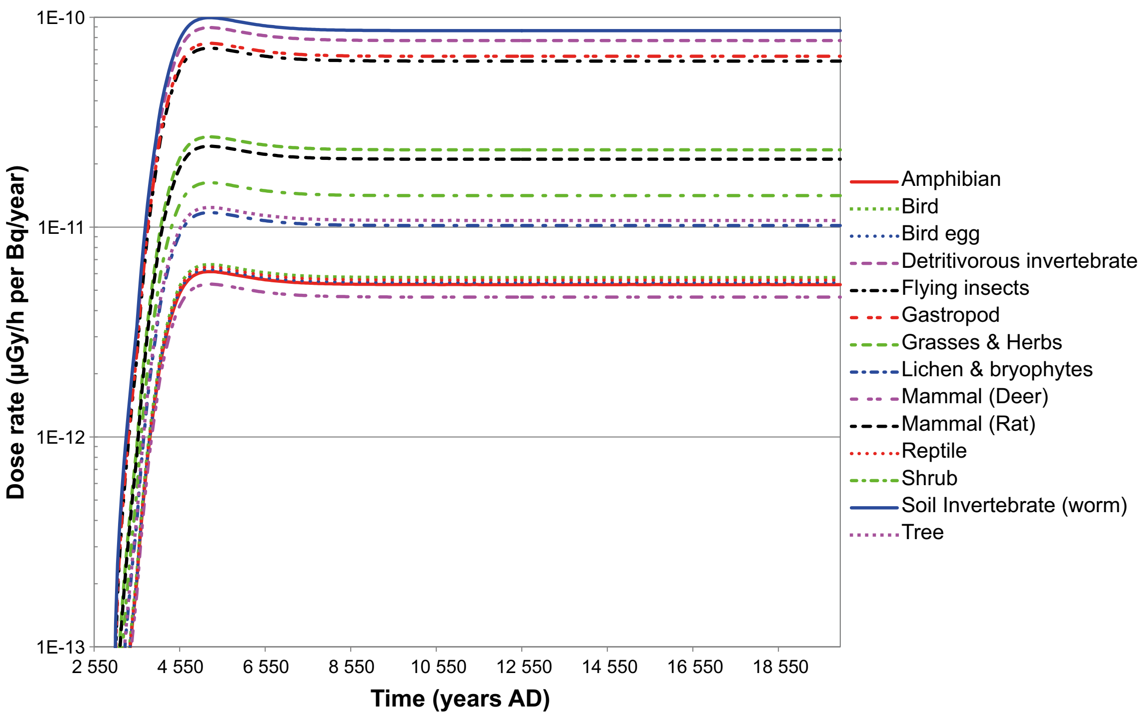


__Figure 10-20.__ Dose rates for organisms living in the mire ecosystem in biosphere object 157_2.

10.5.5 Detailed interpretation of unit release results for Ni-59

Accumulated inventory in model compartments

Ni-59 is a long-lived (76,000 years half-life) and immobile (K_d ranging from 0.8 to about 40 m^3 $kgDW^{-1}$) radionuclide and thus the total radionuclide inventory in the biosphere objects did not reach steady state within the 18,000-year simulation period. During the submerged period, the combination of a low upward water flux and a relatively high K_d led to an almost complete sorption of released radionuclides (1 Bq y^{-1}) in RegoLow in biosphere object 157_2 (Figure 10-21). As the biosphere object emerged out of the sea, the inventory was transferred from the aquatic to the terrestrial lower regolith (by terrestrialisation). Moreover, due to the increased vertical groundwater flux, the inventory in the glacial clay (RegoGL) started to build up. The sorption properties were more than 20 times stronger in glacial clay than in the till, but still small amounts of radionuclides reached overlying regolith layers (as indicated by the overlap between the black and red dotted lines in Figure 10-21a). Consequently, very small amount of radionuclides reached the downstream object 157_1 by transport with surface water (Figure 10-21).

Ni-59 transported into the downstream object (157_1) never reached steady state within the simulation period (Figure 10-21b). Moreover, most of the Ni-59 that reached the object was flushed out (as indicated by the difference between the red dotted line and the black line) and only a small amount (~ 10%) accumulated in the object. During the submerged period, less than one Bq reached the downstream object 157_1. The inventory was primarily contained in the two uppermost aquatic sediment layers (RegoUp and RegoPG, > 90%), including both organic and inorganic forms. The strong dynamics during this period were primarily caused by variation in sedimentation rates, as suspended particulate matter adsorbed Ni strongly (K_d = 15 m^3kgDW^{-1}).

Also during the land period, radionuclides dispersed from the surface regolith layer (RegoUp) downwards. However, as the deeper peat layer (RegoPeat) was much thicker than the surface peat, and had somewhat stronger sorption properties, RegoPeat accumulated the majority of Ni-59 in object 157_1 (~ 90% inorganic form). Only a small fraction of the inventory accumulated in deeper regolith layers below the peat (<10% for most of the simulation period).

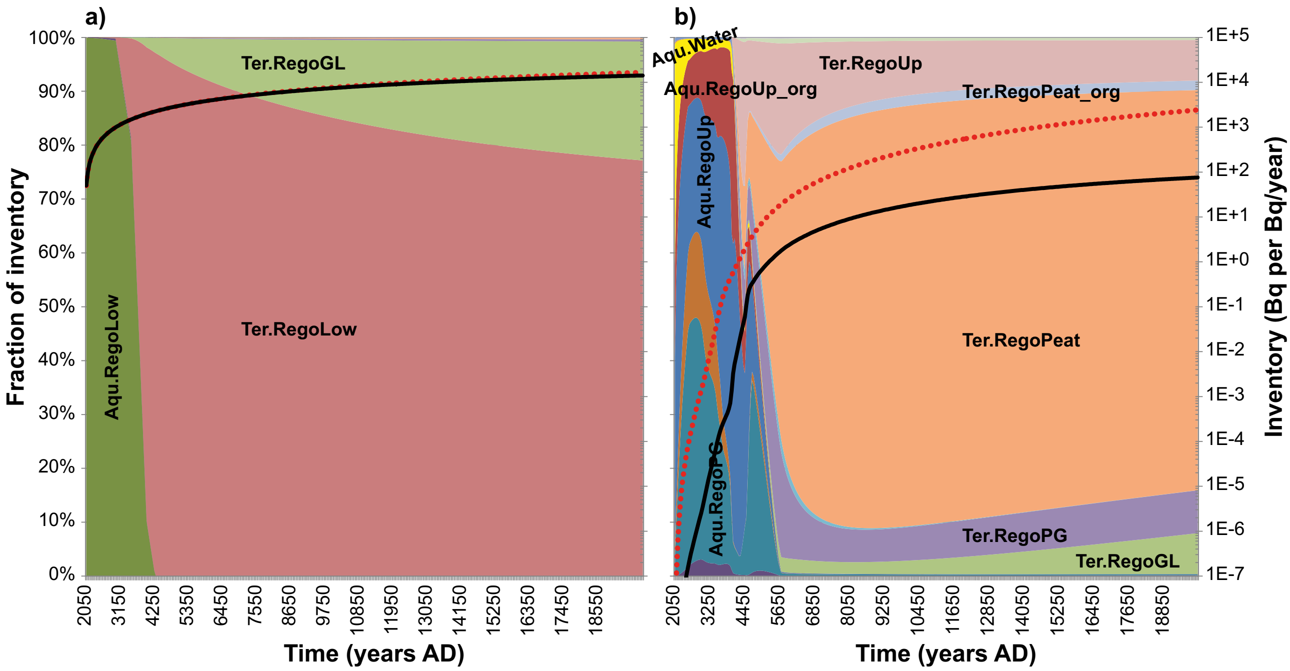


Figure 10-21. *Distribution of the total inventory of Ni-59 among ecosystem compartments, illustrated by the coloured areas (referring to the linear left axis of each figure), and the inventory/release (right axis of each figure), presented as functions of time for two biosphere objects. a) Biosphere object 157_2, which received a constant input of radionuclides (1 Bq y^{-1}) via groundwater from the bedrock. b) Downstream biosphere object 157_1, which received radionuclides by surface water from object 157_2. The lines represent the total inventory of Ni-59 in the object (black line) and the cumulative activity release to the object (accounting for radioactive decay; red dotted line) on the logarithmic right axes.*

Activity concentration in sediments and soils

During the whole simulation period, the activity concentration of Ni-59 in the sediments of biosphere object 157_2 increased, and thus never reached steady state (Figure 10-22a), though for the deepest layer (RegoLow) a steady state was nearly reached at the end of the land period. The stratigraphy (i.e. order of regolith layers), vertical water fluxes, and sorption coefficients (K_d) played a major role in the rate and dynamics of Ni-59 accumulation in regolith layers.

During the submerged period the water fluxes were small, and the simulation time short, and therefore the concentration was higher in the till layer than in the glacial clay layer (Figure 10-22a). During the land period, water fluxes increased, and as the simulation time was long, the activity concentration in glacial clay started to approach its steady-state level. At the end of the simulation, the radionuclide concentration in glacial clay was approximately ten times higher than in till. Radionuclide concentrations in regolith layers on top of glacial clay decreased successively towards the surface at this time. This pattern reflected the decreasing sorption in surface regolith layers and increasing water fluxes (in surface peat), compared to the deeper layers, and the fact that less than a unit release of radionuclides (1 Bq y^{-1}) reached the surface layers (i.e. Ni-59 concentrations were still building up in till and glacial clay).

The activity concentration in all model compartments was consistently lower in 157_1 than in 157_2, reflecting that only a fraction of released radionuclides reached the downstream object (Figure 10-22). Moreover radionuclides reaching 157_1 were further diluted with surface water before they dispersed downwards to deeper regolith layers. As the transport pathway of Ni-59 was reversed in 157_1, the concentration difference between 157_1 and 157_2 increased from top to bottom in the regolith layers. This means that the concentration difference between objects was limited in the surface regolith layer, but large in the deep regolith layers. At the end of the simulation period the concentration was three and six orders of magnitude larger in 157_2 than in 157_1 in glacial clay and till, respectively.

The activity concentration in agricultural soil was primarily a function of the concentration in the upper regolith horizon that can be cultivated (the drained-mire farmer variant), the concentration in fertilisers originating from seaweeds, biofuel ash or mire hay (the garden-plot or infield-outland variants), and the concentration in water used for irrigation of the garden plot. The highest concentration of Ni-59 resulted from draining and cultivating the mire in 157_2 (drained-mire farmer, Figure 10-22a).

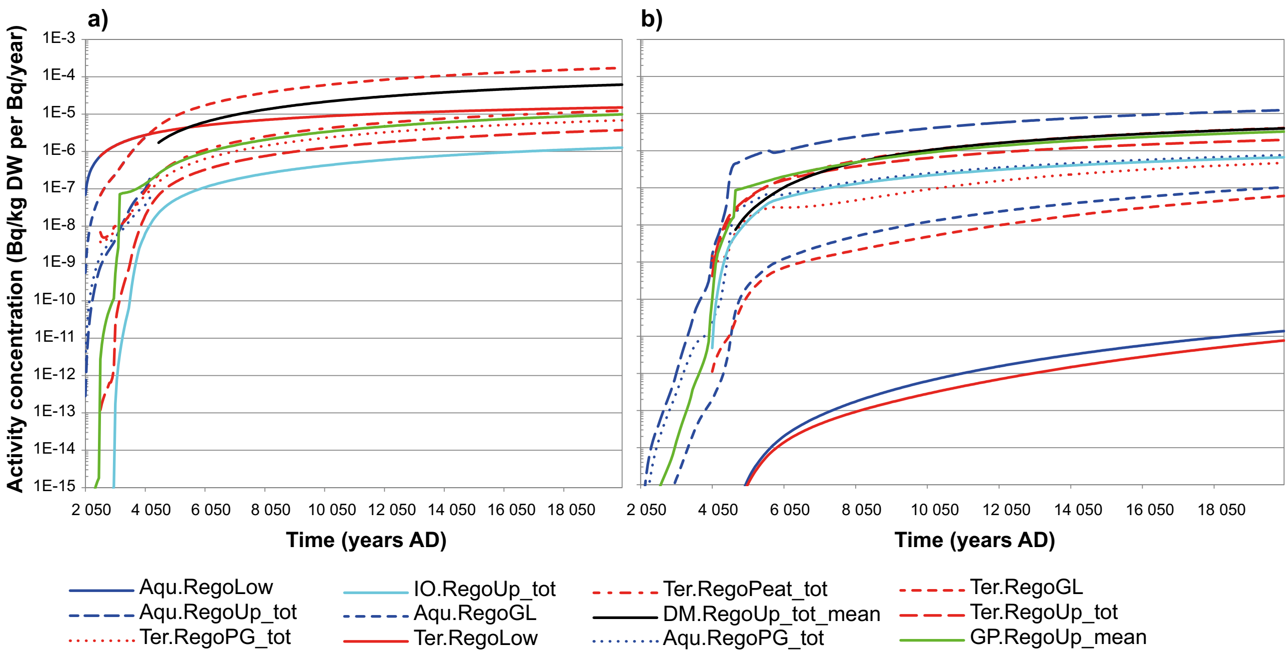


Figure 10-22. *Activity concentrations for unit release rate (Bq kgDW*$^{-1}$ *per Bq y*$^{-1}$*) of Ni-59 in regolith layers in two biosphere objects. a) The biosphere object 157_2 received a constant release of radionuclides (1 Bq y*$^{-1}$*) via groundwater from the repository. b) Downstream biosphere object 157_1 received radionuclides with surface water. Abbreviations of regolith layers are explained in Table 8-1; prefixes represent ecosystems or land use variants. For simplicity, total concentrations are shown for regolith layers with both an organic and an inorganic radionuclide inventory (indicated by "tot").*

The depth of the peat layer in this mire that had developed from paludification was relatively small. Consequently, peat in 157_2 was mixed with and enriched by underlying regolith layers (post-glacial clay gyttja and glacial clay) upon cultivation. As glacial clay had the highest radionuclide concentration, mixing this layer into cultivated soil resulted in a relatively high concentration of the radionuclide.

Activity concentration in water

Activity concentrations of Ni-59 in surface water are shown in Figure 10-23. During the submerged period (until 3000 AD) the exchange of water between neighbouring sea basins was large (see previous section on C-14) and the highest concentration was always found in the biosphere object receiving the groundwater discharge of radionuclides. Peaks and drops in concentrations during this period primarily reflected the effect of the degree of isolation on the water exchange, and shifts in the radionuclide concentration in the basin of 157_2 were also seen in the downstream basins (Figure 10-23).

Moreover, partial isolation of a basin receiving the radionuclide by exchange of water from connected basins led to a decline in concentration in water, and complete isolation led to a continuous concentration decline (e.g. object 160 at 3200 AD, object 121_1 at 3800 AD, and object 159 at 4100 AD). Simultaneously, the concentration in non-isolated sea basins increased, as these received a larger share of contaminated water at this time.

When the biosphere objects emerged out of the sea, contaminated water only reached 157_2 and downstream objects 157_1 and 116. As the flux of surface water was small during the land period, compared with water exchange between sea basins, the activity concentration peaked during this period (Figure 10-23). Steady state was nearly reached in surface waters of objects 157_1, 157_2 and 116.

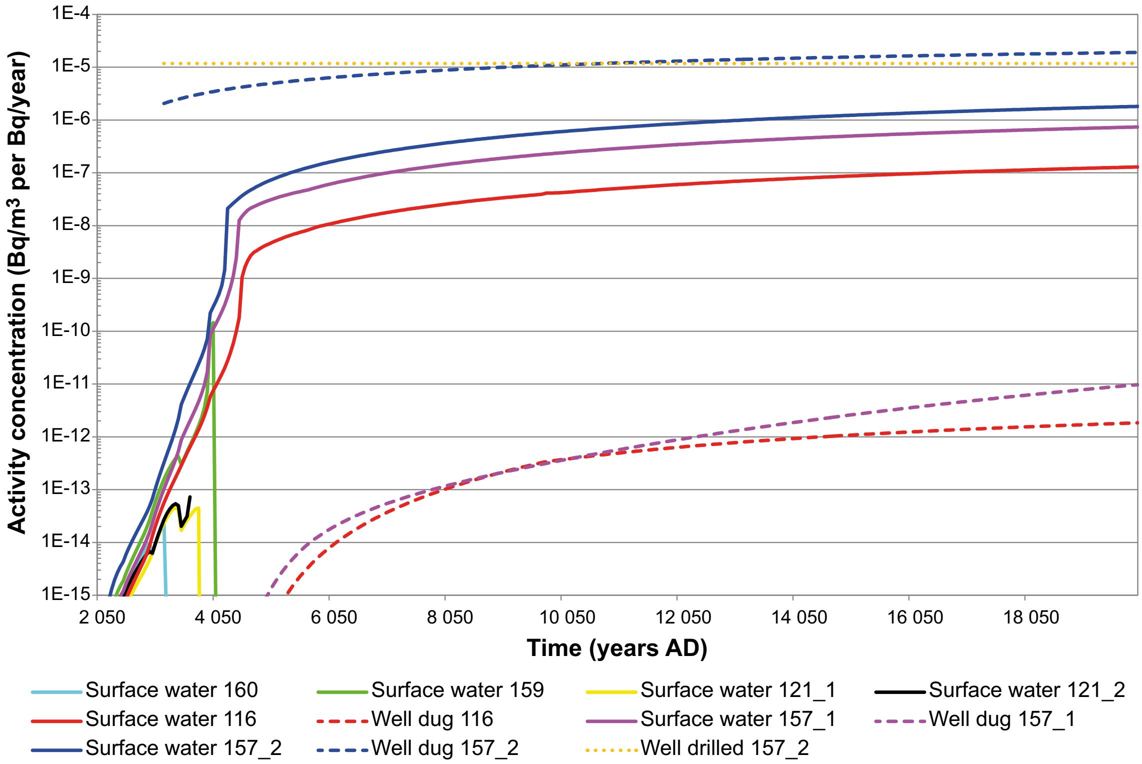


Figure 10-23. *Activity concentrations for unit release rate (Bq m^{-3} per Bq y^{-1}) of Ni-59 in surface water of seven biosphere objects. Solid lines represent concentrations in sea basins during the submerged period and concentrations in surface water on land (lakes, streams or other surface water) during the land period. Biosphere object 157_2 received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. In the land period, objects 157_1 and 116 are located downstream from 157_2. Note that there is no external source of radionuclides to the other biosphere objects (121_1, 121_2, 159 and 160) during the land period.*

In biosphere object 157_2, the activity concentration of Ni-59 was highest in the dug well (Figure 10-23), and thus, drinking and irrigation water for all exposed populations of permanent inhabitants living in or using resources from the object was collected from the dug well (except hunter-gatherers that use surface water only). The concentration in water from a dug well in biosphere object 157_2 was almost twice as high as that from a drilled well, and almost an order of magnitude higher than that of surface water in the object. For the downstream objects 157_1 and 116 the concentration in the dug well was considerably lower than in surface water, and permanent residents in downstream object (with a sufficient level of technology) used water from a drilled well (which had the highest concentration). Steady state was nearly reached at the end of the simulated period for well water in 157_2, whereas the concentration in well water in object 157_1 was still rising, indicating ongoing radionuclide inventory build-up in lower regolith layers (Figure 10-23).

Dose to humans for unit release

Dose to future human inhabitants, living in and/or using natural resources from the biosphere objects (Figure 10-24), results from external exposure (i.e. radiation from the ground), from inhalation of radionuclides, and from ingestion of radionuclides with food or water. For Ni-59, ingestion of food and/or water was the dominating exposure route for all four land use variants (hunter-gatherers, infield-outland farmers, drained-mire farmers, and garden-plot households).

The radionuclide concentration in food items was proportional to that in water (aquatic food items), in the upper peat layer of the mire (terrestrial food items, dairy products and meat), and in cultivated soil (crops, vegetables, dairy products and meat for drained-mire farmers). Thus, it was not surprising that the highest annual dose for drained-mire farmers was found in biosphere object 157_2 (Figure 10-24), which had the highest concentrations of Ni-59 in upper soil layer (Figure 10-22). Other land use variants in 157_2, and in the downstream object 157_1, yielded annual doses at least an order of magnitude lower than those resulting from draining and cultivating the mire in 157_2.

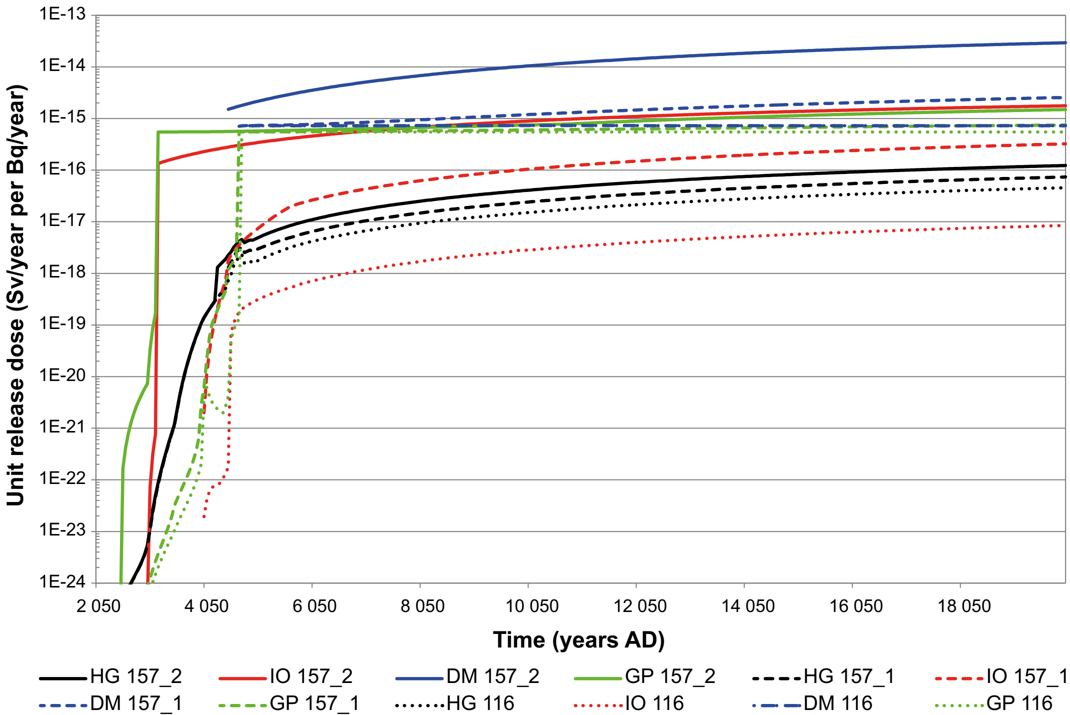


Figure 10-24. *The dose for unit release rate of Ni-59 to human inhabitants living in and/or using natural resources from the biosphere objects. Solid lines represent dose resulting from exposure in biosphere object 157_2, which received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. Dashed and dotted lines represent dose resulting from exposure in downstream objects 157_1 and 116, respectively. Colours indicate different land use variants: hunter-gatherers (HG), drained-mire farmers (DM), infield-outland farmers (IO), and garden-plot households (GP).*

The exposure from drinking water was highest in the land use variant utilising a dug well, and the contribution from this pathway ranged from a few percent (drained-mire farmers in 157_2) to 58% (garden-plot households in 157_2) of the total dose from a unit release at the end of the simulation. Although exposure from drinking surface water was limited as compared to consumption of well water (Figure 10-23), consumption of surface water was the dominating exposure route (68%) for hunters and gatherers living in object 157_2.

Dose rate to non-human biota for unit release

As stated in Section 10.3, temporal and spatial variations in dose rates for any organism group are expected to roughly follow those of the environmental media. For Ni-59, maximum dose rates for unit release resulted from exposure in freshwater ecosystems in objects 157_2 and 157_1 (Figure 10-25). Dose rates from exposure in terrestrial ecosystems in those objects and in freshwater ecosystems in object 116 were approximately one order of magnitude lower, and those in marine ecosystems were even lower.

The exposure in freshwater organisms was dominated by internal exposure and therefore the dynamics mainly followed that of the concentrations in water. The relative difference between organism groups reflected differences in equilibrium concentration ratios between organisms and the environment, which were highest for Zooplankton and lowest for Fish, Amphibians, Birds and Mammals (Figure 10-26). The contribution from external exposure was larger in object 157_1 where the total dose rates for benthic organisms, to some degree, were also partly external (maximum 30% of total dose rate for a few organism types).

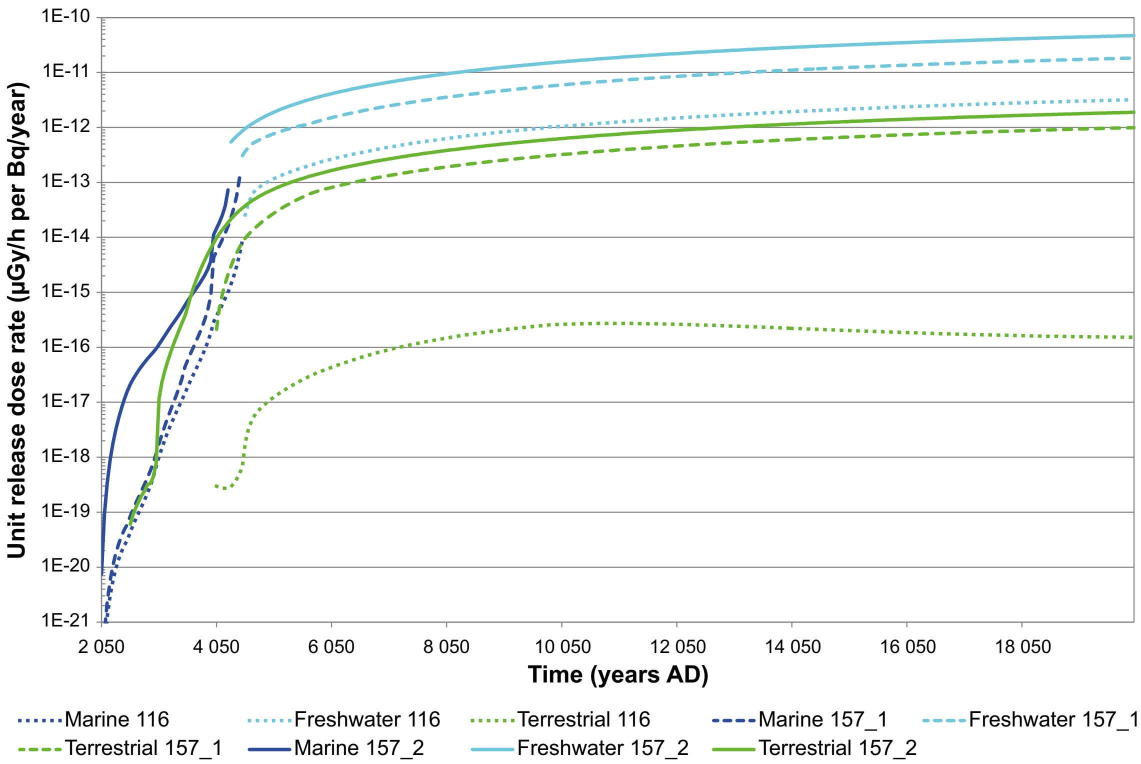


Figure 10-25. *Dose rates for unit release caused by Ni-59 to plants and animals inhabiting the future Forsmark landscape. The lines represent maximum dose rates across all examined organism groups within each ecosystem and biosphere object. Solid lines represent dose rates resulting from exposure in biosphere object 157_2, which received a constant release of radionuclides (1 Bq y^{-1}) via groundwater from the repository. Dashed and dotted lines represent dose rates resulting from exposure in downstream objects 157_1 and 116, respectively. Colours indicate marine, freshwater (lake and stream), and terrestrial (mire) ecosystems.*

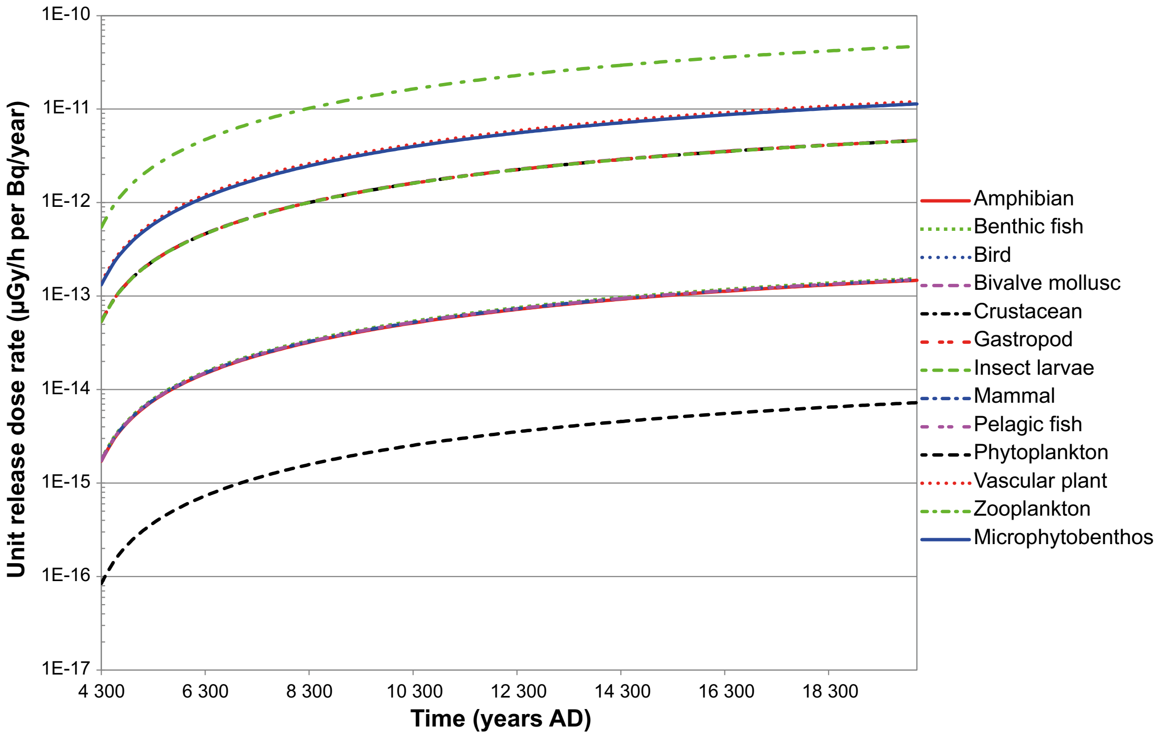


Figure 10-26. *Dose rates for unit release caused by Ni-59 for organisms living in the freshwater ecosystem in biosphere object 157_2.*

In marine ecosystems, Crustaceans and Polychaetes were the most exposed organisms, followed by Zooplankton and Vascular plants/Macroalgae. Internal exposure dominated for pelagic organisms, and external exposure for benthic organisms in object 157_2, whereas external exposure was only of some importance for a few benthic organisms in object 157_1. A general exception to these patterns was the exposure in Phytoplankton which was totally dominated by external exposure in both aquatic ecosystems. Due to its very small size, the internal exposure from beta radiation was limited; a large part of the energy will escape the organism without contributing to internal dose.

The most exposed mire organisms were soil-dwelling invertebrates and small primary producers. Since both internal and external exposure are dependent on the concentration in the upper soil layer, the dynamics of the total dose followed that in the oxygenated peat layer (RegoUp, Figure 10-22) and the most exposed organisms had the highest CR values. External exposure contributed significantly to total exposure only for small, soil-dwelling, mammals (53% of total dose rate) and Grasses and herbs (50%).

10.6 Comparison of climate calculation cases

A number of climate cases describing different future climate developments have been used in the radionuclide transport modelling in SR-PSU. The climate cases cover a time period of 100,000 years and are defined and described in the **Climate report** (see also Chapters 4 and 7 of the present report). The climate cases include different climate conditions (temperate, periglacial and glacial) and submerged conditions in the landscape. The future climate affects the development of the Forsmark landscape, the discharge of groundwater from the repository, the biomass and process rates of ecosystems, and the extent to which natural resources can be utilised by future inhabitants. To cover the effects of climate on transport, accumulation and exposure in surface ecosystems, four different biosphere calculation cases (BCC) were constructed: present conditions (global warming calculation case, BCC1), permafrost conditions (talik calculation case, BCC2), warmer and wetter conditions (extended global warming calculation case, BCC3), and, for illustrative purposes, also submerged conditions following a glacial period (submerged calculation case, BCC4), see Section 7.4 and Table 10-4.

Table 10-4. Unit release simulations used to compare biosphere calculation cases (BCC).

Biosphere calculation case (BCC)	Climate conditions	Climate cases[1]	Simulation period
Global warming calculation case (base case, BCC1)	Present conditions	Global warming climate case	Simulation period is 18,000 years
Talik calculation case (BCC2)	Permafrost conditions (preceded by present conditions)	Early periglacial climate case	Period with permafrost starts at 17,500 AD and ends at 20,500 AD
Extended global warming calculation case (BCC3)	Warmer and wetter (with delayed shoreline displacement)	Extended global warming climate case	Simulation period is 18,000 years. Emergence of land is delayed by 1,000 years.
Submerged calculation case (BCC4)	Present conditions (landscape submerged by the sea)	Weichselian glacial cycle climate case	Simulation is 11,500 years and ends when the present shoreline has been reached

[1] All climate cases cover the 100,000-year assessment period, but only a part of this period is used to compare the behaviour of the biosphere calculation cases.

In this section, we investigate how dose calculations are affected by the four biosphere climate calculation cases. For this comparison of the climate cases, we use four relatively long-lived radionuclides (C-14, Cl-36, Mo-93, and Ni-59), each with its unique set of properties (Section 10.5). The endpoints used are the annual doses to humans and dose rates to non-human biota, resulting from a unit release rate (1 Bq y^{-1}). An 18,000-year simulation period was used for the global warming case and the extended global warming case. The simulation period for the talik case was 500 years longer, but direct release to the discharge taliks was only considered for 3,000 years. For the Submerged case, the period from the last ice retreat (–9500 AD) until the present was included in the simulation.

Results from a unit release rate in the global warming calculation case were discussed in the previous section (10.5). Thus, in this section the outcome of the other three calculation cases are examined using the global warming case as a reference point (also referred to as “base case”). The comparison illuminates how climate related changes in landscape development, location of the discharge, and biosphere parameters, affect dose calculations. However, as the release of radionuclides from the geosphere is also affected by climate conditions, results from the comparisons cannot be directly generalised to risk or dose rates in the safety assessment.

10.6.1 Talik in a periglacial landscape (BCC2)

In the talik calculation case the Forsmark shoreline develops as in the base case (BCC1). Present climatic conditions prevail until 17,500 AD, when the first 3,000-year period of cold climate arises. At this time all of the model area is above the shoreline, and most of the regolith layers will be permanently frozen. Discharge of deep ground water will be restricted to areas on top of unfrozen bedrock and regolith, so-called discharge taliks (Section 7.4.2).

In the unit release simulations of this calculation case, radionuclides will accumulate during 15,500 years of temperate climate conditions, primarily in biosphere object 157_2 but also in the downstream object 157_1. In the following cold period radionuclides will be discharged to a previously uncontaminated near-coastal lake (object 114), or to a wetland in a former lake basin (object 157_1), downstream object 157_2. During the cold period the wetland area will thus receive radionuclides with ground water from the geosphere and with surface water from the upstream object. Moreover, agriculture will not be possible during periods of cold climate and wells in the frozen ground or bedrock will not yield any water. Thus, the land use variant considered in the dose calculations is that of hunter-gatherers. As the landscape is fully emerged from the sea, terrestrial and freshwater biota living in the mire (157_1) and freshwater biota living in the lake (114) are assessed (but not marine biota).

The annual doses for hunter-gatherers foraging the periglacial landscape were similar (Cl-36, Mo-93) or less (C-14, Ni-59) than the maximum dose for the same land use variant in the global warming case (Permafrost 157_1 in Figure 10-27). Most of the Ni-59 discharged from bedrock into object 157_1 was retained in deep regolith layers during the short permafrost period, and did not contribute significantly to the concentrations in surface sediments. Thus, the concentrations of surface sediments in the periglacial period were below those in the base case, where the discharge was constantly located to one area for the full simulation period.

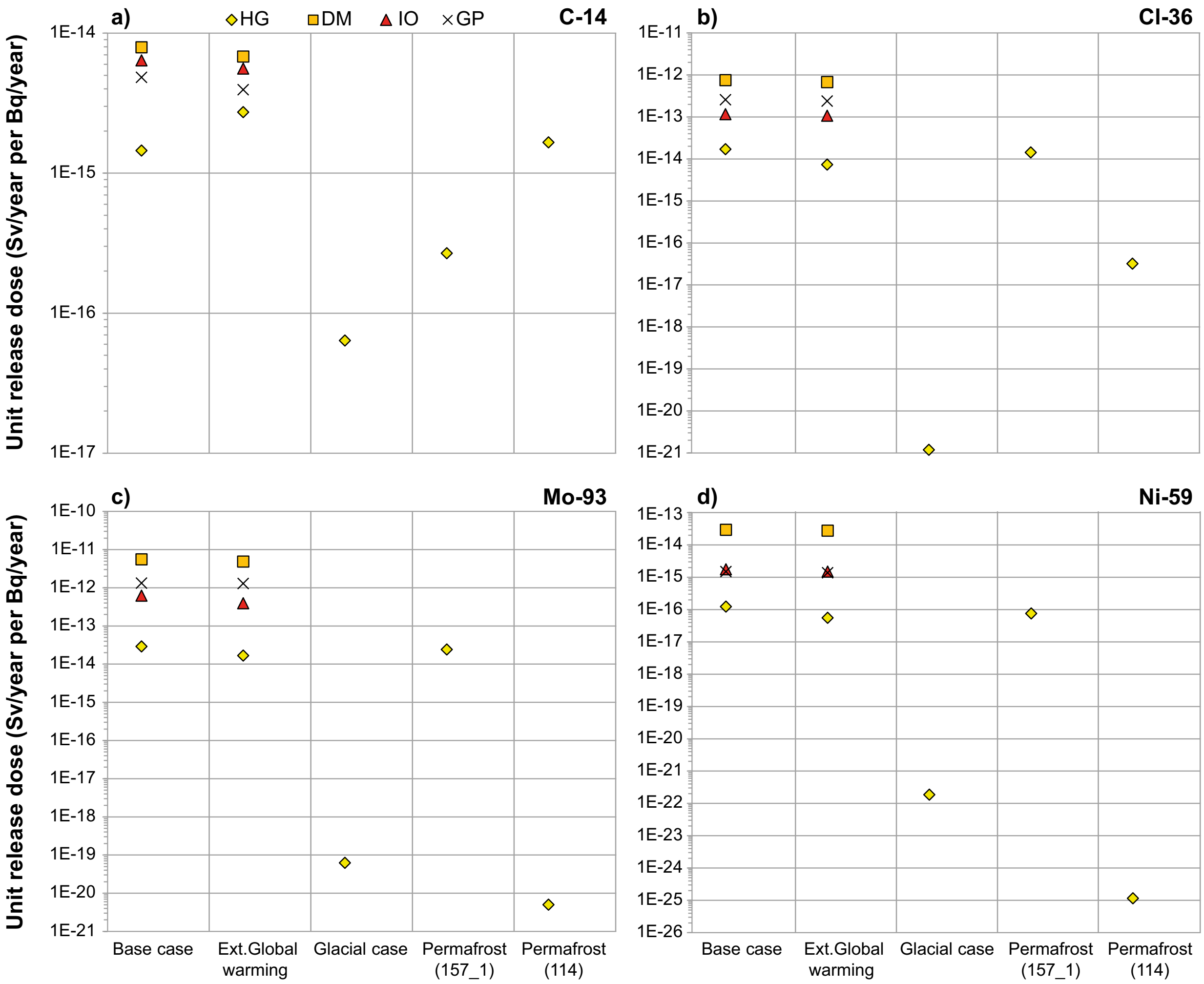


Figure 10-27. *Maximum LDFs for humans (Sv* y^{-1} *per Bq* y^{-1}*) for the biosphere calculation cases related to different climate conditions included in the SR-PSU assessment. 157_1 and 114 refer to biosphere objects above discharge taliks. a) C-14, b) Cl-36, c) Mo-93, d) Ni-59; HG = hunter-gatherers, DM = drained-mire farmers, IO = infield-outland farmers, GP = garden-plot households.*

The small stream in the mire object 157_1 contributed insignificantly to the dose via food consumed by hunter-gatherers. As aquatic food was the main exposure route for C-14, the annual dose in the cold climate was much lower than those received during the earlier temperate period when 157_1 still contained a lake. For non-volatile radionuclides (Cl-36, Mo-93 and Ni-59) the lake talik in object 114 contributed insignificantly to the annual dose to hunter-gatherers, as radionuclides were diluted with surface water from a large watershed. However, as the lake was large and productive, and no C-14 was degassed in the mire areas bordering the lake, the annual dose of C-14 from the lake in object 114 was almost twice as large as the dose to hunter-gatherers in the base case, although still a factor of five below that in the DM land use variant of the base case.

The maximum dose rates to terrestrial and freshwater biota were typically a factor of 1.5 to 3 lower under permafrost conditions, as compared to the global warming case (Figure 10-28). These differences were primarily due to the shift in the location of the release. That is, dilution with surface water in object 157_1, where radionuclides were discharged during the cold climate period, was larger than in the upstream object 157_2, where radionuclides were discharged in the global warming case. In the case of Ni-59, the redirection of the release also resulted in less radionuclides reaching the surface during the short permafrost period (cf. above).

However, for C-14 the dose rates to terrestrial biota were elevated by a factor of two under permafrost conditions. This shift was primarily caused by a decreased atmospheric concentration of stable carbon. Due to differences in watershed size, the dose rates to freshwater biota were always lower in the lake in object 114 than in the small stream in 157_1 in the talik calculations, but the difference was less pronounced for the volatile radionuclide C-14 (cf. above).

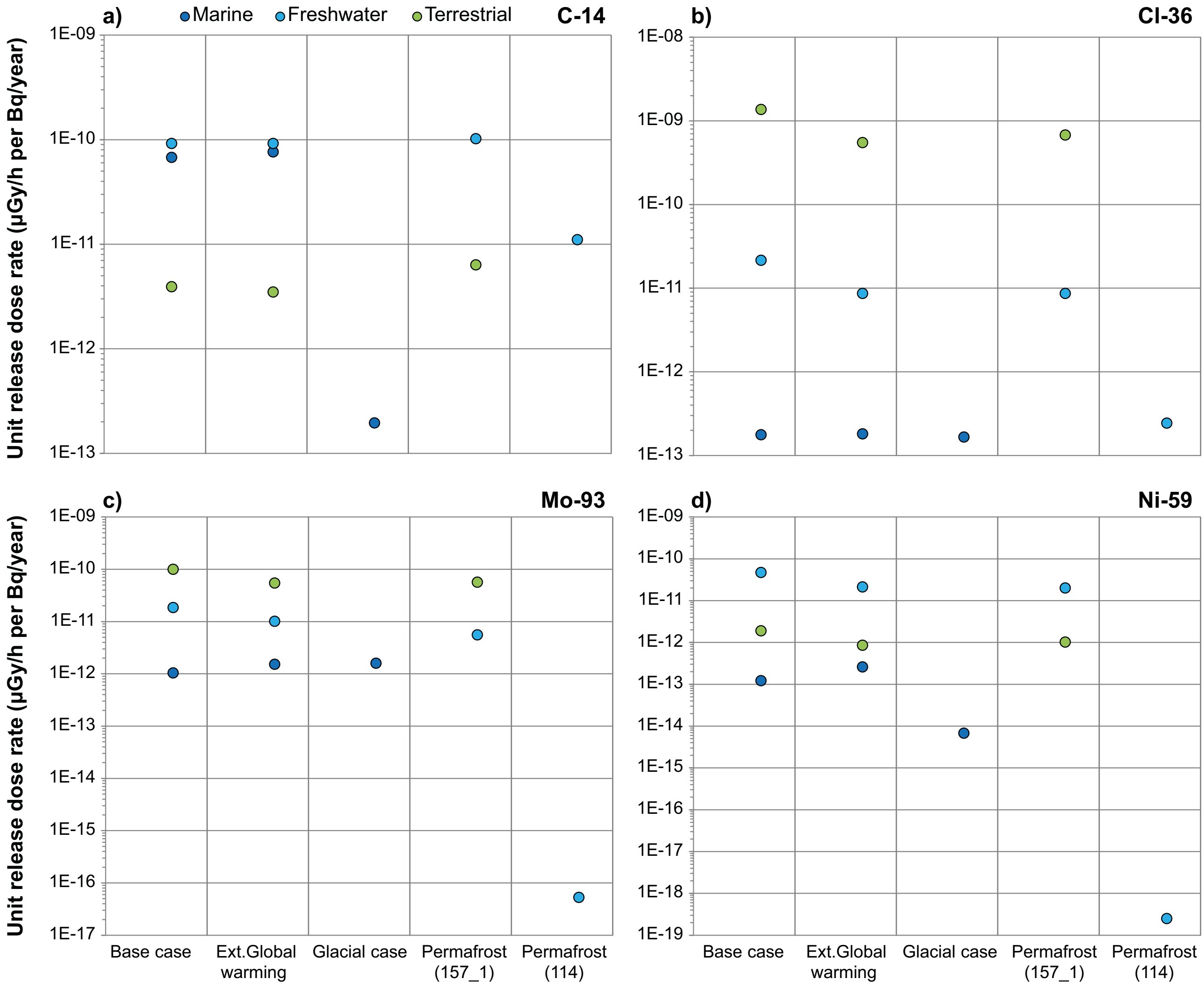


Figure 10-28. *Maximum dose rates from a unit release rate to non-human biota (µGy h^{-1} per Bq y^{-1}) for biosphere calculation cases related to different climate conditions included in the SR-PSU assessment. 157_1 and 114 refer to biosphere objects above discharge taliks. a) C-14, b) Cl-36, c) Mo-93, d) Ni-59; Marine/Freshwater/Terrestrial refers to ecosystem type for non-human biota.*

10.6.2 Extended global warming (BCC3)

In the *extended global warming climate case* the sea level rises, which delays the displacement of the Forsmark shoreline by approximately 1,000 years compared to the *global warming climate case* (1,200 years according to the **Climate report**). In the extended global warming biosphere calculation case (BCC3), a warmer and wetter climate prevails throughout the simulation period. The discharge area for deep groundwater from the repository is the same as in the base case, namely object 157_2 (Section 7.4.2).

The unit release simulation is run for a period of 18,000 years, which is identical with the base case. The submerged period is extended by 1,000 years and the land period will be shortened by the same amount of time, as compared with the base case. Moreover, the hydrology during the land period is significantly affected by the increased precipitation and several ecosystem properties change in response to the assumed 6°C temperature rise. The same land use variants and the same categories of non-human biota as in the base case are evaluated in the extended global warming calculation case.

The extended global warming calculation case resulted in lower maximum annual doses for most land use variants and radionuclides (Figure 10-27). The main reason for this was that the wetter climate implied a higher precipitation, which resulted in an increased horizontal flux of groundwater diluting radionuclides in surface water and surface peat. Lower annual doses were most pronounced for Cl-36, for which the radionuclide concentrations in surface peat and water decreased by a factor of three. As Cl-36 accumulated in organic matter, increased peat and plant concentrations also translated into higher concentrations in cultivated soil, which originated from peat or was fertilised with organic matter. A similar pattern was found for both Mo-93 and Ni-59, with respect to the hunter-gatherers land use variant, and to a less extent in the infield-outland variant.

However, annual doses for the drained-mire farmers and garden-plot households land use variants did not differ much between the extended global warming case and the base case. This was because the main source of radionuclides in cultivated soils was accumulation in regolith layers below surface peat, and consumption of well water was an important exposure route in the GP variant (C-14 and Ni-59). None of these exposure routes were affected by an increased flux of groundwater in surface layers. For the volatile radionuclide C-14 the pattern and mechanisms were different. That is, the warmer climate was associated with a decrease in degassing rate in wetlands, which in turn caused the annual dose to increase somewhat for hunter-gatherers foraging the downstream lake. On the other hand, annual dose rates to all land use scenarios involving cultivation decreased somewhat, as the concentration of stable carbon in the atmosphere was elevated in the *extended global warming climate case*.

For non-volatile radionuclides (Cl-36, Mo-93, Ni-59) the maximum dose rates to terrestrial and freshwater biota were typically a factor of two lower in extended global warming case as compared to the base case (Figure 10-28). As for human hunter-gatherers, this decrease in dose rates was caused by increased horizontal flux of groundwater associated with the wet climate. For C-14, there was a slight increase in dose rate to aquatic biota (due to reduced wetland degassing) and a slight decrease for terrestrial biota (due to elevated concentrations of stable carbon in the atmosphere). The elevated sea level caused higher dose rates of all investigated radionuclides to sediment-living marine biota in the extended global warming case as compared to the base case, although these were still below terrestrial and freshwater biota in the base case. For Cl-36 the increase was small, and associated with conditions of low sediment resuspension at greater water depth than present.

For sorbing radionuclides (Ni-59 and Mo-93) maximum dose rates increased with a factor of two or three in the extended global warming case. As in the base case, dose rates of sorbing radionuclides were highest in a late stage of the sea basin development (after 4000 AD), and the increase was caused by the extended time of accumulation (i.e. 1,000 additional years). The increase in dose rate of C-14 was limited. The maximum dose rate of C-14 also occurred in the late phase of the submerged period, and the slightly higher dose rates in the extended global warming case was caused by a reduction in radionuclide input from the terrestrial part of the object (due to a decrease in wetland degassing).

10.6.3 Submerged conditions after glaciation (BCC4)

The effects of a potential release after a glaciation were evaluated in the submerged (post-glacial) conditions calculation case. This case starts when the ice sheet has retreated from Forsmark at 68,200 AD according to the *Weichselian glacial cycle climate case*. At this time the Forsmark landscape is completely submerged under the sea. However, the isostatic rebound will slowly lift the sea bottom, and the present coastline will be reached after 11,500 years of shoreline displacement.

The unit release simulation spanned the landscape development during the submerged period, starting after the retreat of the ice and ending at the time of the present day landscape (a period of 11,500 years). During this period, all biosphere objects were covered by the sea. As compared to the global warming calculation case the submerged period was considerably longer in this case, but the case excluded the last phase when the biosphere objects transform into bays (and then further to lakes or mire areas). The only land use variant considered in this calculation case was hunter-gatherers foraging the sea, and non-human biota was restricted to marine organisms.

The annual dose received by human inhabitants was one (C-14) or several orders of magnitude (Cl-36, Mo-93, Ni-59) lower than for hunter-gatherers in the global warming calculation case (Figure 10-27). The main exposure route was consumption of fish. The horizontal exchange of water between sea basins diluted the released radionuclides in the submerged landscape.
The concentration of radionuclides in water increased towards the end of the simulation, as the exchange of waters was restricted by straits getting narrower and shallower. However, at the end

of the simulation the biosphere object receiving the discharge of groundwater from the repository (157_2) was still connected to adjacent sea basins (160, 121_2, 157_1 and 116). The relatively small difference in the LDF of C-14 between the submerged case and the base case was caused by a combination of effects, including fish being the main exposure route in both cases, and wetland degassing reducing C-14 release to freshwater ecosystems.

The long period of submerged conditions resulted in lower dose rates of C-14 and Ni-59 to marine biota than in the base case, whereas the opposite was true for Mo-93 and Cl-36 (Figure 10-28). In the base case, and also in the extended global warming case, dose rates of C-14 and Ni-59 to marine biota increased by two and three orders of magnitude, respectively, within the 2,000-year period from the present coastline to the time when biosphere object 157_2 was fully emerged. Thus, it was not surprising that the maximum dose rates were lower in the submerged calculation case, which did not include this period. The dose rate of Mo-93 to marine organisms also increased towards the end of the sea period in the base case.

However, the increase in dose rates between the present and the time for isolation of the biosphere object was less than an order of magnitude. Thus, thousands of years of accumulation under conditions of low sediment resuspension resulted in higher sediment concentrations in the submerged calculation case. This, in turn, led to dose rates to sediment-living organisms that were a factor of three higher than in the base case. The dose rates of Cl-36 to sediment-living marine biota was a factor of two higher in the submerged case than in the base case. Sediment concentrations were quite stable for most of the submerged period. However, dose rates started to decline when the water depth was shallower than 30 m, due to the increased rate of sedimentation, and approached the maximum dose rate of the base case simulation in the end. The dose rates of both Mo-93 and Cl-36 to marine biota were clearly below that of terrestrial and freshwater biota in the base case.

10.7 Distributed release

Hydrogeological modelling indicates that the major fraction of a potential release from the present repository (SFR1) and its planned extension (SFR3) will be discharged into a limited area in the future Forsmark landscape, i.e. into biosphere object 157_2 (Chapter 6). Consequently, dose and dose rate estimates were based on the assumption that *all* radionuclides will be discharged into object 157_2, and that radionuclides reach other biosphere objects only through horizontal fluxes of groundwater and surface water (see BCC1, Section 7.4.1).

However, for a few repository parts, a fraction of the release is expected to be directly discharged to other biosphere objects. To quantify the effects of the simplified handling of the large-scale spatial distribution of the release in the base case (BCC1), an alternative calculation case was set up (BCC6, Section 7.4.6). The 2BMA part of the repository had the largest fraction of exit points located outside of object 157_2. Thus for this simulation the release fractions from 2BMA to each of the biosphere objects were used. Release fractions were determined for 17 hydrogeological simulations (Odén et al. 2014), and in BCC6 the maximum release fraction, over the 17 simulations, was cautiously used for each biosphere object and time (Table 7-5).

The calculation was carried out for the four radionuclides considered in the detailed analyses in the preceding sections (C-14, Cl-36, Mo-93 and Ni-59). In most instances, accounting for the spatial distribution of the release gave a marginal increase in dose and dose rate (Figures 10-29 and 10-30). This was primarily because the highest doses and dose rates occurred in objects 157_2 or 157_1 also in the case of the distributed release. Thus, for Cl-36, Mo-93 and Ni-59 the differences in dose and dose rates between the base case and the distributed release were less than 15%.

For C-14 the results were different from those of the other radionuclides. That is, the dose for hunter-gatherers was elevated by a factor of two or three in three objects (objects 157_1, 159 and 116, Figure 10-29a) when the release was distributed. Similarly, the dose rate for marine biota was elevated by a factor of between two and three (objects 159, 157_2 and 157_1, Figure 10-30a). The dose rate to freshwater biota exceeded those in marine and terrestrial environments, and freshwater dose rates were slightly elevated (30–40%) in two objects (159 and 157_1).

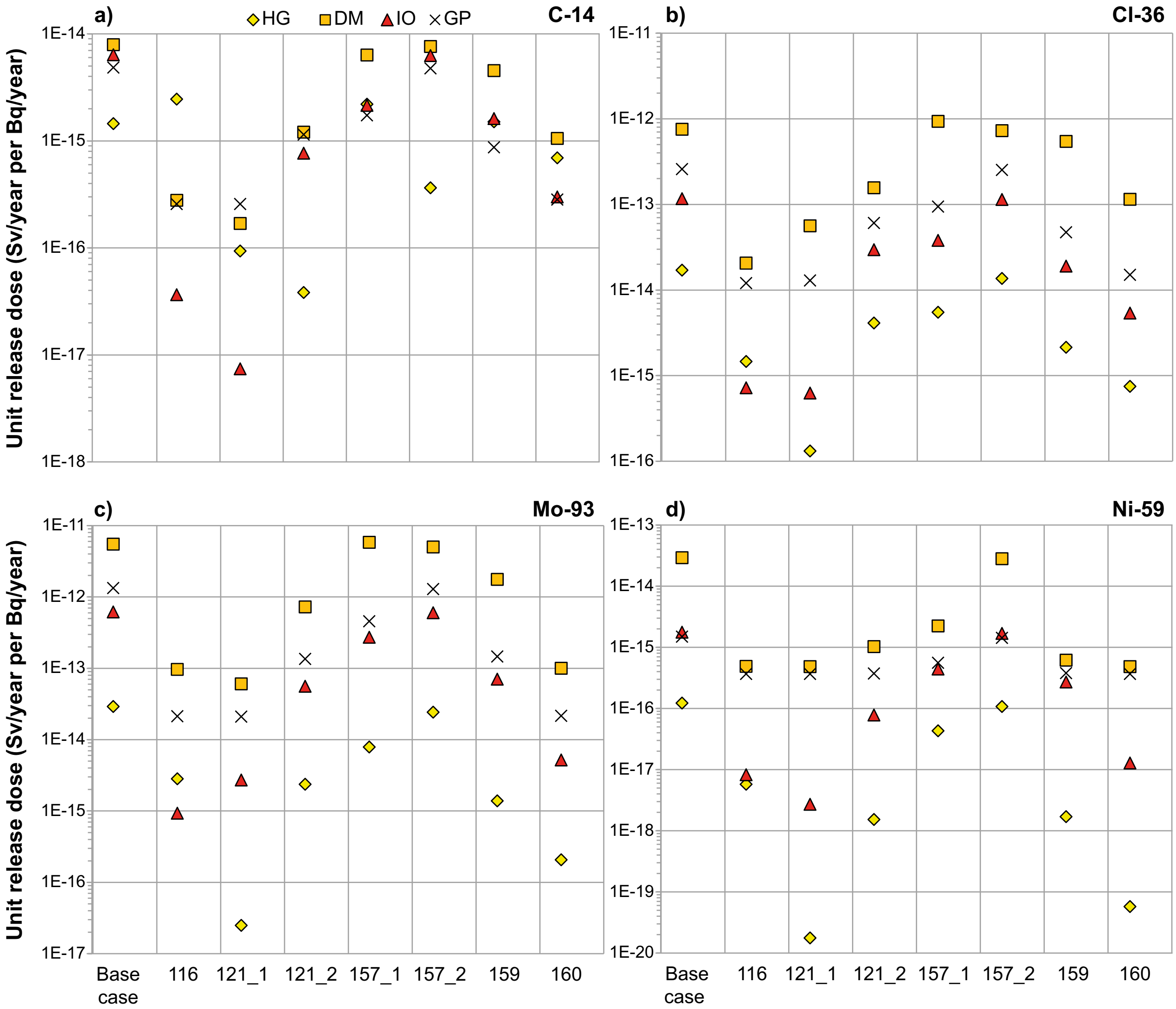


Figure 10-29. *Maximum LDFs for a number of objects for a distributed unit release (1 Bq y*$^{-1}$*), as described in the text. The different land use variants are labelled according to the figure legends, where HG = hunter-gatherers, DM = drained-mire farmers, IO = infield-outland farmers, and GP = garden-plot households. a) C-14, b) Cl-36, c) Mo-93, d) Ni-59.*

The response observed in the C-14 results was due to the volatile nature of carbon. When biosphere object 157_2 had emerged from the sea, only a small fraction of the C-14 released to the object reached downstream sea or lake basins (Section 10.4.1). While the release fractions that reached other objects directly were small in absolute terms (less than 10%, Table 7-2), they were significant compared to the C-14 exported with groundwater from the wetland in 157_2. Hunter-gatherers forage food from several objects in the area. As the production of fish from the small objects 157_1 and 159 was not sufficient to cover the full protein demand of a hunter-gatherer group, the annual dose from consuming fish from all three objects (157_1, 159 and 116) would elevate the annual dose by a factor of two to three (data not shown). However, as the annual dose for hunter-gatherers was more than one order of magnitude less than that for farmers draining the mire in the base case, the distributed release had no effect on the maximum annual dose over all land use variants (Figure 10-29).

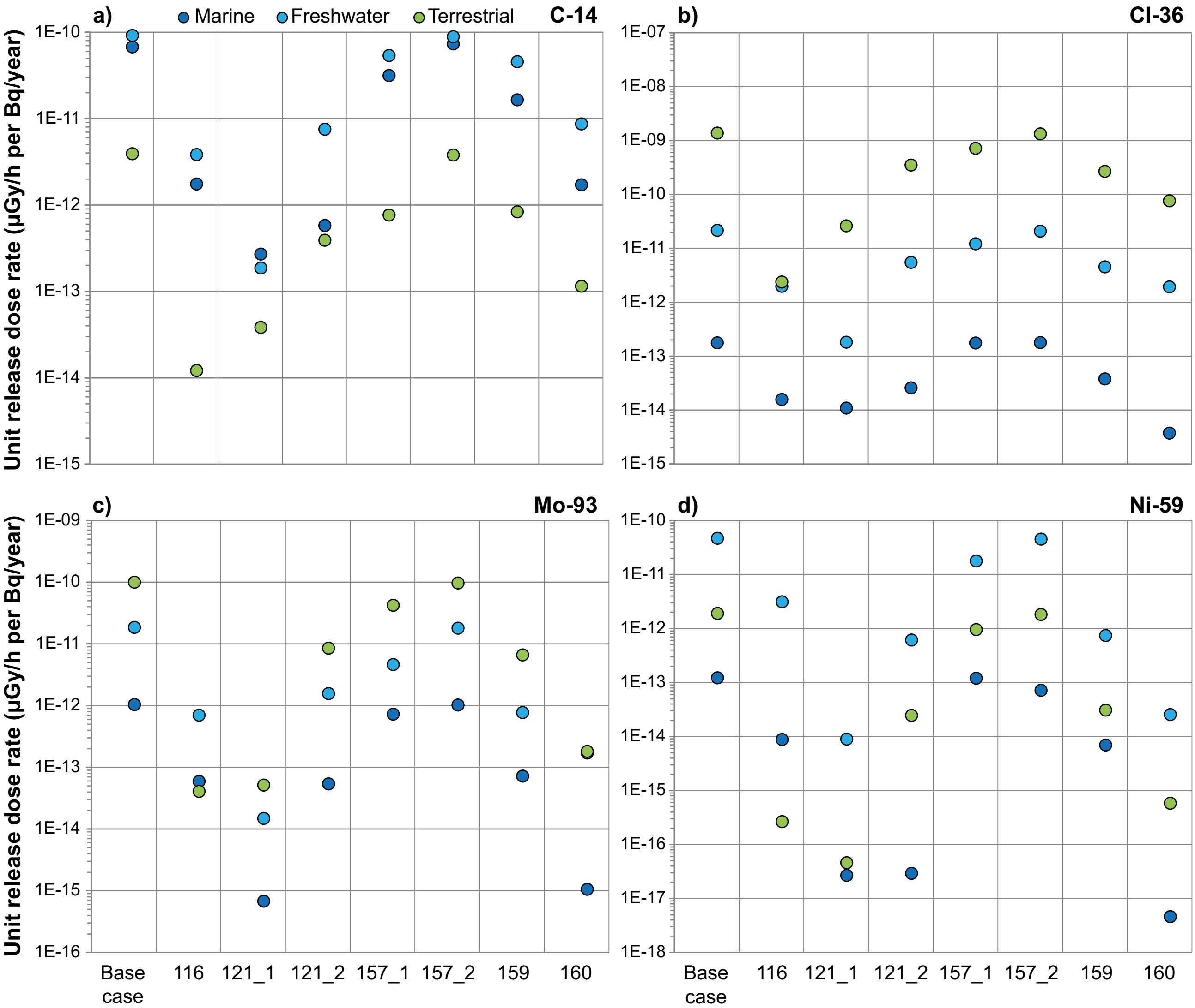


Figure 10-30. *Maximum dose rates to non-human biota for a number of objects for a distributed unit release (1 Bq y^{-1}). Marine/Freshwater/Terrestrial refers to ecosystem type. a) C-14, b) Cl-36, c) Mo-93, d) Ni-59.*

10.8 Alternative object delineation

The methodology to delineate biosphere objects is described in Chapter 6. To examine how the object delineation may affect object properties and the environmental concentrations resulting from a constant release rate, the biosphere object 157_2 was outlined in four alternative ways (Section 6.4). In short, these alternative delineations were defined as follows:

1) *Areas with upward hydraulic gradients* (UpwGrad) representing areas with a steady upward flux of groundwater from the bedrock through the geosphere-biosphere boundary and all regolith layers (~ 13 $\cdot 10^4$ m^2).

2) *Wetland areas* (Wetl) representing open wetland areas, with respect to predicted groundwater level and vegetation types (~ 8.4 $\cdot 10^4$ m^2).

3) *Main area for discharge points* (HD-disch) representing an area with a high density of repository discharge points at the geosphere-biosphere boundary (~ 4.7 $\cdot 10^4$ m^2).

4) *Potential arable land* (Arabl) representing areas with a combined thickness of the arable regolith layers of at least 0.5 m (~ 2.9 $\cdot 10^4$ m^2).

Each of the alternative delineations reflects a stylised approach of outlining a biosphere object derived from a different assessment perspective. Thus, the resulting objects should not be seen as equally likely representations of areas affected by deep groundwater from the repository. For example, discharge areas with a steady upward flux of groundwater from the bedrock to the surface (1), and open wetland areas connected by a horizontal exchange of surface water (2), are likely to receive most of the radionuclides discharged to the object (see Section 6.3). On the other hand, the area superimposed on bedrock with a high density of discharge points (3), and the area representing potential arable land (4), illustrate aspects of potential variations in object-specific properties, but they were derived from hypothetical "what if" perspectives.

In this section, we present results from simulations based upon all four of the alternative object delineations (BCC 8, Section 7.4.8). In the simulations, 1 Bq y^{-1} was released to till (RegoLow) in each of the alternatively outlined areas, and the resulting environmental concentrations were compared with those obtained for the original object (Ref). The simulations were run until 20,000 AD, assuming landscape development and ecosystem parameters from the base variant (BCC1, global warming). In addition, object-specific parameters were derived from each of the outlined areas, including object area (time-dependent), all hydrological flux rates, and regolith depths.

10.8.1 Results for alternative delineations

Pore water in deep till layer

In the Forsmark area till rests on the bedrock, and consequently it is the first regolith layer reached by radionuclides transported to the biosphere objects with deep groundwater. While humans and non-human biota are not directly exposed to this deep regolith layer, drinking water may be extracted from a dug well, which is assumed to be possible once the area is one metre above the sea level. The concentration in pore water of till is a good approximation of the radionuclide concentration in water extracted from a dug well (Werner et al. 2013a).

The pore water concentration of all four studied radionuclides declined with increasing size of the outlined biosphere object (Figure 10-31a, maximum levels after land having risen to at least one metre above sea level and exposure may occur through a dug well). Compared with the concentration for the original outline of biosphere object 157_2, the increase in concentration was typically limited to a factor of three in till, under the areas with an upward hydraulic gradient, under the open wetland area and under the area with a high density of bedrock discharge points. However, the concentration in pore water in the smallest outlined area (potentially arable land) was approximately seven-fold higher than in the original object. The trend of decreasing concentration in pore water with object area was primarily driven by variation in the upward groundwater flux rate [m^3 h^{-1}] through the till layer (Figure 6-15c).

There was also a strong influence of marine sediments on concentrations of radionuclides in pore water, as the maximum concentrations of C-14 and Cl-36 in the early land period (starting at 3100 AD) were approximately five- and ten-fold larger than in steady-state conditions, respectively. The shift in radionuclide concentrations between the submerged and land periods was caused by a systematic increase in vertical water flux through all regolith layers. The response to this shift was less pronounced in the case of sorbing radionuclides; the maximum land period concentration of Mo-93 was just above steady-state levels, whereas Ni-59 concentrations increased steadily during the full simulation period. The decreased concentration associated with land emergence may be an effect of the unit release methodology, in which the release to the object is de-coupled from the hydrological flux into the object.

The upper peat layer

Radionuclides in the upper, biologically active peat layer may expose humans and non-human biota to external radiation. Radionuclides from this layer may also accumulate in mire vegetation and be transferred to consumers and detritivores in the mire ecosystem. Surface water in mire areas is an important habitat for water-dwelling organisms. Although unlikely to be utilised, it may provide drinking water for human inhabitants, at least for parts of the year. Surface water is also the only export pathway of water-bound radionuclides to areas downstream of the primary biosphere object (157_2).

The concentrations of Cl-36 and Mo-93 in the upper peat layer were similar in all alternatively outlined areas, with the exception of surface peat above the area with a high density of bedrock discharge points. The concentrations of these radionuclides in this area were two to three times higher than the concentrations in other areas (Figure 10-31b). The pattern of Ni-59 concentrations was somewhat similar, but the Ni-59 level was four times greater in the high-density area than in the original object, and the concentration in the smallest area was only one fifth of that in the original object.

The observed differences with respect to Cl-36 and Mo-93 concentrations were primarily caused by dilution of radionuclides in surface water. That is, the radionuclide concentration was proportional to the inverse of the horizontal water flux through surface peat (q_downstream, Figure 6-15c). The same pattern would have emerged for Ni-59 if the simulation time had been extended beyond 100,000 years. However, as Ni-59 adsorbed more strongly to soil particles, accumulation dynamics also became important for the concentrations observed at the end of the simulation time. Thus, the thick glacial clay layer in the smallest object slowed down the accumulation of radionuclides in the overlying surface peat, whereas a high area-specific groundwater flux (especially in glacial clay) sped up accumulation in the area with a high density of bedrock discharge points (Figure 6-15a, b). Nevertheless, the differences in Ni-59 concentration between the original object and any of the alternative outlined areas were within a factor of five.

The total concentration of C-14 in the upper peat layer decreased with increasing size of the outlined area (Figure 10-31b). This was because the primary pathway of dilution (or export) of C-14 from surface peat was through degassing of CO_2. The rate of degassing was three times greater than the mass flux of dissolved radionuclides with horizontal groundwater transport in the smallest area and twenty times greater in the original object. The total rate of degassing was proportional to the surface area. As the range in object sizes spanned a factor of five, the variation in the concentration of the upper peat was also limited to a factor of five between the smallest and the original object. Although it was the flux of inorganic radionuclides that governed the differences in concentrations in regolith between outlined objects, the majority of the C-14 (and Cl-36) inventory was stored in organic matter (Figures 10-2 and 10-9), which was not directly affected by degassing or horizontal water fluxes.

According to the hydrological description of the area, the groundwater in the primary biosphere object 157_2 was in contact with partly ephemeral pools of shallow surface water. In the radionuclide model this surface water is represented by the pore water of the upper peat layer. As adsorbed and dissolved radionuclide inventories are assumed to be in equilibrium, and as plant uptake and incorporation of radionuclides into organic matter is proportional to concentrations in soil in the model, it was not surprising that the variation in concentration in surface water (among outlined areas) mirrored that of total concentrations in peat (Figure 10-31b, c). The activity concentrations of C-14 and Cl-36 in surface water reached steady state relatively fast. Mo-93 approached steady state at the end of the simulation, whereas Ni-59 was a factor of two to 20 (smallest area) below its steady-state condition (as indicated by the Cl-36 concentration).

Drained and cultivated soil

Radionuclides stored in, or adsorbed to, organic matter will be subject to long-term accumulation, especially in deep peat layers. If the mire is drained, inhabitants cultivating the soil will be exposed to radionuclides that have accumulated, possibly over very long periods of time. As drainage and cultivation cause the soil to subside, due to initial compaction and continuous oxidation, and as ploughing and bioturbation will mix soil layers, radionuclides from deeper regolith layers (i.e. post-glacial clay gyttja and glacial clay) will also be transferred to the cultivated soil layer.

The concentration of all four radionuclides in drained and cultivated soil tended to decrease with increasing area of the outlined object, with the exception of Ni-59 in the smallest object (Figure 10-31d). The difference in concentration between the original object (reference) and the area with continuous vertical discharge (upward gradient), the open wetland area and the area on top of a high density of bedrock discharge points, were typically within a factor of three. However, the smallest area (potential arable land) stood out, as the concentrations in soil of C-14, Cl-36 and Mo-93 were one order of magnitude higher than in the original object (see further discussion in Chapter 11).

The variation in concentration between outlined objects primarily depended on the initial concentration in the agricultural soils, which in turn was governed by several different environmental factors and radionuclide-specific properties. The C-14 concentration differences were the result of variation in the initial concentrations and the thickness of all four contributing regolith layers, i.e. glacial clay, post-glacial clay gyttja, deep peat and surface peat. Moreover, the fraction of the initial inventory that was in organic form and the input of radionuclides from saturated soil layers also contributed to the differences in concentration in soil between the outlined areas.

The variations in the concentrations of Cl-36, Mo-93 and Ni-59 in cultivated soil were primarily driven by the initial concentrations in deeper regolith layers. That is, most of Mo-93 in agricultural soil had accumulated in post-glacial clay gyttja, whereas the Ni-59 in agricultural soil originated from accumulation in the glacial clay layer. Cl-36 accumulated in both of these layers. Initial concentrations in soil of Cl-36 and Mo-93 were in or close to steady-state conditions (in the mire). Thus, the difference between objects primarily reflected variation in upward groundwater flux in glacial clay and clay gyttja prior to cultivation (through a reciprocal relationship). However, Ni-59 was still accumulating when the soil was drained and cultivated. Thus, between-area variation reflected the combined effect of steady-state concentrations (decreasing with upward groundwater flux rate) and time to reach steady-state conditions (increasing with regolith thickness and decreasing with area-specific groundwater flux) in the glacial clay layer.

Surface water in downstream object

During the land period, radionuclides from the primary object (157_2) will be exported with surface water to the downstream lake basin 157_1. As this object is a proper lake between isolation (4500 AD) and full mire expansion (5600 AD), lake organisms, and humans foraging the lake for food or for drinking water, may be exposed to radionuclides from the repository. After the mire expansion is completed, humans and non-human biota may be exposed through stream water.

The concentration of all four radionuclides in surface water of the downstream object varied little between radionuclide export from the four largest areas (Figure 10-32), and the concentration differences between the reference and alternative areas as sources were within a factor of two. However, when radionuclides were released to the smallest area, the concentration of Ni-59 in downstream water was reduced (by a factor of five), whereas the opposite was true for C-14 (i.e. the concentration increased by a factor of five).

Variations in the concentration in surface water in the downstream object reflected variations in the export of radionuclides from the outlined primary biosphere object. The export of radionuclides was simply the product of radionuclide concentration in surface water (Figure 10-31c) and the horizontal discharge of water (Figure 6-15c) in the primary biosphere object. At steady state, all radionuclides exported from 157_2 would reach the surface water in the downstream object, and Mo-93 and Ni-59 concentrations in this object would approach that of Cl-36, which reached steady state in this simulation (Figure 10-32). However, C-14 was not only diluted by surface water fluxes in the downstream object, but was also lost through degassing. Thus, the maximum C-14 concentration was reached shortly after lake isolation when degassing in the mire area bordering the lake was at its minimum.

10.8.2 Conclusions regarding object delineation

Environmental concentrations of radionuclides in areas receiving a constant input of radionuclides (1 Bq y^{-1}) were affected by object size and the regolith thickness and hydrological fluxes associated with each of the alternatively outlined areas. Of these factors, groundwater fluxes diluting the released radionuclides were perhaps the most important for explaining variations between the outlined areas.

The vertical groundwater flux in the radionuclide model is the product of the object area and the area-specific flux, which in turn is influenced by both topography and the regolith profile. In this analysis the surface area of the outlined objects varied by a factor of five, whereas the area-specific flux varied by a factor of 2.5 (Section 6.4). Thus, object size was the most important factor explaining dilution of radionuclides from a unit release rate to the deep regolith layers (see, for example, differences in Figure 10-31a).

The horizontal flux of surface water is primarily determined by the size of the local catchment area. Three of the outlined areas had a local catchment similar to that of the original object. The area outlined on a high density of bedrock discharge points was located higher in the terrain, and thus had a smaller local catchment area (approximately half of the original one). Since the variation in the size of the local catchment was small, the outline of the biosphere object had a limited effect on the concentration of low-sorbing and non-volatile radionuclides in surface peat (see Cl-36 and Mo-93 in Figure 10-31a, c). On the other hand, as degassing dominated horizontal groundwater transport of C-14, the size of the outlined area had a direct and significant effect on concentrations of C-14 in surface peat for this radionuclide (Figure 10-31b, c).

If the potential for radionuclide accumulation is large in deeper regolith layers, then only small amounts of radionuclides will reach surface layers during the simulation period. Thus, concentrations in regolith of medium and highly sorbing radionuclides depended as much on accumulation dynamics as on steady-state conditions. A continuous accumulation in the thick glacial clay layer in the smallest outlined area reduced Ni-59 concentrations in surface peat and agricultural soil, as compared to the concentrations of more mobile radionuclides (Figure 10-31b-d).

Though alternative outlines of the primary biosphere objects had a clear effect on environmental concentrations, the effect was limited. That is, the concentrations in the three largest alternatively outlined areas were typically not more than two or three times larger than the concentration in the original object. On the other hand, in the smallest outlined object, concentrations in till pore water were elevated by a factor of eight (all radionuclides), concentrations in drained and cultivated soil were elevated by a factor of ten (C-14, Cl-36 and Mo-93) and the concentration in surface peat was elevated (C-14), or decreased (Ni-59), by a factor of five. However, the increased concentrations in the smallest object is conditioned on the "what if" assumption that all radionuclides would be released to this area, which is not likely to occur (see further discussion in Section 11.2.3).

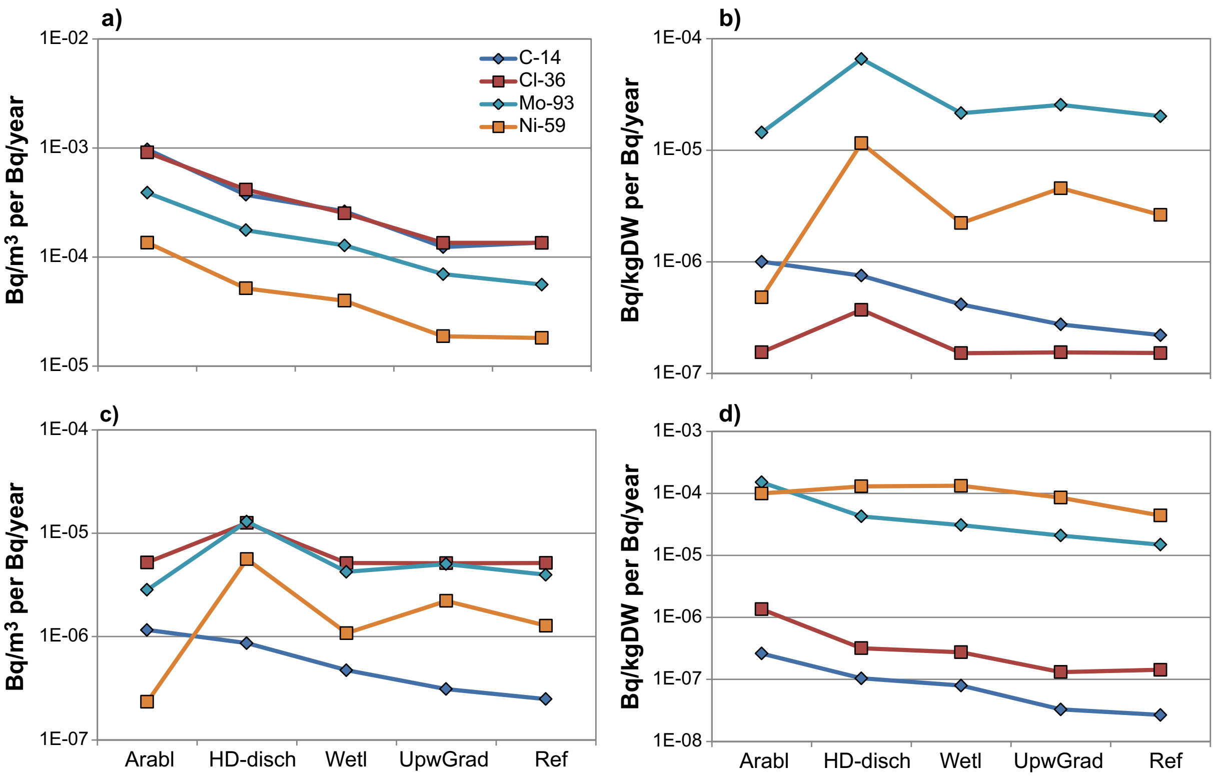


Figure 10-31. *Concentrations of four radionuclides in environmental media, which may cause exposure of humans and non-human biota, as a function of object delineation. a) Pore water concentrations in till (RegoLow) available through a dug well. b) Total concentrations in surface peat (RegoUp). c) Concentrations in surface water in contact with peat. d) Concentration in drained and cultivated soil. Values are maximum values for simulations until 20,000 AD under temperate climate conditions (global warming biosphere calculation case, BCC1). The alternative object delineations are listed in size order within each figure (smallest to the left) with the original object to the right, see text for further description of the different delineations.*

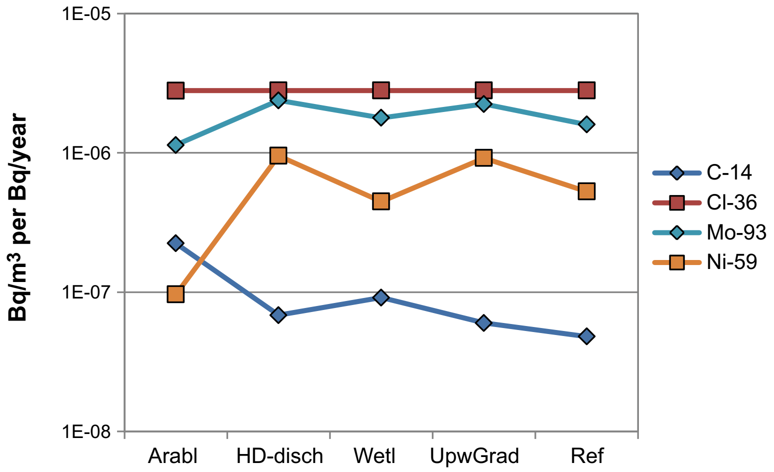


Figure 10-32. *Concentrations of four radionuclides in surface water in the lake-mire system downstream of the primary biosphere object. Values are maximum values for simulations until 20,000 AD under temperate climate conditions (global warming biosphere calculation case, BCC1). The alternative object delineations are listed in size order (smallest to the left) with the original object to the right.*

10.9 Effects of parameter uncertainty

The sections above have discussed the results of unit release simulations when parameters are fixed at values expected to be typical for Forsmark, i.e. deterministic simulations with best estimate parameter values. This section is focused on how parameter uncertainty (including natural variation) affects predicted doses and dose rates, and what parameters have the largest influence on model endpoints. The results in this section are based on Monte-Carlo simulations, where parameter values have been randomly sampled from their assigned distributions. These so-called probabilistic simulations were of the same kind as those used in SR-PSU to calculate expected dose and the resulting risk (**SR-PSU Main report** and **Radionuclide transport report**), but were based on a unit release rate.

10.9.1 Comparison of deterministic and probabilistic results

For each radionuclide, simulations were performed by applying Monte-Carlo simulations to the chain of three biosphere objects (i.e. objects 157_2, 157_1 and 116). A Latin hypercube sampling scheme was used to draw random samples of parameters, where each parameter was sampled independently from its probability density function (PDF). For a few parameters ("NPP_ter", "f_refrac_ter", "z_regoUp_ter", "f_C_peat", "dens_regoUp_ter" and "minRate_regoUp_ter") some combinations of parameter values violated mass balances of carbon and/or radionuclides. These parameters were also randomly sampled, but parameter combinations that were not physically possible were excluded. Otherwise, correlations between parameters were not taken into account in these simulations. Parameters for which values had been selected based on cautious or conservative assumptions, e.g. those describing human land use and the release fraction to a drilled well, were not included in the analysis.

The parameters describing regolith thickness of a soil column co-vary systematically in time, as a function of the local topography and shoreline displacement (Section 9.3.1). Similarly, parameters describing hydrological flux rates are tightly coupled as mass conservation requires each compartment to be in water balance. The effects of variation in regolith depth and hydrological flux rates were not examined with Monte-Carlo simulations. Instead the combined effect of co-variation in these parameters was examined as a function of object delineation (Section 10.7).

For all radionuclides, the maximum mean annual dose rate from the probabilistic simulations, given a unit release rate, was contrasted with the corresponding value calculated from best estimates of parameter values (i.e. the LDFs presented in Table 10-1). The arithmetic mean values from the probabilistic simulation were always equal to or higher than the corresponding values from a single simulation based on best estimate parameter values (Figure 10-33).

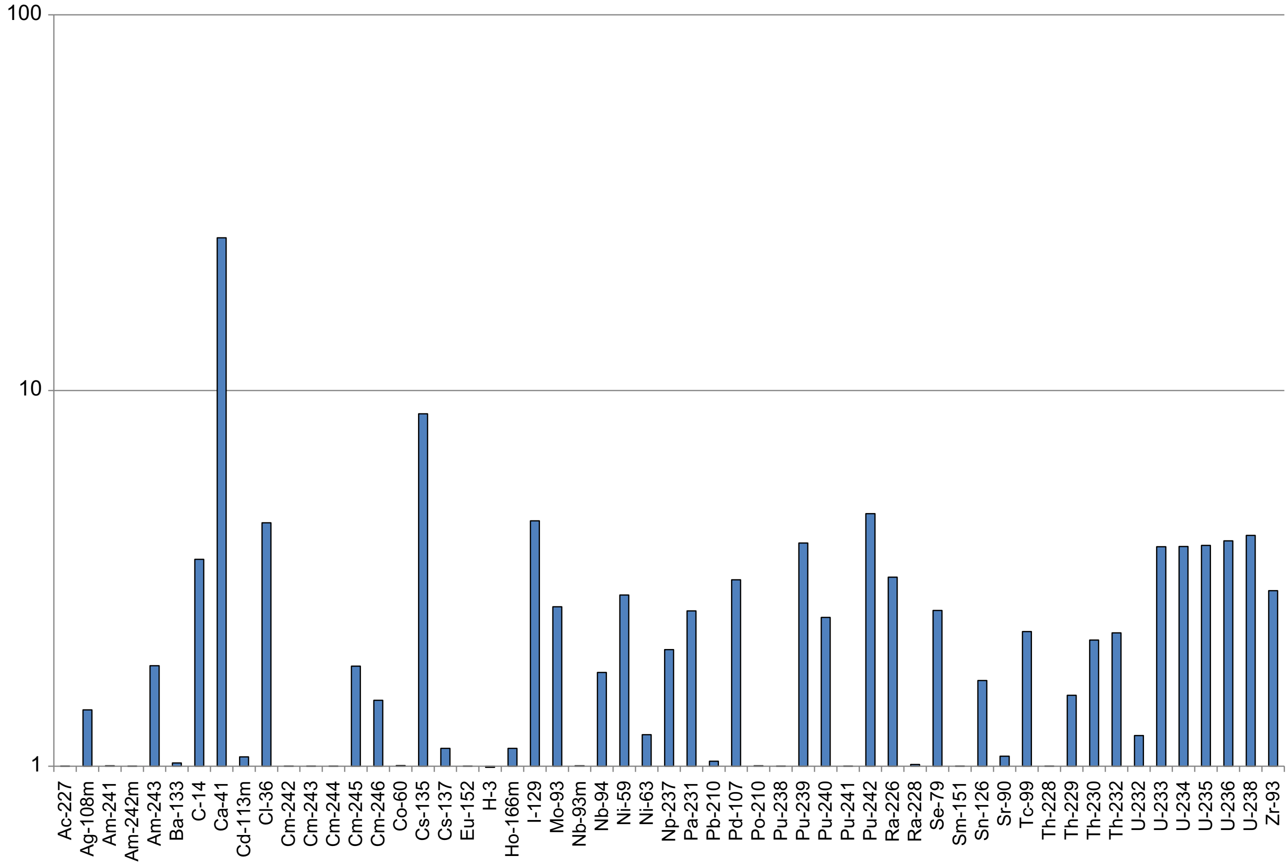


Figure 10-33. *Ratio between LDFs calculated for each radionuclide as the mean value from Monte-Carlo simulations and the value calculated from best estimates of parameter values.*

This was expected since the input distributions of many parameters were positively skewed (e.g. K_d and CR values), resulting in approximately log-normal distributions of the calculated dose conversion factors. For the majority of radionuclides (75%) the difference in the LDF was typically within a factor three. However, for a few elements the differences were as much as a factor of nine (Cs-135) or even twenty-five (Ca-41). For short-lived radionuclides with well water as the main exposure pathway, the difference was insignificant. This was also expected as the parameters affecting the concentration of water in a drilled well were handled by cautious assumptions rather than assigned a best estimate and a probability density function.

10.9.2 Analysis of selected radionuclides

For each of the four radionuclides C-14, Cl-36, Mo-93 and Ni-59, the results from the 1,000 Monte-Carlo simulations were also used in sensitivity analyses to identify individual parameters with a strong influence on the assessment endpoint. The results were focused on endpoint variations, i.e. variations in LDFs and dose rates to non-human biota, with respect to the uncertainty of individual parameters. That is, the parameters that were identified as important both had a clear influence on end results (typically a proportional effect) and a PDF spanning a large variation. Thus, the analysis identified parameters or processes with a large potential gain from improved understanding or measurements. The metric used in the sensitivity analysis was the standardised regression coefficients of first-order effects (SRC, Schroeder et al. 1986). This coefficient indicates both the direction of the effects of a parameter on the endpoint, and its importance (in terms of explained variation). As most of the underlying relationships were expected to be multiplicative, the sensitivity analysis was carried out on logarithmic scales.

C-14

The land use variant resulting in the highest annual dose of C-14 was draining and cultivating the mire in object 157_2, and the dose was stable throughout the simulated period (Figure 10-34a). The mean LDF from the probabilistic simulations was approximately four times higher than the LDF calculated from best estimates of parameter values, indicating that parameter variation had a limited effect on the estimate of the maximum dose.

The dominating exposure pathway was ingestion of crops. The C-14 concentration in crops was a function of plant uptake from the atmosphere and from soil solution (Saetre et al. 2013a), and the uptake was fairly well balanced between the two sources (Table 10-3). Parameter variation had a limited effect on variation in the specific activity of the canopy atmosphere. Thus, the main source to LDF variation was variation in parameters affecting the concentration in soil solution. The parameter contributing most to uncertainty in dose was the coefficient for diffusivity of CO_2 in drained soil originating from clay-gyttja "D_CO2_soil_clay" (50% contribution, Figure 10-34a). A high value of this parameter resulted in a more effective degassing of carbon in the soil solution. As the dilution in the canopy atmosphere was much more effective than in soil solution, the overall effect of an increased degassing was a decrease in crop C-14 concentration, and in dose (SRC was -0.7).

The second largest contribution to LDF uncertainty was caused by the parameter "f_rootuptake"; it explained 20% of LDF variation. This parameter determines the fraction of photosynthesised carbon that originates from root uptake. As the specific activity in soil solution was more than one order of magnitude larger than in the canopy atmosphere (Table 10-3), a high root uptake led to a high C-14 crop concentration and a high LDF (SRC was 0.4). Other parameters influencing the LDF uncertainty were the concentration of dissolved inorganic stable carbon in soil pore water of cultivated soil (conc_DIC_regoUp, 16% of variation) and the water flux from the saturated to the unsaturated zone in a cultivated soil (Flux_water_satSoil_agri, 5% of variation). The first parameter was negatively correlated to dose, as the specific activity of C-14 is reciprocal to the concentration of stable carbon (SRC was -0.4). The second parameter was positively correlated to the LDF, as the flux of C-14 from the saturated zone into the biologically active layer where root uptake occurs was proportional to the upward flux of groundwater (SRC was 0.2).

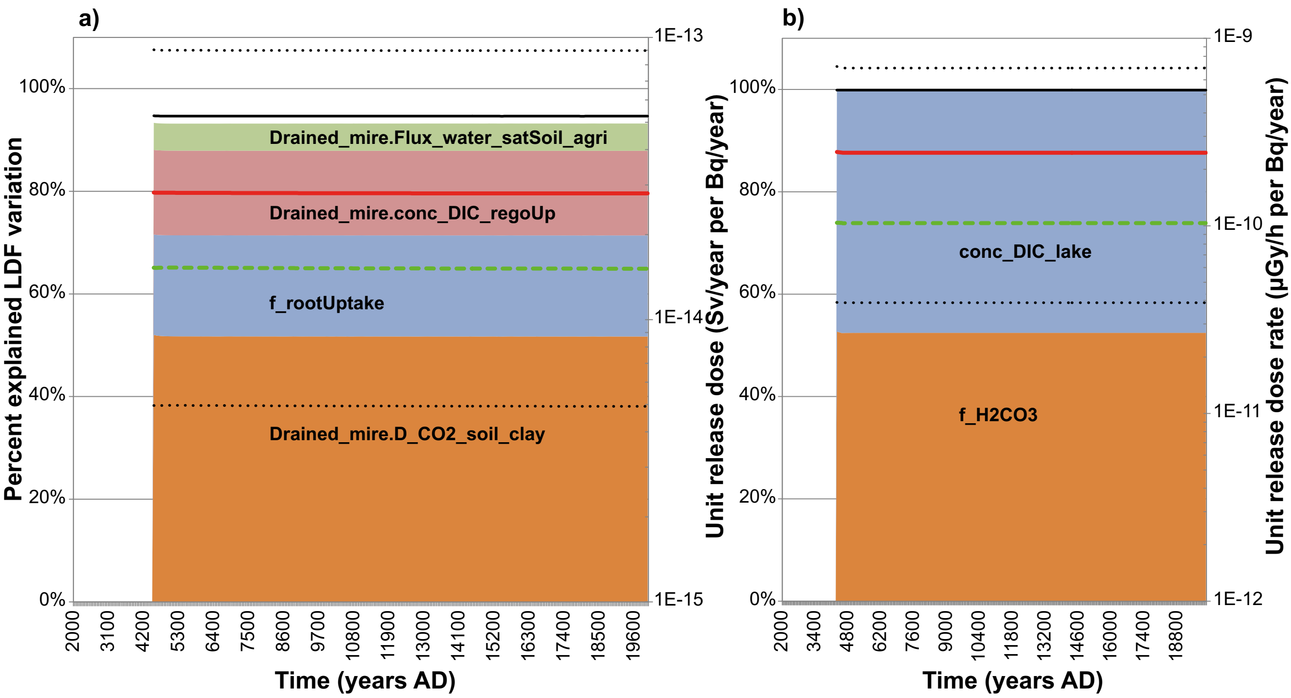


***Figure 10-34.** Effects of parameter variations on landscape dose conversion factors for a) the most exposed human population (drained-mire farmers in object 157_2), and b) the most exposed organism (Freshwater bird in object 157_2) with respect to C-14. The total fraction of LDF variation explained by a linear combination of parameters is indicated by the black line (r^2). Parameters explaining most LDF variation are shown as coloured areas (% explained variation; left axis of each figure). The mean LDF from probabilistic simulations (red line) is shown together with the median (green dashed line) and the 5th and 95th percentiles (dotted lines).*

The most exposed organism type was the freshwater Bird in object 157_2. The mean dose conversion factor was two times higher than the median value, indicating that the effect of parameter uncertainty on the calculated dose rate was limited. The two most important parameters for variation in dose rates were the fraction of dissolved inorganic carbon in lake water in the form of CO_2/H_2CO_3 ("f_H_2CO_3_lake") and the concentration of stable inorganic carbon dissolved in lake water ("conc_DIC_lake"). These parameters explained 52% and 47% of the variation in dose rate during the land period, respectively (Figure 10-34b). Both parameters were negatively correlated with dose (SRC was -0.7 for both parameters), and high parameter values led to a low degassing rate (loss) of radiocarbon from the lake ecosystem and a low specific C-14 activity in lake water, respectively.

Cl-36

The land use variant resulting in the highest annual dose of Cl-36 was draining and cultivating the mire in object 157_2, and maximum dose occurred towards the end of the simulated period. The mean LDF from the probabilistic simulations was approximately 4 times higher than the LDF calculated from best estimates of parameter values (Figure 10-33), indicating that parameter variation had a limited effect on the estimate of the maximum dose.

The dominating exposure pathways at maximum dose were consumption of milk and meat. Thus, it was not surprising that the parameter contributing most to the uncertainty in dose was CR for fodder "CR_agri_fodder". This parameter contributed with 56% of the LDF variation (Figure 10-35a) and a high CR was associated with high Cl-36 concentrations in fodder and a high LDF (SRC was 0.6). Similarly, the transfer coefficients for milk and meat, "TC_milk" and "TC_meat", also contributed to LDF variation (19% and 6% of the variation, respectively). These parameters accounted for the transfer of Cl-36 in fodder to animals and the dairy products, and consequently a high transfer was associated with a high concentration in food products and high dose (SRC were 0.4 and 0.2, respectively).

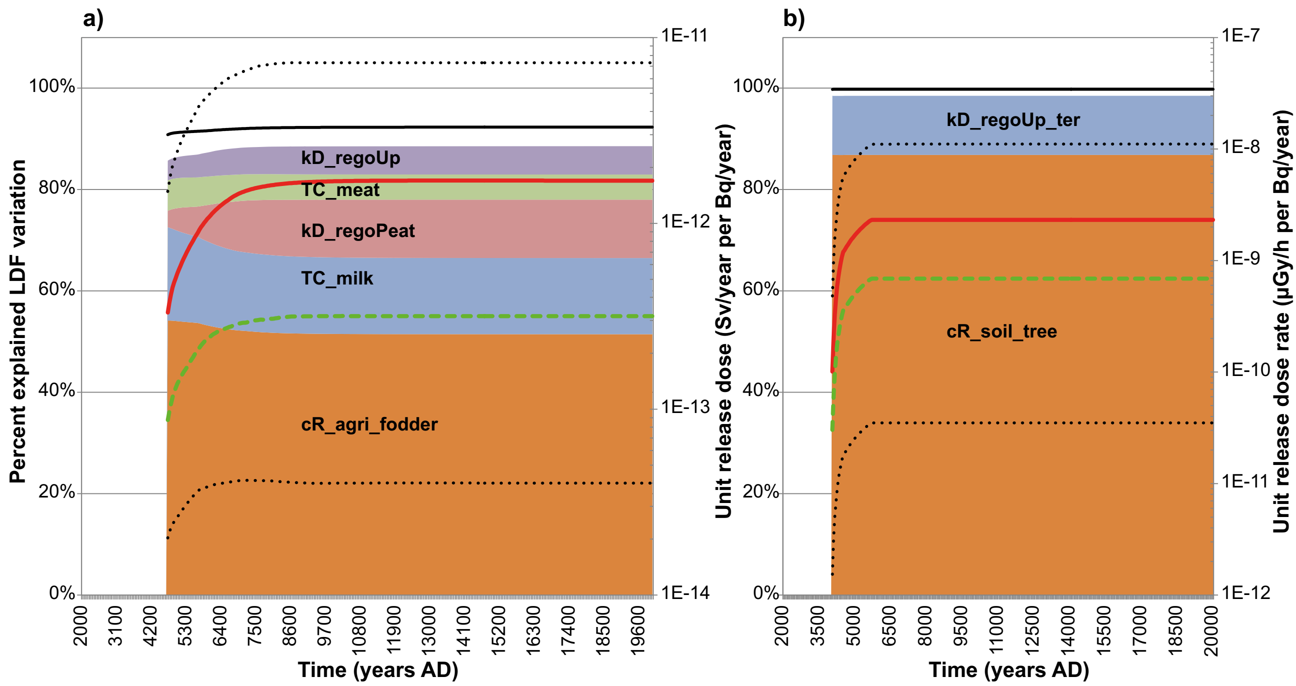


__Figure 10-35.__ Effects of parameter variations on landscape dose conversion factors for a) the most exposed human population (drained-mire farmers in object 157_2), and b) the most exposed organism (Tree in object 157_1) with respect to Cl-36. The total fraction of LDF variation explained by a linear combination of parameters is indicated by the black line (r^2). Parameters explaining most LDF variation are shown as coloured areas (% explained variation; left axis of each figure). The mean LDF from probabilistic simulations (red line) is shown together with the median (green dashed line) and the 5th and 95th percentiles (dotted lines).

The most exposed organism type was Tree in terrestrial object 157_1. The mean dose conversion factor was about three times higher than the median value (Figure 10-35b), indicating that the effect of parameter variation on dose rates was limited for Cl-36. The parameter contributing most to dose rate variation was the concentration ratio (CR), describing Cl uptake in the exposed organism. CR contributed 87% of the uncertainty in dose rate, and a high CR value was associated with a high internal concentration of Cl-36, and consequently with a high dose rate (SRC was approximately 0.9). The adsorption of chloride in surface peat was also an important parameter for dose rate variation. The K_d-value for surface peat, "Kd_regoUp_ter", explained an additional 12% of the dose rate variation, and a high K_d-value was associated with increased peat and tree concentrations (SRC was 0.3).

Mo-93

When parameter variation was included in the dose calculations, the land use variant resulting in the highest doses of Mo-93 was drained-mire farmers. However the biosphere object yielding the highest LDF shifted to object 157_2 (Table 10-1). The maximum annual dose occurred at the end of the simulated period (Figure 10-36a). At this time the probabilistic mean was only twice as large as the best estimate of the maximum dose (Figure 10-33), indicating a limited effect of parameter variation on the estimated LDF for Mo-93.

The dominating exposure pathway at the end of the simulation was consumption of cereals and potatoes. Consequently it was not surprising that variation in the CRs for cereals and potatoes contributed significantly to LDF variation (54 and 6.5 percent, respectively, Figure 10-36a). As CR determines plant uptake and concentration in crops, these parameters were positively correlated with dose (SRC was 0.7 and 0.3, respectively). K_d values for the lower regolith layers were also important for variation in dose. Sorption in till slowed down the upward transport to the regolith layers above, which are the layers that could be cultivated. When cultivation first was possible (4500 AD), the K_d for lower till (RegoLow) explained 10% of the LDF variation (SRC was –0.3), but the influence decreased with time as Mo-93 approached equilibrium conditions. On the other hand, sorption in post-glacial clay gyttja (RegoPG), which was mixed into the cultivated soil when the mire was drained, increased soil concentrations and the annual dose. The K_d for RegoPG was important throughout the simulation period and explained 18% of the LDF variation at the end of the simulation period (SRC was 0.4).

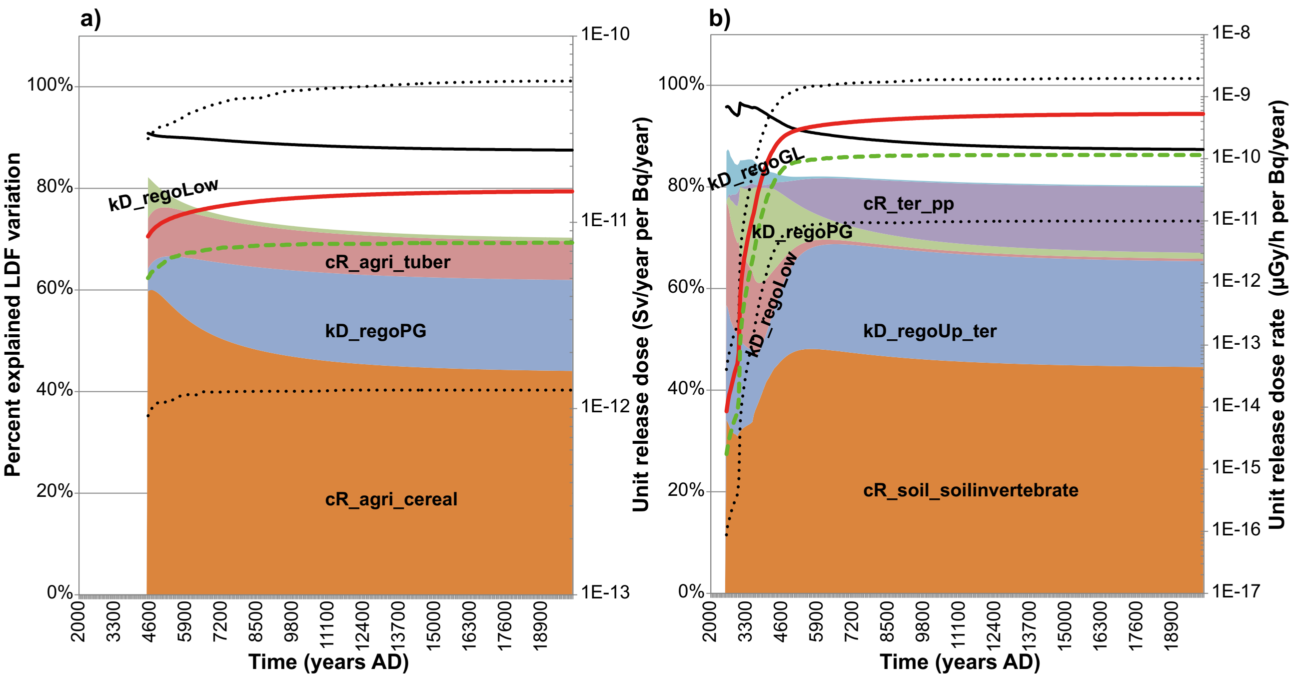


Figure 10-36. Effects of parameter variations on landscape dose conversion factors for a) the most exposed human population (drained-mire farmers in object 157_2), and b) the most exposed organism (Soil invertebrate in object 157_2) with respect to Mo-93. The total fraction of LDF variation explained by a linear combination of parameters is indicated by the black line (r^2). Parameters explaining most LDF variation are shown as coloured areas (% explained variation; left axis of each figure). The mean LDF from probabilistic simulations (red line) is shown together with the median (green dashed line) and the 5th and 95th percentiles (dotted lines).

The most exposed organism type was terrestrial Soil invertebrate in object 157_2. The mean dose conversion factor was about four times higher than the median value (Figure 10-36b), indicating that parameter uncertainty had a limited effect on the estimate of the maximum dose rate. The parameter contributing most to uncertainty was the CR quantifying the uptake of Mo in the exposed organism (52% at steady state) followed by K_d in upper regolith layer (28%) (Figure 10-36b). The exposure of Soil invertebrate increased with higher values of both of these parameters (the SRC was 0.7 and 0.5, respectively).

CR for terrestrial primary producers was also of some importance for the uncertainty of the dose rate of Soil invertebrate (10% at steady state). This indicated that plant uptake and subsequent accumulation in soil organic matter increased the concentration of Mo-93 in surface peat and the exposure (SRC was 0.3). The effects of deeper-regolith K_d values on the dose rate to Soil invertebrate were largest in the beginning of the simulated period. During this period the K_d of deep till (RegoLow) explained 21% of dose rate variation, whereas the corresponding figures for post-glacial clay gyttja (RegoPG) and glacial clay (RegoGL) were 20% and 11%, respectively. K_d values for deeper regolith layers were all negatively correlated with dose rates (SRC were –0.1, –0.06 and –0.03 for post-glacial deposits, deep till and glacial clay, respectively), indicating that a high K_d value for deeper regolith delayed the transport of Mo-93 to surface peat.

Ni-59

The land use variant resulting in the highest doses of Ni-59 was drained-mire farmers in object 157_2 (Table 10-1). The maximum annual dose occurred at the end of the simulated period (Figure 10-37a). At this time the probabilistic mean was three times as large as the best estimate of the maximum dose (Figure 10-33), indicating a limited effect of parameter variation on the estimated LDF for Ni-59.

The dominating exposure pathway at the end of the simulation was consumption of meat and potatoes. Consequently, it was not surprising that variation in the CRs for potatoes and fodder, and the transfer coefficient for radionuclides from fodder to meat, contributed significantly to LDF variation (10, 12 and 25 percent, respectively, Figure 10-37a). As CR and TF affects the concentrations in plants and meat respectively, these parameters were positively correlated with dose (SRC was 0.3, 0.3 and 0.5 respectively). K_d values for the lower regolith layers were also important for variations in dose. Sorption in till slowed down the upward transport to the regolith layers above, which are the layers that could be cultivated. Shortly after cultivation first became possible, the K_d for lower till (RegoLow) explained 39% of the LDF variation (SRC was –0.6), but the influence decreased with time as Ni-59 approached equilibrium conditions in the till layer. On the other hand, a high degree of sorption in glacial clay (RegoGL), which was mixed into the cultivated soil when the mire was drained, increased soil concentrations and the annual dose. The importance of K_d for RegoGL increased throughout the simulation period (as RegoLow was approaching steady state) and explained 13% of the LDF variation at the end of the simulation period (SRC was 0.4).

The most exposed organism type was freshwater Zooplankton in object 157_2. The mean dose conversion factor was less than three times higher than the median value (Figure 10-37b), indicating that parameter uncertainty had limited effect on the estimate of the maximum dose rate. Steady state was not reached in all simulations during the period studied. Nevertheless, CR of the exposed organism dominated the dose rate variation during the entire simulation period; it explained 53% of variation at lake isolation and 77% at the end of the simulation. This parameter quantifies the uptake of Ni in the exposed organism, and internal exposure and dose rates increased with higher parameter values (SRC was 0.9 at the end of the period).

As for human exposure, variations in parameters describing sorption in lower regolith layers also had a significant influence on variation in dose rate of Zooplankton. The influence of sorption on dose rate variation decreased with time, as steady-state was more likely to have been reached. Thus, the K_d in the deepest regolith (till) layer explained 22% of dose rate variation at lake isolation, and 14% at the end of the simulation period. Similarly, the K_d in the glacial clay explained 22% and 8% of variation at lake isolation and the end of the simulation, respectively. As high sorption retards radionuclide transport to the surface, K_d values were negatively correlated to the dose rate in both till and glacial clay (SRC were –0.4 and –0.3 at the end of the period).

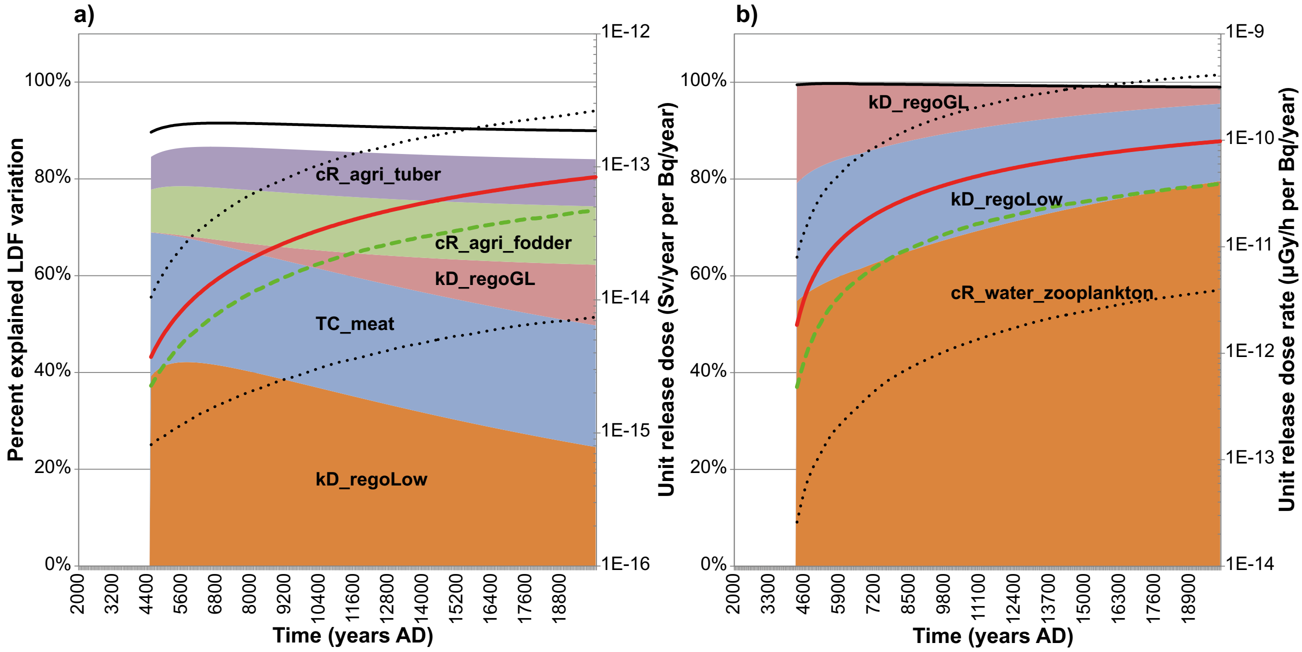


Figure 10-37. *Effects of parameter variations on landscape dose conversion factors for a) the most exposed human population (drained-mire farmers in object 157_2), and b) the most exposed organism (freshwater Zooplankton in object 157_2) with respect to Ni-59. The total fraction of LDF variation explained by a linear combination of parameters is indicated by the black line (r^2). Parameters explaining most LDF variation are shown as coloured areas (% explained variation; left axis of each figure). The mean LDF from probabilistic simulations (red line) is shown together with the median (green dashed line) and the 5th and 95th percentiles (dotted lines).*

Summary

Variations in sorption coefficients (K_d) and ratios between concentrations in environmental media and organisms (CR and TR) often dominated dose and dose rate variations (see results for Cl-36, Mo-93 and Ni-59 above). This reflects that retardation in lower regolith layers, sorption in surface layers and organism uptake are key components in the calculations. As for many other parameters, a change in the value of CR, K_d or TR typically resulted in a proportional change of environmental or organism concentrations; relatively large effects were primarily caused by parameters with wide-ranging probability density functions (Tröjbom et al. 2013).

In the SR-PSU assessment, radiocarbon did not adsorb onto regolith particles, and organism concentrations were assumed to be in equilibrium with the ratio between radiocarbon and stable carbon in the environment. Moreover, C-14 in surface water and peat degassed to the atmosphere, where it was rapidly diluted. Thus, it was not surprising that parameters affecting degassing and the concentration of stable carbon were most important for dose and dose rate variation of C-14.

10.10 Other exposure pathways

In this section the doses from residual exposure pathways are evaluated. These pathways were identified in the exposure pathway analysis (Chapter 7 and in SKB 2014), but were not included in the land use variants used to calculate dose to the most exposed populations. In this section the dose from a unit release to the biosphere (from 2000 to 20,000 AD) is used to compare the potential contribution from residual pathways of 55 radionuclides (Table 10-1) with the LDF from exposure pathways included in the assessment. If the potential contribution is small compared to that from the included pathways, the exclusion of the residual pathway is regarded as reasonable. The residual exposure pathways examined and discussed are:

- Exposure from inadvertent ingestion of inorganic and organic soil.
- External exposure from the vegetation.
- External exposure from aquatic sediment.

10.10.1 Exposure from inadvertent ingestion of inorganic and organic soil

Inadvertent ingestion of soil and dust may result from activities such as eating vegetables, and hand to mouth contact following gardening, gathering of food items or other activities leading to soil/dust contact. However, intentional soil ingestion, such as the medical conditions pica and geophagy, is not included in this exposure pathway (see SKB 2014 for further discussion). Some exposure from inadvertent soil ingestion is already accounted for in the land use variants that are part of the biosphere calculation cases. For example, as the CR values for vegetables and root crops are empirically derived parameters, the calculated concentration in food items includes small amounts of soil left after washing. Moreover, the dose contribution from inhalation of soil dust (see below) was included in all land use variants (see Section 8.5).

To quantify the residual doses from inadvertent soil ingestion two land use variants were examined: 1) the cultivation of vegetables in a garden plot with mineral soil outside the house (the garden-plot household land use variant, GP), and 2) self-sufficient small scale agriculture on soil resulting from draining a mire (the drained-mire land use variant, DM). The two land use variants were chosen because they represent two different soil types (with potential for accumulation of different radionuclides). The garden plot soil originated from glacial clay and was rich in minerals, whereas the soil resulting from draining a mire primarily originated from organic sediments (peat and clay-gyttja). In addition, the garden plot was irrigated with well water (containing short-lived radionuclides), and fertilised with seaweeds or biofuel ash (see Section 10.2). For a brief description of the two land use variants and their exposure pathways, see Section 7.2. The screening calculation for soil ingestion was based on the principles used to calculate dose from intake of food. That is, the dose was calculated from the amount of soil ingested and the radionuclide concentration in the ingested soil.

The dose from inadvertent soil ingestion was calculated from the maximum soil concentrations (Bq $kgDW^{-1}$) during the full simulation period (see above). It was assumed that an adult individual ingested 50 mg soil per day spent working in the garden plot or on arable land. This is the central value for soil ingestion recommended by US EPA (2011) and ATSDR (2005), based on reviews of empirical studies, and it is similar to the values suggested in Ministry for the Environment of New Zealand (2011) (25–50 mg d^{-1}). The contributed inhalation of soil dust may account for over 50% of the total inadvertent soil intake (US EPA 2008). However, as it is difficult to differentiate between sources of radionuclide behind empirical estimates, no attempts were made to split soil intake into components of e.g. hand to mouth contact and soil dust inhalation. An exposure time of six days a year was used, representing the expected time in direct contact with the soil working with ploughing, sowing and harvesting or cultivating vegetables, respectively (parameter "time_exposure", Grolander 2013). Dose coefficients for ingestion of food were used to convert radionuclide intake (Bq y^{-1}) to annual dose (Sv) for each radionuclide respectively ("dosCoef_ing_food", Grolander 2013).

Both residual calculation cases were compared with the corresponding maximum LDF (GP and DM) resulting from all exposure pathways included in the two land use variants (see Table 10-1 for examples). Inadvertent soil ingestion typically resulted in far less than 1% of the combined dose from ingestion of food and water, inhalation and direct external exposure. However, for uranium isotopes (U-234, U-238 and U-235) inadvertent soil ingestion resulted in 2–3% of the maximum LDF for the garden plot. Similarly, inadvertent ingestion of organic soil resulted in a residual dose of U-238 that was approximately 1% of the maximum LDF in the drain mire scenario. Based on these it can be concluded that exposure from inadvertent ingestion of soil and peat can be disregarded as significant sources to dose.

10.10.2 External exposure outdoors from the vegetation

External exposure from vegetation could potentially contribute to the dose from radionuclides which accumulated in biomass of primary producers and emit gamma (or high energy beta) radiation. To estimate an upper boundary for external exposure from vegetation a simple calculation case was set up, assuming that the exposure from mire vegetation could be approximated with that from a ground surface. No shielding from vegetation biomass, snow or any other material was accounted for. Thus the radionuclide content in vegetation (expressed as Bq m^{-2}) was converted to an external dose using dose coefficients for external exposure from a surface source (Sv h^{-1} per Bq m^{-2}) (Grolander 2013, Chapter 3). Moreover it was cautiously assumed that inhabitants were exposed to radiation from vegetation 24 hours a day. These calculations could be thought of as the maximum exposure for a hunter-gatherer group setting up camp in one biosphere object, and being in close contact with vegetation all year around. The contribution to dose from external vegetation exposure was calculated for a unit release rate reaching biosphere objects 157_1 and 157_2, the two objects with the highest concentrations of radionuclides in mire vegetation in the base biosphere calculation case (BCC1).

The maximum dose from external exposure from vegetation over the full simulation time was generally several orders of magnitude lower than the maximum LDF from the base calculation case. Radiation from Sn-126 and Ag-108m caused the largest external exposure relative to that of the base case, and the dose was 8% and 3% of the maximum LDF, respectively. The external dose from the highly bioaccumulating radionuclide Cl-36 was only 0.2% of the maximum LDF, reflecting that Cl-36 is a pure beta emitter. Based on these results, it can be concluded that external exposure from vegetation can be disregarded as a significant source to dose.

10.10.3 External exposure from sediment

External irradiation from gamma-emitting radionuclides on beaches or in sediments normally needs to be considered (EC 2002). In the present biosphere assessment radionuclides will reach aquatic surface sediments in areas where groundwater from the repository is discharged, during the submerged period. In other areas radionuclides may reach marine sediments with surface water during the submerged period and lake sediments during the land period. Human exposure to aquatic sediments could primarily be expected in shallow coastal areas or near lake shores, Exposure could occur during activities such as bathing, fishing or gathering seaweeds in ice free periods.

To estimate an upper boundary for external exposure from aquatic sediments a simple calculation case was set up. It was assumed that the dose from being in contact with aquatic sediments could be sufficiently approximated with the method used for direct exposure from the ground and no shielding from water was accounted for. Thus the radionuclide content in the two uppermost regolith layers, representing the thin layer of surface sediments and the underlying clay-gyttja, was used to calculate the radionuclide concentration (Bq m^{-3}). The annual dose was then calculated using the dose coefficient for external exposure (Sv h^{-1} per Bq m^{-3}) ("dosCoef_ext", Grolander 2013) and assuming that inhabitants spent one hour a day during the three summer months in this environment (i.e. 90 hours or 0.01 y^{-1}). These calculations could be thought of as the exposure for a hunter-gatherer group catching fish with nets in near-shore environments, or foraging lake shores for crayfish. The contribution to dose from external exposure to aquatic sediments was calculated for a unit release rate reaching biosphere objects 157_1 and 157_2, the two objects with the highest concentrations of radionuclides in mire vegetation in the base biosphere calculation case (BCC1).

The maximum dose from external exposure from aquatic sediments over the full simulation time was generally several orders of magnitude lower than the maximum LDF from the base calculation case. As with exposure from vegetation radiation from Sn-126 and Ag-108m caused the largest external exposure relative to that of the base case, and the dose was 3% of the maximum LDF. Based on these results, it can be concluded that external exposure from aquatic sediments can be disregarded as a significant source to dose.

11 Summary and discussion of uncertainties

11.1 Summary of the SR-PSU biosphere modelling

This report presents the biosphere part of the SR-PSU safety assessment, which essentially means that the report is focused on the surface systems where humans and non-human biota potentially could be exposed to radionuclides released from the SFR repository (both the existing part and the planned extension) in Forsmark (see Chapters 1 and 2 for description of context). Specifically, the report summarises and analyses the data, process descriptions and models that have been used to develop and parameterise models for calculating radionuclide transport, exposure and resulting doses in the biosphere, including the support for various simplifications and assumptions made in this process of model development and parameterisation.

While the focus of the present report is on models and data used in the biosphere component of the modelling chain employed in the overall safety assessment calculations, it also contains some modelling results not presented elsewhere. This modelling was performed with the aim of investigating processes, properties and parameters specifically associated with the biosphere, without having the influence of other parts of the system confounding the interpretations. Furthermore, it should be noted that most chapters of this report summarise background reports produced within the SR-PSU biosphere modelling project, which means that more detailed descriptions are provided in those background reports. The main exceptions are the modelling of landscape development (Chapter 5) and biosphere objects (Chapter 6), and the above-mentioned model calculations focusing on the biosphere (Chapter 10); these parts of the biosphere assessment are not covered by dedicated background reports.

Following a general introduction, and descriptions of SR-PSU and SR-PSU Biosphere in Chapter 1, Chapter 2 gives the methodological and regulatory background to the work, including legal requirements and an account of relevant earlier safety assessments. The actual model descriptions begin with a summary of relevant parts of the site descriptive model (SDM), which describes the present conditions at Forsmark (Chapter 3). This presentation includes central underlying models such as the digital elevation model (DEM) and the regolith depth and stratigraphy model (RDM), which provide important geometrical descriptions used not only within the biosphere modelling but also in other parts of the safety assessment, such as in the hydrogeological modelling (Odén et al. 2014). The SDM is the basis for the development of models describing future conditions in the following chapters.

The first part of the description of future developments in Forsmark (Chapter 4) deals with climate and the associated shoreline displacement, as expressed by the SR-PSU climate cases, and their implications for processes and ecosystems in the Forsmark area. The site-specific coupled regolith-lake development model (RLDM) is an important tool for the modelling of landscape succession and possible future geometrical-geological conditions. In the next step (Chapter 5), human land use is introduced and analysed, with emphasis on the conditions for agriculture in potential future Forsmark landscapes. The results of the coupled analysis of natural conditions and effects of human interventions are formulated as a time-dependent landscape development model (LDM). The LDM is presented in terms of five variants of possible landscape development representing different combinations of climate and human land use.

The LDM is then used in combination with results of hydrogeological modelling and information on present and future geometrical conditions to develop a model for biosphere objects (Chapter 6). Essentially, this implies that the areas where groundwater potentially carrying radionuclides from the extended SFR repository discharges are identified and described. The resulting model for biosphere objects under temperate climate conditions, which is used in the majority of the safety assessment calculations, consists of seven biosphere objects divided into one southern branch (three objects) and one northern (four objects) branch. However, one biosphere object (referred to as object 157_2) receives most of the potentially radionuclide-containing water from the repository, and hence is the object of main interest in the safety assessment.

An important component of the object descriptions is how they develop in time, i.e. how landscape succession is reflected in the timing of transitions between different stages in the succession of the specific objects. It is found that the SR-PSU biosphere objects are of two main types: objects that have a lake stage in their succession, which means that they go from sea (bay) to lake to wetland and then possibly are developed further into agricultural land, and objects without a lake stage in their succession. The object of main interest in the safety assessment (object 157_2) is of the type that lacks a lake stage. The modelling of radionuclide transport under periglacial climate conditions considers two biosphere objects, of which one (157_1) is included also in the modelling of temperate climates. Glacial conditions and the next interglacial are of little relevance in SR-PSU (**SR-PSU Main report**).

Once the data and models describing the site and its development are in place, the next major step is the analysis of features, events and processes (FEPs) and exposure pathways, and the formulation of calculation cases (all described in Chapter 7 and the associated background report). The FEP and exposure analysis utilises and combines external input in the form of recommendations and requirements with the site-specific knowledge from data and models, in order to identify and describe what is relevant and needs to be included in the model calculations of transport, exposure and doses. The analysis of potentially most-exposed groups results in the identification of four potentially exposed populations that represent four alternative land use variants considered in the modelling: hunter-gatherers (HG), infield-outland farmers (IO), drained-mire farmers (DM), and garden-plot households (GP).

Exposure routes for these four populations in natural and agricultural systems are identified, and the exposure analysis also includes an identification of non-human biota endpoints based on an analysis of organism types in terrestrial, marine and limnic ecosystems. The effects on exposed populations are assessed in seven biosphere calculation cases (BCCs) that are formulated and described in terms of different climate cases, ecosystems and where (to which biosphere object) radionuclides are released. These BCCs are mapped to the main calculation cases studied in the safety assessment.

Following the identification of what needs to be modelled in Chapter 7, and the descriptions of the systems to be modelled that are summarised in the preceding chapters, the development of a numerical compartment model for calculating radionuclide transport in the biosphere at Forsmark is presented in Chapter 8. During the land period, a modelled biosphere object is subdivided into one mire part and one aquatic part, where the aquatic part decreases in size with time due to infilling. Objects that lack a lake stage (such as object 157_2) consist solely of a mire during the whole model period after the marine stage. The vertical subdivision into compartments is based on the geometrical-geological modelling of the site, i.e. on the RDM and the RLDM. The description of models is completed by a summary of the data used in the parameterisation of the radionuclide transport model (Chapter 9). This finalises the reporting of the data and models used in the overall safety assessment.

Chapter 10 presents modelling results for a constant unit radionuclide release rate (1 Bq y^{-1}), i.e. radionuclide inventories and activity concentrations in different media and associated doses to humans and dose rates to non-human biota for this particular type of input to the biosphere. The unit release results for doses to humans are presented in the form of landscape dose conversion factors (LDFs), which are expressed in units of Sv y^{-1} per Bq y^{-1}. These results are used to make comparisons with previous safety assessments, where LDFs or similar quantities were the main deliverables from the biosphere modelling, and to provide a detailed analysis for selected radionuclides, including an evaluation of sources of uncertainty. For non-human biota, dose rates to various types of organisms in different ecosystems (marine, freshwater and terrestrial) are presented. These unit-release-rate modelling results are summarised in Tables 10-1 and 10-2. The next section discusses how uncertainties have been handled in the biosphere analyses.

11.2 Handling and assessment of uncertainties

The final risk estimates presented in the **SR-PSU Main report** built upon a number of approximations and modelling results that have various different simplifications, degrees of caution and uncertainties. In Chapter 10, results are presented in which a constant unit release rate was used in combination with different climate cases, alternative outlines of the main biosphere object (157_2) and Monte-Carlo simulations of parameter sets, to illustrate how the handling of uncertainties affected calculations of radionuclide transport and radiation exposure. In this chapter, these results are summarised and discussed in the broader context of how different sources of uncertainty have been handled in the biosphere modelling for SR-PSU. When relevant, the approach used in the present safety assessment is related to the previous SKB safety assessment for a deep geological repository for spent fuel, SR-Site.

11.2.1 Background

Thorough site investigations have been conducted to understand transport and accumulation of elements in the biosphere at Forsmark. This understanding underpins conceptual and numerical models. Moreover, data from Forsmark and the site models have been used to parameterise the radionuclide model of the biosphere. Uncertainties enter all aspects of data collection, interpretation, conceptual model formulation and mathematical implementation.

The presentation in this section on uncertainties follows the framework outlined by Galson and Khursheed (2007) and its application in the previous SKB safety assessment SR-Site (SKB 2010, Avila et al. 2010). Thus, uncertainties have been categorised into three types: system uncertainties, model uncertainties and parameter uncertainties (see below). As in Chapter 10, the discussion in this chapter mainly builds on results with respect to four long-lived radionuclides, all with the potential to contribute significantly to doses and dose rates.

A number of issues were raised following reviews and workshops on the previous safety assessment of SFR (SAR-08). The responses to the specific questions raised by SSM on the previous safety assessment are presented in the **SR-PSU Main report**. Issues that concerned modelling of transport and accumulation in the surface ecosystems (i.e. the biosphere) are discussed in various sections of this chapter (see also Section 2.5 of the present report).

11.2.2 System uncertainties

In the biosphere analysis, system uncertainties refer to uncertainties associated with the geosphere-biosphere link (i.e. in terms of the location of the release), the development of the biosphere and future human utilisation of natural resources. The handling of these sources of uncertainty in the biosphere analysis is described and discussed below.

The location of the release

Hydrogeological modelling indicates that the majority of a potential release from the present repository (SFR1), and its planned extension (SFR3), is expected to be discharged into a limited area, and thus all radionuclides was discharged into object 157_2 in the biosphere base calculation case (BCC1, Section 7.4.1). The consequences of this simplification (given a unit release) were quantified in a separate calculation case (BCC6). The distributed release calculation case set an upper boundary on the potential impact of a release discharged into several different areas as a function of time. Despite the cautious handling of the release in BCC6, which resulted in the total release rate exceeding 1 Bq y^{-1}, the differences in calculated doses and dose rates between BCC6 and BCC1 were insignificant for all non-volatile radionuclides. The distributed release gave elevated annual doses of C-14 for hunter-gatherers (a factor of six) and marine biota (a factor of three). However, the maximum annual dose from a distributed release was still below that of the base case drained-mire farmers, and the dose rate to marine organisms in BCC6 was below the dose rates of the freshwater organisms in the base case.

From this model comparison it can thus be concluded that the handling of uncertainties with respect to the location and timing of the release (i.e. the geosphere-biosphere link) did not have a significant effect on estimates of annual effective doses to humans and absorbed dose rates to non-human biota. The results indicate that the use of a release concentrated to a single biosphere object is adequate and reasonable.

Development of the biosphere

The main features of the Forsmark landscape are determined by bedrock topography, which is expected to change only marginally over the next 100,000 years. However, wave erosion, sedimentation and vegetation colonising lakes and wetland areas will affect the geometries of the sediments overlying the bedrock. The expected development of regolith layers and wetland vegetation has been included in the regolith-lake development model (RLDM).

Uncertainties associated with the geometry and the development of the future landscapes are discussed in Section 5.6.1. Briefly, the largest uncertainties in the configuration and development of the landscape (and biosphere objects within the landscape) are due to uncertainties in the future climate, and the corresponding sea level and shoreline displacement. These uncertainties have been handled by using two different patterns of development for the surface ecosystems, where the extended global warming calculation case illustrates the effects of a delay in shoreline displacement by assuming that the shoreline remains at its present location for 1,000 years (see Section 4.2).

No specific attempts were made to quantify effects of uncertainties in the parameters describing the development of the landscape within the two calculation cases (cf. above). However, as predictions from the RLDM were deemed acceptable (Section 5.6 and Brydsten and Strömgren 2013), uncertainties in landscape geometries and regolith depths (relevant for dose and dose rate predictions) were considered to be covered within the relatively large parameter ranges spanned in the use of alternative outlines of object 157_2 (Section 6.4, BCC7).

Climate conditions

In the SR-PSU assessment, the uncertainty of future climates was handled by using three different biosphere calculation cases, namely: the global warming calculation case (BCC1, base case), the talik calculation case (BCC2, periglacial conditions) and the extended global warming calculation case (BCC3, warm conditions), see Section 7.4 for further details.

The global warming calculation case was seen as the starting point and the reference point for all biosphere calculations, and it corresponds to the reference evolution (**SR-PSU Main report**), which describes a reasonable development of the surface ecosystems. In the other two biosphere calculation cases, parameters affected by the climate were changed systematically to reflect the expected change with respect to the following factors: the link between the geosphere and the biosphere (BCC2), the sea level (BCC3), the surface hydrology (BCC2 and BCC3), and the biotic components of aquatic and terrestrial ecosystems (BCC2 and BCC3); for details the reader is referred to Section 7.4 and Grolander (2013).

The results from the unit release rate simulations demonstrated that the model responses were compatible with conceptual understanding and expectations with respect to changes in release area, sea level, surface hydrology, and ecosystem properties (Section 7.4). Thus, it was concluded that the handling of the uncertainties with respect to the future climatic conditions in the biosphere modelling was adequate and reasonable.

Chemical evolution

Most of the easily weathered calcite in the upper regolith of the Forsmark area will be dissolved and ultimately washed out over time. This means that the influence of the calcium-rich deposits on freshwater and the terrestrial ecosystems will be reduced. Thus, the future chemical environment in the area is expected to approach the low-calcite conditions more common in Sweden, implying a pH drop between one and 1.5 units in freshwater and wetlands/agricultural soils when data from Forsmark are compared to areas low in calcite (Section 4.4.2).

The uncertainty of potential effects of an outwash of calcite was handled by allowing the probability density functions of pH sensitive parameters to span the expected response to a decrease in pH (Grolander 2013). In natural wetland and freshwater ecosystems pH sensitive parameters included those describing the carbonate system ("f_H_2CO_3", see "C-14" part of Section 10.9.2) and wetland vegetation parameters (e.g. biomass and Net Primary Productivity – NPP). Thus the potential effects of a loss of calcite were included in the outcome of the probabilistic Monte-Carlo simulations (Section 10.8), and thus this uncertainty was included in the risk calculations from the full model chain.

The potential effect of a calcite outwash for cultivated soils was not handled explicitly. Instead the use of K_d-values for soil representing present (calcite-influenced) conditions was considered to be cautious. This is because sorption (and K_d) of most pH-sensitive elements (including Ni and Mo) tend to increase with pH (Sheppard 2011, Sohlenius et al. 2013b). Thus, K_d values reflecting present conditions will overestimate radionuclide retention under more acid conditions, and consequently also the exposure of inhabitants cultivating the soil.

Use of natural resources by future human inhabitants

The uncertainties with respect to the degree that future humans will inhabit and/or utilise natural resources in the biosphere object have been handled according to Swedish regulations and international standards and guidance. That is, the most exposed groups used in the assessment represented credible bounding cases with respect to identified exposure pathways (Sections 7.2 and 7.3). The assigned characteristics and habits of the most exposed group are reasonable with respect to physical constraints of the landscape, to human needs for nutrients and energy, and to present and/or historical land use (Saetre et al. 2013b). However, they are unlikely to provide a realistic representation of real human beings in the far future.

The exposure pathways covered by the four exposed groups include ingestion, inhalation and direct exposure from inhabiting or using natural resources. Use of natural and agricultural ecosystems was covered by the groups, as was the exposure from ingestion of radionuclides with surface and well water. In addition, potential exposure resulting from irrigation, from burning of biomass fuel (peat or wood) and from fertilisation with ash or seaweeds, was included on the scale of a household garden plot. Long-term irrigation of soils that can be sustainably cultivated for thousands of years was not included in the assessment, as it has previously been shown to result in considerably lower accumulation of radionuclides than the accumulation in wetlands (Avila et al. 2010). By assessing exposure for four different exposed populations (land use variants), uncertainties in the effects of use of different natural resources by humans are judged to be duly covered.

11.2.3 Model uncertainties

Model uncertainties refer 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, in the radionuclide model, complex ecosystems are represented by compartments that are considered internally homogeneous. With the model approach used, radionuclides entering, for example, a regolith layer are assumed to be homogeneously distributed within the relevant time scales. The correctness of such an assumption is of course dependent on the horizontal distribution of the source, and the spatial and temporal scales considered. Thus, the uncertainty associated with the size of the object and the discretisation of deep regolith layers is discussed below.

Soil retention and biological uptake of radionuclides are complex processes. These have been represented in the biosphere assessment by simple equilibrium parameters (for CR and K_d see Sections 9.3.6 and 9.3.7, respectively). The uncertainties associated with this highly stylised and simplified approach are handled by using parameter values spanning a relevant range of environmental conditions. Consequences of this approach for the uncertainty of calculated annual effective dose and absorbed dose rates are discussed in Section 10.9. The general assumptions and limitations of the K_d and CR approaches, in relation to the natural variation at the site, are discussed in detail in Tröjbom et al. (2013).

Size of the biosphere object

The SR-PSU biosphere objects represent areas potentially affected by the discharge of deep groundwater from the extended SFR repository (Section 6.3). Several characteristics of the biosphere objects affect the transport and accumulation of radionuclides. Some of these are related to the size of the object. To examine to what extent results from the radionuclide model depended on the size of the biosphere objects, a calculation case based on a series of alternative object outlines was constructed (BCC 7, Section 7.4.7).

Each of the alternative representation of biosphere object 157_2 reflects a stylised approach to outlining the area of interest, based on one specific assessment perspective (Section 6.4). Thus the alternative outlined areas should not be seen as equally likely representations of areas affected by groundwater from the repository. For example, areas with a steady upward flux of groundwater from the bedrock to the surface, and open wetland areas connected by a horizontal exchange of surface water, are likely to receive most of the radionuclides discharged to the object. On the other hand, the area superimposed on bedrock with a high density of discharge points, and the area representing possible arable land, illustrate aspects of potential variation in area specific properties, but they were derived from hypothetical "what if" perspectives. Consequently the discussion below is based on the first two alternative object delineations (areas with an upward hydraulic gradient and open wetland areas).

The surface areas of the original biosphere object 157_2 and the above two alternative delineations spanned a factor of two. The depth of the peat and the glacial clay layers, and the upward flux of groundwater ($m^3\ y^{-1}$) from the lower regolith layers (till, glacial clay and post glacial clay-gyttja) also varied by a factor of two. Moreover, flux rates and regolith depths were not strongly linked at the object scale. Other object specific parameters varied to a lesser extent (see Figure 6-15 for details).

The variations in surface area, groundwater fluxes and regolith depths covered by the delineations had clear effects on the accumulation of radionuclides. In most cases the effect in the concentration of an environmental medium was approximately linearly related to one parameter. Thus, the concentration of a radionuclide in a certain medium also typically spanned a factor of two between the outlined objects (Section 10.8). For example, upward flux of groundwater primarily determined the pore water concentration in till, and the horizontal groundwater flux (or the rate of degassing for C-14) controlled the concentration in surface peat. For Ni-59 (which did not reach steady state in upper regolith layers) transport dynamics were also important for the resulting concentrations, and thus additional parameters influenced the results (e.g. area-specific water flux and regolith depth). Similarly, the C-14 concentration in cultivated soil was influenced by several environmental parameters. However, due to the co-variation the effects of individual parameters did not propagate in a multiplicative manner, and the response range in environmental concentration was limited to a factor of three.

In conclusion, the outlined surface area of biosphere object 157_2 affected transport and accumulation calculations, and a smaller area resulted in larger environmental concentrations. However, decreasing the area affected by groundwater discharged is unlikely to affect environmental concentrations by more than a factor of three. The variation in environmental concentrations could in most cases be linearly related to a first-order effect of a change in hydrological fluxes or in regolith depths. Even for environmental media that were influenced by several parameters, the effect on concentrations did not exceed a factor of 1.5 larger than that due to the change in the most influential parameter.

It is reasonable to expect that the variation in exposure of future human inhabitants and of non-human biota would be proportional to the change in environmental concentrations. For human inhabitants, ingestion is the primary route for exposure to long-lived radionuclides (Table 10-1). As the production of the biosphere object limits exposure of inhabitants foraging the landscape, the effect of an increased concentration in food would be offset by a decreased availability of food in a smaller object. For non-human biota with a limited home range and for humans cultivating the mire there would be no dilution from areas outside the biosphere object, unless the support area exceeded the biosphere object. However, note that the object representing possible arable land (derived from hypothetical "what if" perspectives) would only suffice to support one family with arable land after draining, and would provide less than a third of the hay needed for the most exposed group given infield-outland agriculture.

Representation of regolith layers

All regolith layers are represented by a single compartment in each of the aquatic (if present) and terrestrial parts of the radionuclide model (Figure 8-1). In the lowest regolith layer (till) of the primary discharge area (object 157_2), the vertical flow rate is slow in relation to the thickness of this layer.

Thus, the characteristic travel time of water exceeds one year. A single-compartment representation will thus underestimate the time for breakthrough and overestimate dispersion of radionuclides and these effects are strongly amplified by sorption to solid matter. Avila et al. (2010) showed that the retardation of radionuclides with a moderate or high K_d may be increased by orders of magnitude when the model discretisation of the lowest regolith layer is refined.

As exposure of humans and non-human biota primarily occurs as a consequence of radionuclide accumulation in surface regolith layers (Table 10-1), an underestimation of retardation in the deep regolith, i.e. an overestimation of transport to surface layers, is a cautious representation of transport. The vertical discretisation of a given area has little effect on the steady-state concentrations of long-lived radionuclides in the pore water of the lowest regolith layer, which the inhabitants are exposed to when extracting water from a dug well. Moreover, discretisation does not affect exposure from short-lived radionuclides that reach the surface directly from the geosphere, through a bedrock well. Thus, the single compartment representation is considered a cautious model simplification with respect to dose and dose rate calculations.

Advective transport during transition phases

The area-specific upward flux of groundwater from the lower regolith layer is six times higher under land conditions than under submerged conditions (object 157_2, Grolander 2013). In this report, all transport and dose calculations are based on a constant release rate to the lower regolith (1 Bq y^{-1}). This means that an increased upward flux of groundwater will be associated with a proportional decrease in the steady-state concentration of radionuclides with a long half-life in the lowest regolith layer (see Section 10.5). This may result in a transient release of radionuclides to above-lying layers during a transition from sea to land conditions.

However, this response is an artefact of applying a constant input of radionuclides to surface ecosystems. As the dominating flow path through the lowest regolith layer is in the vertical direction, it is not surprising that groundwater flow from the geosphere into the lowest regolith layer responds to shoreline displacement in the same way as the upward flux (Werner et al. 2013a). Thus, if the activity concentration in the geosphere groundwater does not change, the steady-state concentration of a long-lived radionuclide in the till is not expected to change much in response to the passage of the shoreline.

The consequences introduced by decoupling the biosphere from the geosphere, by the use of a unit release rate, were quantified by Avila et al. (2010) in the SR-Site safety assessment. However, in SR-PSU the geosphere and biosphere models are coupled in the calculation chain, and consequently these model artefacts introduced by the constant release should not be an issue during the transition from submerged to land conditions in the present safety assessment.

11.2.4 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 radionuclide, Monte-Carlo simulations were also performed to incorporate uncertainties associated with input parameters. The results from Monte-Carlo simulations were also used in sensitivity analyses, to identify the biosphere parameters contributing most to uncertainty in annual effective doses to humans and absorbed dose rates to non-human biota, given a constant unit release rate.

The parameters describing regolith thickness of a soil column co-vary systematically in time, as a function of the local topography and shoreline displacement (Section 9.3.1). Similarly, parameters describing hydrological flux rates are tightly coupled, as mass conservation requires each compartment to be in water balance. Thus, the effects of variations in regolith depth and hydrological flux rates were not examined with Monte-Carlo simulation. Instead the combined effect of co-variation in these parameters was examined as a function of object delineation (see “Size of the biosphere object” in Section 11.2.3 above).

Uncertainty analysis

The uncertainty analysis was carried out to contrast estimated annual doses to humans and dose rates to non-human biota, given a unit release rate, with corresponding estimates incorporating parameter variations. The arithmetic mean of endpoints from 1,000 simulations was used as the expected value for the Monte-Carlo simulations (Section 10.9). This was also the method used for the risk calculations in the full calculation chain (**SR-PSU Main report**).

Because of the positively skewed distributions of the annual doses and dose rates, the arithmetic mean from the probabilistic simulations was always higher than the values corresponding to the best estimates of parameters. The difference was typically within a factor of three, but for a few elements the difference was as large as a factor of nine (Cs-135) or even twenty-five (Ca-41). For short-lived radionuclides, for which well water was the main exposure pathway, the difference was insignificant. As the parameter uncertainties were included by the use of probabilistic simulations for the transport calculations (**Radionuclide transport report)**, the differences between arithmetic mean and best estimates indicate the potential to reduce the calculated risk by reducing uncertainties in biosphere parameters.

Sensitivity analysis

The Monte-Carlo simulations described above were also used in a sensitivity analysis of four long-lived radionuclides, namely C-14, Cl-36, Ni-59 and Mo-93. This analysis aimed to identify individual parameters with a strong influence on the assessment endpoints. The results related endpoint variation to the variation of individual parameters. In general, parameters describing sorption and organism uptake contributed the most to variation in human dose and dose rates to non-human biota. Parameters related to degassing were important for dose and dose rate variation of C-14, as were parameters describing stable carbon concentrations (especially in surface water).

The uncertainty in doses and dose rates introduced by parameter variation was limited for most radionuclides (including C-14, Cl-36, Ni-59 and Mo-93). Nevertheless, if uncertainty is to be reduced, parameters describing sorption (K_d) and plant uptake (CR) and the transfer rate between fodder and meat or milk, should be key targets for improved understanding. The SR-PSU model of C-14 transport in surface ecosystems has been updated with several processes, making comparisons with previous SKB safety assessments difficult. Nevertheless, the finding of variation in stable carbon concentration as a key driver of uncertainty in dose calculations was consistent with results from the previous safety assessment of SFR 1 (Bergström et al. 2008).

11.2.5 Overall uncertainty

The annual effective doses and absorbed dose rates calculated in Chapter 10 were obtained for a constant unit release rate. These endpoints are best estimates for a representative individual in the most exposed group, or for a representative organism living in the biosphere object. The simulations are based on the combined results of process understanding, the most precise description of the site available, and extensive modelling of the future development of the area.

In the SR-PSU safety assessment, the biosphere calculations have been integrated into the calculation chain of the safety assessment. That is, the discharge of radionuclides to the regolith layer resting on bedrock was driven by simulated groundwater fluxes, which varied with time, repository part and calculation case. Parameter uncertainty in all model domains (i.e. the repository, the geosphere and the biosphere) was propagated to the risk estimation. Thus, rather than using best estimates, parameter values were drawn from probability density functions, and calculations were repeated for multiple randomly drawn parameter datasets. Therefore, the results presented in this chapter (and the previous) cannot be directly generalised to the final risk estimates. Nevertheless, the results should give good insights into model behaviour and performance, especially for radionuclides with little sorption, and for long-term releases of sorbing radionuclides.

The radionuclide model for the biosphere used in this assessment is similar to the model developed in the previous safety assessment of the final repository for spent nuclear fuel (Avila et al. 2010, SKB 2010). However, the handling and impact of uncertainties on end results differ in several ways. For example, in SR-Site several different discharge areas were analysed in parallel, whereas in SR-PSU only one biosphere object was identified as being likely to receive deep groundwater from the SFR repository. Moreover, in SR-Site, the timing of the release and mismatches between biosphere and geosphere hydrological fluxes, were identified as uncertainties with a potential effect on endpoint estimates. In SR-PSU, these uncertainties were reduced by linking the geosphere and the biosphere.

In SR-Site, best estimates of parameters were used for the assessment, whereas the SR-PSU assessment explicitly included parameter variation for calculations of dose or dose rate to both humans and non-human biota. In other areas, such as human use of future land and water resources, SKB has used a thorough analysis of exposure pathways to identify bounding cases for exposure in SR-PSU. This handling of uncertainty is intrinsically cautious, but SKB understands this to be in compliance with international recommendations on how to handle the large uncertainties in the habits and behaviour of future human inhabitants (Saetre et al. 2013b).

From the analysis of the size of the biosphere object it was shown that a smaller biosphere object is likely to result in elevated environmental concentrations. However, decreasing the area affected by groundwater discharged is unlikely to affect environmental concentrations by more than a factor of three. Moreover, the variations in parameters describing regolith depths and hydrological fluxes obtained for the three object delineations based on discharge areas, open wetland areas and the original object delineation are likely to exceed the uncertainty of these parameters in the original object. Thus SKB argue that this calculation case also sets an upper boundary for the effect of uncertainties in tightly linked object specific parameters.

SKB realise that surface ecosystems are complex, and that our understanding of transport and accumulation in the future Forsmark area is incomplete (Section 2.6). Thus, it is inevitable that some cautious assumptions have to be introduced to handle the uncertainties in the biosphere. (For example, the fate of radionuclides during combustion and mulching has been handled using cautious assumptions, Saetre et al. 2013a). In addition, some model simplifications are likely to lead to overestimations of radionuclide concentrations in surface ecosystems (see discussion on sorbing radionuclides Section 10.3.2). Finally, as parameters with a large effect on estimated annual dose and dose rates tend to be negatively correlated and approximately log normally distributed (i.e. CR and K_d in surface soils, Sheppard et al. 2011), the expected outcome from Monte-Carlo simulations will be somewhat too large, as compared to an analysis accounting for parameter co-variation.

Thus, SKB argues that the handling of system, model and parameter uncertainties has been balanced in SR-PSU. Moreover, the effect of quantified uncertainties was found to be limited and is therefore not expected to have a significant effect on the assessment endpoints. Taken together we are confident that the radionuclide model of the biosphere, as implemented in the transport model chain, yields robust estimates of annual effective dose for the most exposed group and absorbed dose rates for non-human biota, reflecting process understanding and a relevant description of the site.

11.3 Considerations regarding future work on assessments

In SR-PSU a number of improvements have been made in the surface system analysis compared with the last safety assessment of SFR (SAR-08). For example, the digital elevation model (DEM) and the regolith depth and stratigraphy model (RDM) have been updated, and the radionuclide transport model has been developed such that it, amongst other things, represents the transport and accumulation of C-14 in the surface systems better than earlier models. The new exposure pathway analysis identified a set of populations based on historical and present land use and consumption for use as bounding cases for the potentially most exposed groups. However, there are still several desirable improvements of surface system modelling. Research topics for the surface systems identified at SKB are described in the R&D program (SKB 2013a). Future work related to SR-PSU will be performed in close relation to the long-term research, but with special focus on the time scales and special conditions relevant for assessment of the SFR repository.

In SR-PSU, the radionuclide model for the surface ecosystems was updated in several aspects to better mimic the transport and accumulation of C-14 (Saetre et al. 2013a, SKB 2014). However, there is likely still some conservatism in the current model that should be further investigated. Literature suggests that terrestrial organic carbon may be of great importance in the aquatic food web when taken up by bacteria and subsequently transferred to higher trophic levels (Hessen and Tranvik 1998, Jansson et al. 2000, Berggren et al. 2010, Laudon et al. 2011). This implies a dilution factor with respect to C-14 in the aquatic food web, since present models are based solely on the production of aquatic plants (including algae and bacteria), in which inorganic carbon (including C-14) in the water is the sole source of carbon taken up by the primary producers. Supplementary field studies and modelling are planned to investigate the potential importance of this dilution of C-14 in lakes in the Forsmark area. Likewise, a finer temporal resolution in the modelling may lead to less C-14 uptake into biota, since primary production occurs only during certain periods of the year.

In addition to C-14, efforts are required to better describe the cycling of chlorine and accumulation of Cl-36 and Mo-93 in surface system models. The cycling of chlorine in terrestrial ecosystems is, to a high degree, influenced by biological processes such as uptake in vegetation and chlorination of organic matter in, for example, superficial soil layers. However, little is known about how chlorination and dechlorination processes are regulated and how these processes affect transport under different environmental conditions. An in-depth evaluation of the distribution pattern of chlorine in terrestrial ecosystems relating the observed pattern to processes and properties in soil and vegetation is desirable (Bastviken et al. 2013). Information from these studies could be used in further development of the radionuclide transport model. Furthermore, the description of atmospheric exchange can be broadened from carbon dioxide to include other compounds that can exist in the gas phase, for example, radon, iodine, selenium and chlorine.

More research may be performed to identify the dominant fluxes of organic matter, nutrients and water within the different ecosystems and the factors that regulate these fluxes, in order to update the representation of biological uptake in the radionuclide modelling. This information can then be used to obtain a more realistic representation of the uptake of radionuclides in aquatic and terrestrial food webs. This can replace or supplement the concentration ratios (CR values) for organisms with mechanistic models. The research in each ecosystem should both identify the dominant fluxes and uptake factors, and provide a basis for modifying the radionuclide transport models. The advantage of a more process-oriented description of biological uptake is that many processes are common to many organisms and are radionuclide-independent. Moreover, it is possible to explicitly take into account how accumulation in the food web is affected by climate and other changes in the environment and this could reduce uncertainties about the effects of future conditions.

In SR-PSU a great effort has been made to use a systematic approach and update K_d and CR values with new site data and more literature data. Aspects of K_d that should be further investigated are effects of long-term changes in soil conditions on the K_d values. In terrestrial ecosystems, soil chemical properties change as soils evolve over long periods of time. Certain substances (e.g. Ca) are leached out while others are enriched, which changes the conditions for sorption of radionuclides, thereby affecting the effective annual doses to humans and absorbed dose rates to non-human biota. The coming review of SR-PSU could also raise additional questions that need to be taken into account in coming research programs.

The SR-PSU biosphere assessment is based on a unique dataset and experiences gained from a series of earlier safety assessments. It represents the current state of the art in terms of modelling techniques and assessment methodology. The main uncertainties have been identified and analysed. Even though uncertainties exist and needs for further development can and will be identified (cf. above), the overall confidence in the biosphere assessment is high.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

References with abbreviated names

Biosphere synthesis report, 2014. Biosphere synthesis report for the safety assessment SRPSU. SKB TR-14-06, Svensk Kärnbränslehantering AB.

Climate report, 2014. Climate and climate related issues for the safety assessment SR-PSU. SKB TR-13-05, Svensk Kärnbränslehantering AB.

FEP report, 2014. FEP report for the safety assessment SR-PSU. SKB TR-14-07, Svensk Kärnbränslehantering AB.

FHA report, 2014. Handling of future human actions in the safety assessment SR-PSU. SKB TR-14-08, Svensk Kärnbränslehantering AB.

Initial state report, 2014. Initial state report for the safety assessment SR-PSU. SKB TR-14-02, Svensk Kärnbränslehantering AB.

Radionuclide transport report, 2014. Radionuclide transport and dose calculations for the safety assessment SR-PSU. SKB TR-14-09, Svensk Kärnbränslehantering AB.

SR-PSU Main report, 2014. Safety analysis for SFR. Long-term safety. Main report for the safety assessment SR-PSU. SKB TR-14-01, Svensk Kärnbränslehantering AB.

Other references

Adrian R, O'Reilly C M, Zagarese H, Baines S B, Hessen D O, Keller W, Livingstone D M, Sommaruga R, Straile D, van Donk E, Weyhenmeyer G A, Winder M, 2009. Lakes as sentinels of climate change. Limnology and Oceanography 54, 2283–2297.

Andersson E (ed), 2010. The limnic ecosystems at Forsmark and Laxemar-Simpevarp. SKB TR-10-02, Svensk Kärnbränslehantering AB.

Andersson E, Aquilonius K, Sivars Becker L, Borgiel M, 2011. Site investigation SFR. Vegetation in streams in the Forsmark area. SKB P-11-18, Svensk Kärnbränslehantering AB.

Andersson J, Riggare P, Skagius K, 1998. Project SAFE. Update of the SFR-1 safety assessment Phase 1. SKB R-98-43, Svensk Kärnbränslehantering AB.

Andersson P, Garnier-Laplace J, Beresford N A, Copplestone D, Howard B, Howe P, Oughton D, Whitehouse P, 2009. Protection of the environment from ionising radiation in a regulatory context (protect): proposed numerical benchmark values. Journal of Environmental Radioactivity 100, 1100–1108.

Aquilonius K (ed), 2010. The marine ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere. SKB TR-10-03, Svensk Kärnbränslehantering AB.

Aquilonius K, Qvarfordt S, Borgiel M, 2011. Validation of the marine vegetation model in Forsmark. SFR-Site Forsmark. SKB P-11-10, Svensk Kärnbränslehantering AB.

ATSDR, 2005. Public health assessment guidance manual (Update). U.S. Department of Health and Human Services, Public Health Service Agency for Toxic Substances and Disease Registry (ATSDR), Atlanta, Georgia.

Avila R, Moberg L, 1999. A systematic approach to the migration of ^{137}Cs in forest ecosystems using interaction matrices. Journal of Environmental Radioactivity 45, 271–282.

Avila R, Pröhl G, 2008. Models used in the SFR 1 SAR-08 and KBS-3H safety assessments for calculation of ^{14}C doses. SKB R-08-16, Svensk Kärnbränslehantering AB.

Avila R, Ekström P-A, Åstrand P-G, 2010. Landscape dose conversion factors used in the safety assessment SR-Site. SKB TR-10-06, Svensk Kärnbränslehantering AB.

Avila R, Kautsky U, Ekström P-A, Åstrand P-G, Saetre P, 2013. Model of the long-term transport and accumulation of radionuclides in future landscapes. Ambio 42, 497–505.

BACC, 2008. Assessment of climate change for the Baltic Sea basin. The BACC (BALTEX Assessment of Climate Change for the Baltic Sea basins) author team. Berlin: Springer.

Bastviken D, Svensson T, Sandén P, Kylin H, 2013. Chlorine cycling and fates of ^{36}Cl in terrestrial environments. SKB TR-13-26, Svensk Kärnbränslehantering AB.

Beresford N A, Brown J, Copplestone D, Garnier-Laplace J, Howard B, Larsson C M, Oughton D, Pröhl G, Zinger I (eds), 2007. D-ERICA: An integrated approach to the assessment and management of environmental risk from ionising radiation. Description of purpose, methodology and application. EC contract number FI6R-CT-2004-508847, European Commission, Brussels.

Beresford N, Barnett C L, Howard B J, Scott W A, Brown J E, Copplestone D, 2008. Derivation of transfer parameters for use within the ERICA Tool and the default concentration ratios for terrestrial biota. Journal of Environmental Radioactivity 99, 1393–1407.

Berg J, Jansson U, Wästfelt A, 2006. Landscape history and people in a geographical perspective. Studies of land-use, settlement and livehood in Oskarshamn and Forsmark. SKB R-06-37, Svensk Kärnbränslehantering AB.

Berggren M, Ström L, Laudon H, Karlsson J, Jonsson A, Giesler R, Bergström A-K, Jansson M, 2010. Lake secondary production fueled by rapid transfer of low molecular weight organic carbon from terrestrial sources to aquatic consumers. Ecology Letters 13, 870–880.

Berglund K, 1989. Ytsänkning av mosstorvjord: sammanställning av material från Lidhult, Jönköpings län. Uppsala: Swedish University of Agricultural Sciences, Department of Soil Sciences. (Hydrotechnics Report 89:3) (In Swedish.)

Berglund K, 1996a. Agricultural improvement of cultivated organic soils II. Effects of liming and deep cultivation on soil properties and root development. Soil Use and Management 12, 169–175.

Berglund K, 1996b. Cultivated organic soils in Sweden: properties and amelioration. Uppsala: Swedish University of Agricultural Sciences, Department of Soil Sciences. (Reports and dissertations 28)

Berglund S, Bosson E, Sassner M, 2013a. From site data to safety assessment: analysis of present and future hydrological conditions at a coastal site in Sweden. Ambio 42, 425–434.

Berglund S, Bosson E, Selroos J-O, Sassner M, 2013b. Identification and characterization of potential discharge areas for radionuclide transport by groundwater from a nuclear waste repository in Sweden. Ambio 42, 435–446.

Berglund Ö, Berglund K, Sohlenius G, 2009. Organogen jordbruksmark i Sverige 1999–2008. Uppsala: Swedish University of Agricultural Sciences, Department of Soil Sciences. (Rapport 12) (In Swedish.)

Bergström E, 2001. Late Holocene distribution of lake sediment and peat in NE Uppland, Sweden. SKB R-01-12, Svensk Kärnbränslehantering AB.

Bergström U, Nordlinder S, Aggeryd I, 1999. Models for dose assessments. Modules for various biosphere types. SKB TR 99-14, Svensk Kärnbränslehantering AB.

Bergström U, Albrecht A, Kanyar B, Smith G, Thorne M C, Yoshida H, Wasiolek M, 2006. BIOPROTA: Key issues in biosphere aspects of assessment of the long-term impact of contaminant releases associated with radioactive waste management. Theme 2 Task 1: Model review and comparison for spray irrigation pathway. SKB TR-06-05, Svensk Kärnbränslehantering AB.

Bergström U, Avila R, Ekström P-A, de la Cruz I, 2008. Dose assessments for SFR 1. SKB R-08-15, Svensk Kärnbränslehantering AB.

BIOMOVS, 1993. BIOMOVS: final report. BIOMOVS Technical report 15, Swedish Radiation Protection Institute, Stockholm.

BIOMOVS II, 1996a. Biosphere modelling for dose assessments of radioactive waste repositories. Final report of the Complementary Studies Working Group. BIOMOVS II Technical report 12, BIOMOVS II Steering Committee, Swedish Radiation Protection Institute, Stockholm.

BIOMOVS II, 1996b. Development of a reference biospheres methodology for radioactive waste disposal. Final report of the Reference Biospheres Working Group. BIOMOVS II Technical report 6, BIOMOVS II Steering Committee, Swedish Radiation Protection Institute, Stockholm.

Bosson E, Gustafsson L-G, Sassner M, 2008. Numerical modelling of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-09, Svensk Kärnbränslehantering AB.

Bosson E, Sassner M, Sabel U, Gustafsson L-G, 2010. Modelling of present and future hydrology and solute transport at Forsmark. SR-Site Biosphere. SKB R-10-02, Svensk Kärnbränslehantering AB.

Bosson E, Selroos J-O, Stigsson M, Gustafsson L-G, Destouni G, 2013. Exchange and pathways of deep and shallow groundwater in different climate and permafrost conditions using the Forsmark site, Sweden, as an example catchment. Hydrogeology Journal 21, 225–237.

Breckle S-W, 2002. Walter's vegetation of the earth: the ecological systems of the geo-biosphere. 4th ed. Berlin: Springer.

Brown J E, Alfonso B, Avila R, Beresford N A, Copplestone D, Pröhl G, Ulanovsky A, 2008. The ERICA Tool. Journal of Environmental Radioactivity 99, 1371–1383.

Brunberg A-K, Nilsson E, Blomqvist P, 2002. Characteristics of oligotrophic hardwater lakes in a postglacial land-rise area in mid-Sweden. Freshwater Biology 47, 1451–1462.

Brunberg A-K, Carlsson T, Blomqvist P, Brydsten L, Strömgren M, 2004. Forsmark site investigation. Identification of catchments, lake-related drainage parameters and lake habitats. SKB P-04-25, Svensk Kärnbränslehantering AB.

Brydsten L, 2009. Sediment dynamics in the coastal areas of Forsmark and Laxemar during an interglacial. SKB TR-09-07, Svensk Kärnbränslehantering AB.

Brydsten L, Strömgren M, 2010. A coupled regolith-lake development model applied to the Forsmark site. SKB TR-10-56, Svensk Kärnbränslehantering AB.

Brydsten L, Strömgren M, 2013. Landscape development in the Forsmark area from the past into the future (8500 BC – 40,000 AD). SKB R-13-27, Svensk Kärnbränslehantering AB.

Cerdan O, Govers G, Le Bissonnais Y, Van Oost K, Poesen J, Saby N, Gobin A, Vacca A, Quinton J, Auerswald K, Klik A, Kwaad F J P M, Raclot D, Ionita I, Rejman J, Rousseva S, Muxart T, Roxo M J, Dostal T, 2010. Rates and spatial variations of soil erosion in Europe: A study based on erosion plot data. Geomorphology 122, 167–177.

Chapin F S, Matson P A, Mooney H A, 2002. Principles of terrestrial ecosystem ecology. New York: Springer.

EC, 2002. Guidance on the realistic assessment of radiation doses to members of the public due to the operation of nuclear installations under normal conditions. Luxembourg: Office for Official Publications of the European Communities. (Radiation protection 129)

Eckerman K F, Leggett R W, 1996. DCFPAK: Dose coefficient data file package for Sandia National Laboratory. Report ORNL/TM-13347, Oak Ridge National Laboratory, Tennessee.

Eckerman K F, Ryman J C, 1993. External exposure to radionuclides in air, water, and soil: exposure-to-dose coefficients for general application, based on the 1987 Federal Radiation Protection Guidance. Federal Guidance Report 12, U.S. Environmental Protection Agency, Washington, DC.

Edlund O, Bergström U, Hallberg B, Karlsson S, 1999. A summary of biospheric research 1975–1997. SKB TR-99-40, Svensk Kärnbränslehantering AB.

Eliasson P, 1992. ”Genom helvetets port, men…” – skogsdikning som mål och medel. Aktuellt om historia 3–4, 46–60. (In Swedish.)

Eng T, Hudson J, Stephansson O, Skagius K, Wiborgh M, 1994. Scenario development methodologies. SKB TR 94-28, Svensk Kärnbränslehantering AB.

Engdahl A, Rådén R, Borgiel M, Omberg L-G, 2008. Oskarshamn and Forsmark site investigation. Chemical composition of suspended material, sediment and pore water in lakes and sea bays. SKB P-08-81, Svensk Kärnbränslehantering AB.

Erichsen A C, Konovalenko L, Møhlenberg F, Closter R M, Bradshaw C, Aquilonius K, Kautsky U, 2013. Radionuclide transport and uptake in coastal aquatic ecosystems: a comparison of a 3D dynamic model and a compartment model. Ambio 42, 464–475.

Follin S, 2008. Bedrock hydrogeology Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-95, Svensk Kärnbränslehantering AB.

Franzén L G, Lindberg F, Viklander V, Walther A, 2012. The potential peatland extent and carbon sink in Sweden, as related to the Peatland/Ice age hypothesis. Mires and Peat 10, 1–19.

Fredriksson D, 2004. Forsmark site investigation. Peatland investigation Forsmark. SKB P-04-127, Svensk Kärnbränslehantering AB.

Galson D A, Khursheed A, 2007. The treatment of uncertainty in performance assessment and safety case development: state-of-the art overview. PAMINA Milestone Report M1.2.1, European Commission.

Gentzschein B, Levén J, Follin S, 2007. A comparison between well yield data from the site investigation in Forsmark and domestic wells in northern Uppland. SKB P-06-53, Svensk Kärnbränslehantering AB.

Grolander S, 2013. Biosphere parameters used in radionuclide transport modelling and dose calculations in SR-PSU. SKB R-13-18, Svensk Kärnbränslehantering AB.

Gustafsson B G, 2004. Millennial changes of the Baltic Sea salinity. Studies of the sensitivity of the salinity to climate change. SKB TR-04-12, Svensk Kärnbränslehantering AB.

Hamrén U, Collinder P, 2010. Vattenverksamhet i Forsmark. Ekologisk fältinventering och naturvärdesklassificering samt beskrivning av skogsproduktionsmark. SKB R-10-16, Svensk Kärnbränslehantering AB. (In Swedish.)

Harrison J P, Hudson J A, 2006. Comprehensive hazard identification in rock engineering using interaction matrix mechanism pathways. In Golden Rocks 2006: the 41st U.S. Symposium on Rock Mechanics (USRMS), Golden, CO, 17–21 June 2006. Golden, CO: Colorado School of Mines.

Hedenström A, Sohlenius G, 2008. Description of the regolith at Forsmark. Site descriptive modelling, SDM-Site. SKB R-08-04, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, Strömgren M, Brydsten L, Nyman H, 2008. Depth and stratigraphy of regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-07, Svensk Kärnbränslehantering AB.

Hesböl R, Puigdomenech I, Evan, S, 1990. Source terms, isolation and radiological consequences of carbon-14 waste in the Swedish SFR repository. SKB TR 90-02, Svensk Kärnbränslehantering AB.

Hessen D O, Tranvik L J (eds), 1998. Aquatic humic substances: ecology and biogeochemistry. Berlin: Springer.

Hill M D, Clark M J, Smith G M, Lawson G L, Hemming C R, Fearn H, 1984. Review of "Final Storage Spent Nuclear Fuel – KBS3" for the Ministry of Industry, Sweden. NRPB-M107, National Radiological Protection Board, UK.

Hjertstedt H, 1946. De organogena odlingsjordarnas beskaffenhet i olika län med avseende på torvslag, förmultningsgrad och reaktion samt innehåll av kalk och kväve, kali och fosforsyra, organisk substans, seskvioxider och svavelsyra. Svenska Vall- och Mossekulturföreningens kvartalsskrift 8, 255–277. (In Swedish.)

Hyenstrand Å, 1994. Kulturminnen och kulturmiljövård. In Selinge K-G (ed). Sveriges nationalatlas. Kulturminnen och kulturmiljövård. Stockholm: SNA. (In Swedish.)

IAEA, 1992. Effects of ionising radiation on plants and animals at levels implied by current radiation protection standards. IAEA Technical Reports Series 332, International Atomic Energy Agency, Vienna.

IAEA, 2003. "Reference Biospheres" for solid radioactive waste disposal. Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme. Part of the IAEA Co-ordinated Research Project on Biosphere Modelling and Assessment (BIOMASS). IAEABIOMASS-6, International Atomic Energy Agency.

ICRP, 1991. 1990 recommendations of the international commission on radiological protection. Oxford: Pergamon. (ICRP Publication 60; Annals of the ICRP 21)

ICRP, 1996. International Commission on Radiological Protection. Age-dependent doses to members of the public from intake of radionuclides: Part 5, compilation of ingestion and inhalation dose coefficients. Oxford: Pergamon. (ICRP Publication 72; Annals of the ICRP 26)

ICRP, 2003. A framework for assessing the impact of ionising radiation on non-human species. Oxford: Pergamon. (ICRP Publication 91; Annals of the ICRP 33)

ICRP, 2007. The 2007 recommendations of the International Commission on Radiological Protection. Oxford: Elsevier. (ICRP Publication 103; Annals of the ICRP 37)

ICRP, 2008. Environmental protection: the concept and use of reference animals and plants. Oxford: Elsevier. (ICRP Publication 108; Annals of the ICRP 38)

ICRP, 2014. Protection of the environment under different exposure situations. Oxford: Elsevier. (ICRP Publication 124; Annals of the ICRP 43).

Ingmar T, Moreborg K, 1976. The leaching and original content of calcium carbonate in northern Uppland, Sweden. Geologiska Föreningen i Stockholm Förhandlingar 98, 120–132.

IPCC, 2013. Working group I contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis, Summary for Policymakers. Available at: htp://www.ipcc.ch.

Jackson D, Smith K, Wood M D, 2014. Demonstrating compliance with protection objectives for non-human biota within post-closure safety cases for radioactive waste repositories. Journal of Environmental Radioactivity 133, 60–68.

Jaeschke B, Smith K, Nordén S, Alfonso B, 2013. Assessment of risk to non-human biota from a repository for the disposal of spent nuclear fuel at Forsmark. Supplementary information. SKB TR-13-23, Svensk Kärnbränslehantering AB.

Janssen F, Schrum C, Backhaus J, 1999. A climatological dataset of temperature and salinity for the Baltic Sea and the North Sea. Deutsche Hydrografische Zeitschrift 51, Suppl. 5–245.

Jansson M, Bergström A-K, Blomqvist P, Drakare S, 2000. Allochtonous organic carbon and phytoplankton/bacterioplankton relationships in lakes. Ecology 81, 3250–3255.

Johansson P-O, 2008. Description of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-08, Svensk Kärnbränslehantering AB.

Johansson P-O, Werner K, Bosson E, Berglund S, Juston J, 2005. Description of climate, surface hydrology, and near-surface hydrogeology. Preliminary site description Forsmark area – version 1.2. SKB R-05-06, Svensk Kärnbränslehantering AB.

Karlsson A, Eriksson C, Borell Lövstedt C, Liungman O, Engqvist A, 2010. High-resolution hydrodynamic modelling of the marine environment at Forsmark between 6500 BC and 9000 AD. SKB R-10-09, Svensk Kärnbränslehantering AB.

Kasimir-Klemedtsson Å, Klemedtsson L, Berglund K, Martikainen P, Silvola J, Oenema O, 1997. Greenhouse gas emission from farmed organic soils: a review. Soil Use and Management 13, 245–250.

Kautsky U (ed), 2001. The biosphere today and tomorrow in the SFR area. SKB R-01-27, Svensk Kärnbränslehantering AB.

Kellner E, 2003. Wetlands – different types, their properties and functions. SKB TR-04-08, Svensk Kärnbränslehantering AB.

Kjellström E, Strandberg G, Brandefelt J, Näslund J-O, Smith B, Wohlfarth B, 2009. Climate conditions in Sweden in a 100,000 year time perspective. SKB TR-09-04, Svensk Kärnbränslehantering AB.

Kumblad L, Bradshaw C, 2008. Element composition of biota, water and sediment in the Forsmark area, Baltic Sea. Concentrations, bioconcentration factors and partitioning coefficients (K_d) of 48 elements. SKB TR-08-09, Svensk Kärnbränslehantering AB.

Laudon H, Berggren M, Ågren A, Buffam I, Bishop K, Grabs T, Jansson M, Köhler S, 2011. Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: the role of processes, connectivity, and scaling. Ecosystems 14, 880–893.

Leclerc-Cessac E, Thorne M, Thomson G, 2006. Guidance on site-specific biosphere characterisation and experimental research and field research protocols. Published on behalf of the BIOPROTA Steering Committee by Andra, Châtenay-Malabry, France.

Leggett R W, 2004. A biokinetic model for carbon dioxide and bicarbonate. Radiation Protection Dosimetry 108, 203–213.

Lidberg M, Johansson J M, Scherneck H-G, Milne A, 2010. Recent results based on continuous GPS observations of the GIA process in Fennoscandia from BIFROST. Journal of Geodynamics 50, 8–18. doi:10.1016/j.jog.2009.11.010

Limer L M C, Smith K, Albrecht A, Marang L, Norris S, Smith G M, Thorne M C, Xu S, 2012. C-14 long-term dose assessment: data review, scenario development, and model comparison. Stockholm: Swedish Radiation Safety Authority. (SSM 2012:47)

Lindborg T (ed), 2008. Surface system Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-11, Svensk Kärnbränslehantering AB.

Lindborg T (ed), 2010. Landscape Forsmark – data, methodology and results for SR-Site. SKB TR-10-05, Svensk Kärnbränslehantering AB.

Lindborg T, Schüldt R, 1998. The biosphere at Aberg, Beberg and Ceberg – a description and evaluation of climate, physical geography, ecology, land use and environment. SKB TR-98-20, Svensk Kärnbränslehantering AB.

Lindborg T, Brydsten L, Sohlenius G, Strömgren M, Andersson E, Löfgren A, 2013. Landscape development during a glacial cycle: modeling ecosystems from the past into the future. Ambio 42, 402–413.

Lindgren M, Pettersson M, Karlsson S, Moreno L, 2001. Project SAFE. Radionuclide release and dose from the SFR repository. SKB R-01-18, Svensk Kärnbränslehantering AB.

Loreth T, 2005. Quantification of one spring fish migration in a small coastal stream in the Forsmark area, Sweden. Uppsala: Institute of Limnology, Uppsala University. (Scripta Limnologica Upsaliensia 2005 B:7)

Lundin L, Lode E, Stendahl J, Melkerud P-A, Björkvald L, Thorstensson A, 2004. Soils and site types in the Forsmark area. SKB R-04-08, Svensk Kärnbränslehantering AB.

Lundqvist G, 1963. Beskrivning till jordartskarta över Gävleborgs län (Quaternary deposits of Gävleborgs län, central Sweden). Karta i skala 1:200 000. (Sveriges Geologiska Undersökning Ca 42) (In Swedish.)

Löfgren A (ed), 2010. The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere. SKB TR-10-01, Svensk Kärnbränslehantering AB, Stockholm, Sweden.

Löfgren A, 2011. Dissolved inorganic carbon and organic carbon in mires in the Forsmark area. A pilot study. SKB P-11-23, Svensk Kärnbränslehantering AB.

Löfroth M, 1991. Våtmarkerna och deras betydelse. (Wetlands and their importance). Rapport 3824, Naturvårdsverket (Swedish Environmental Protection Agency). (In Swedish.)

Maljanen M, Sigurdsson B D, Guðmundsson J, Óskarsson H, Huttunen J T, Martikainen P J, 2010. Greenhouse gas balances of managed peatlands in the Nordic countries – present knowledge and gaps. Biogeosciences 7, 2711–2738.

Miliander S, Punakivi M, Kyläkorpi L, Rydgren B, 2004. Human population and activities in Forsmark. Site description. SKB R-04-10, Svensk Kärnbränslehantering AB.

Ministry of the Environment, 2007. Sverige inför klimatförändringarna: hot och möjligheter. Stockholm: Ministry of the Environment. (SOU 2007:60) (In Swedish.)

Ministry for the Environment of New Zealand, 2011. Methodology for deriving standards for contaminants in soil to protect human health. Wellington: Ministry for the Environment.

Mäkilä M, Goslar T, 2008. The carbon dynamics of surface peat layers in southern and central boreal mires of Finland and Russian Karelia. Suo 59, 49–69.

Nilsson A-C, Borgiel M, 2005. Forsmark site investigation. Sampling and analysis of near surface groundwater. Results from sampling of shallow soil monitoring wells, BAT pipes, a natural spring and private wells, May 2003–April 2005. SKB P-05-171, Svensk Kärnbränslehantering AB.

Nordlinder S, Bergström U, Mathiasson L, 1999. Ecosystem specific dose conversion factors for Aberg, Beberg and Ceberg. SKB TR-99-15, Svensk Kärnbränslehantering AB.

Nyberg J, Elhammer A, Sohlenius G, Kjellin B, Nordgren P, 2011. Results from marine geological investigations outside Forsmark. SKB P-11-39, Svensk Kärnbränslehantering AB.

Odén M, Follin S, Öhman J, Vidstrand P, 2014. SR-PSU Bedrock hydrogeology. Groundwater flow modelling methodology, setup and results. SKB R-13-25, Svensk Kärnbränslehantering AB.

OECD/NEA, 2012. The post-closure radiological safety case for a spent fuel repository in Sweden: an international peer review of the SKB licence-application study of March 2011. Paris: OECD/NEA.

Osvald H, 1937. Myrar och myrodling. Stockholm: Kooperativa förbundets bokförlag. (In Swedish.)

Peel M C, Finlayson B L, McMahon T A, 2007. Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences 11, 1633–1644.

Pers K, Skagius K, Södergren S, Wiborgh M, Hedin A, Morén L, Sellin P, Ström A, Pusch R, Bruno J, 1999. SR 97 – Identification and structuring of processes. SKB TR-99-20, Svensk Kärnbränslehantering AB.

Påsse T, 2001. An empirical model of glacio-isostatic movements and shore-level displacement in Fennoscandia. SKB R-01-41, Svensk Kärnbränslehantering AB.

Qvarfordt S, Borgiel M, Berg C, 2010. Monitering Forsmark. Hydrochemical investigations in four calciferous lakes in the Forsmark area. Results from complementary investigations in the Forsmark area, 2008–2009. SKB P-10-25, Svensk Kärnbränslehantering AB.

Saetre P, Nordén S, Keesmann S, Ekström P-A, 2013a. The biosphere model for radionuclide transport and dose assessment in SR-PSU. SKB R-13-46, Svensk Kärnbränslehantering AB.

Saetre P, Valentin J, Lagerås P, Avila R, Kautsky U, 2013b. Land use and food intake of future inhabitants: outlining a representative individual of the most exposed group for dose assessment. Ambio 42, 488–496.

Schroeder L D, Sjoquist D L, Stephan P E, 1986. Understanding regression analysis: an introductory guide. Beverly Hills, CA: Sage.

Sheppard S C, 2011. Robust prediction of K_d from soil properties for environmental assessment. Human and Ecological Risk Assessment: An international Journal 17, 263–279.

Sheppard S, Long J, Sanipelli B, Sohlenius G, 2009. Solid/liquid partition coefficients (K_d) for selected soils and sediments at Forsmark and Laxemar-Simpevarp. SKB R-09-27, Svensk Kärnbränslehantering AB.

Sheppard S, Sohlenius G, Omberg L-G, Borgiel M, Grolander S, Nordén S, 2011. Solid/liquid partition coefficients (K_d) and plant/soil concentration ratios (CR) for selected soils, tills and sediments at Forsmark. SKB R-11-24, Svensk Kärnbränslehantering AB.

Sitch S, Smith B, Prentice I C, Arneth A, Bondeau A, Cramer W, Kaplan J O, Levis S, Lucht W, Sykes M T, Thonicke K, Venevsky S, 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Global Change Biology 9, 161–185.

Skagius K, Ström A, Wiborgh M, 1995. The use of interaction matrices for identification, structuring and ranking of FEPs in a repository system. Application on the far-field of a deep geological repository for spent fuel. SKB TR 95-22, Svensk Kärnbränslehantering AB.

SKB, 1999a. Deep repository for spent nuclear fuel. SR 97 – Post-closure safety. Main report – Vol. I, Vol. II and Summary. SKB TR-99-06, Svensk Kärnbränslehantering AB.

SKB, 1999b. Deep repository for long-lived low- and intermediate-level waste. Preliminary safety assessment. SKB TR-99-28, Svensk Kärnbränslehantering AB.

SKB, 2001. Project SAFE. Scenario and system analysis. SKB R-01-13, Svensk Kärnbränslehantering AB.

SKB, 2004. Interim main report of the safety assessment SR-Can. SKB TR-04-11, Svensk Kärnbränslehantering AB.

SKB, 2006a. 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.

SKB, 2006b. The biosphere at Forsmark. Data, assumptions and models used in the SR-Can assessment. SKB R-06-82, Svensk Kärnbränslehantering AB.

SKB, 2006c. The biosphere at Laxemar. Data, assumptions and models used in the SR-Can assessment. SKB R-06-83, Svensk Kärnbränslehantering AB.

SKB, 2007. Forsmark site investigation. Programme for long-term observations of geosphere and biosphere after completed site investigations. SKB R-07-34, Svensk Kärnbränslehantering AB.

SKB, 2008a. Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. SKB TR-08-05, Svensk Kärnbränslehantering AB.

SKB, 2008b. Safety analysis SFR 1. Long-term safety. SKB R-08-130, Svensk Kärnbränslehantering AB.

SKB, 2010. Biosphere analyses for the safety assessment SR-Site – synthesis and summary of results. SKB TR-10-09, Svensk Kärnbränslehantering AB.

SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project, Volume I-III. SKB TR-11-01, Svensk Kärnbränslehantering AB.

SKB, 2013a. RD&D Programme 2013. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB TR-13-18, Svensk Kärnbränslehantering AB.

SKB, 2013b. Components, features, processes and interactions in the biosphere. SKB R-13-43, Svensk Kärnbränslehantering AB.

SKB, 2013c. Site description of the SFR area at Forsmark at completion of the site investigation phase. SDM-PSU Forsmark. SKB TR-11-04, Svensk Kärnbränslehantering AB.

SKB, 2014. Handling of biosphere FEPs and recommendations for model development in SR-PSU. SKB R-14-02, Svensk Kärnbränslehantering AB.

SKBF/KBS, 1983. Final storage of spent nuclear fuel – KBS-3. Vol I–IV. Svensk Kärnbränsleförsörjning AB.

Smith B, Prentice I C, Sykes M T, 2001. Representation of vegetation dynamics in the modeling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. Global Ecology & Biogeography 10, 621–637.

Sohlenius G, Strömgren M, Hartz F, 2013a. Depth and stratigraphy of regolith at Forsmark. SR-PSU Biosphere. SKB R-13-22, Svensk Kärnbränslehantering AB.

Sohlenius G, Saetre P, Nordén S, Grolander S, Sheppard S, 2013b. Inferences about radionuclide mobility in soils based on the solid/liquid partition coefficients and soil properties. Ambio 42, 414–424.

Sohlenius G, Schoning K, Baumgartner A, 2013c. Development, carbon balance and agricultural use of peatlands – overview and examples from Uppland, Sweden. SKB TR-13-20, Svensk Kärnbränslehantering AB.

Sonesten L, 2005. Chemical characteristics of surface waters in the Forsmark area. Evaluation of data from lakes, streams, and coastal sites. SKB R-05-41, Svensk Kärnbränslehantering AB.

SSM, 2008a. The Swedish Radiation Safety Authority's regulations and general advice concerning the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste. Stockholm: Swedish Radiation Safety Authority. (SSMFS 2008:37)

SSM, 2008b. The Swedish Radiation Safety Authority's regulations and general advice concerning safety in connection with the disposal of nuclear material and nuclear waste. Stockholm: Swedish Radiation Safety Authority. (SSMFS 2008:21)

Sternbeck J, Land M, Nilsson Ö, 2006. Oskarshamn and Forsmark site investigations. ^{210}Pb and ^{14}C dating of sediments and peat. Accumulation rates of carbon, nitrogen and phosphorus. SKB P-06-301, Svensk Kärnbränslehantering AB.

Strack M, Waddington J M, Turetsky M, Roulet N T, Byrne K A, 2008. Northern peatlands, greenhouse gas exchange and climate change. In Strack M (ed). Peatlands and climate change. Jyväskylä: International Peat Society, 44–69.

Strömgren M, Brydsten L, 2008. Digital elevation models of Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-62, Svensk Kärnbränslehantering AB.

Strömgren M, Brydsten L, 2013. Digital elevation model of Forsmark. SR-PSU Biosphere. SKB R-12-03, Svensk Kärnbränslehantering AB.

Strömgren M, Lindgren F, 2011. Mapping of reed in shallow bays. SFR-Site Forsmark. SKB P-11-09, Svensk Kärnbränslehantering AB.

Svanberg O, Vilborg I, 2001. Från surhål och mygghelvete till myllrande våtmarker: utvärdering av arbetet mot ett miljökvalitetsmål (From swampy pits and mosquito-hells to flourishing wetlands: an evaluation of work towards an environmental quality objective). Rapport 5146, Naturvårdsverket (Swedish Environmental Protection Agency). (In Swedish.)

Swedish Ministry of Industry, 1984. Review of the KBS-3 plan for handling and final storage of unreprocessed spent nuclear fuel. Swedish Ministry of Industry. Stockholm: Liber. (Ds I 1984:17)

Söderbäck B (ed), 2008. Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas. Site descriptive modelling. SDM-Site. SKB R-08-19, Svensk Kärnbränslehantering AB.

Torudd J, 2010. Long term radiological effects on plants and animals of a deep geological repository. SR-Site Biosphere. SKB TR-10-08, Svensk Kärnbränslehantering AB.

Tröjbom M, Grolander S, 2010. Chemical conditions in present and future ecosystems in Forsmark. Implications for selected radionuclides in the safety assessment SR-Site. SKB R-10-27, Svensk Kärnbränslehantering AB.

Tröjbom M, Nordén S, 2010. Chemistry data from surface ecosystems in Forsmark and Laxemar-Simpevarp. Site specific data used for estimation of CR and K_d values in SR-Site. SKB R-10-28, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, 2006. Chemical characteristics of surface systems in the Forsmark area. Visualisation and statistical evaluation of data from shallow groundwater, precipitation, and regolith. SKB R-06-19, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, Johansson P-O, 2007. Hydrochemistry in surface water and shallow groundwater. Site descriptive modelling, SDM-Site Forsmark. SKB R-07-55, Svensk Kärnbränslehantering AB.

Tröjbom M, Grolander S, Rensfeldt V, Nordén S, 2013. K_d and CR used for transport calculations in the biosphere in SR-PSU. SKB R-13-01, Svensk Kärnbränslehantering AB.

Ulanovsky A, Pröhl G, 2006. A practical method for assessment of dose conversion coefficients for aquatic biota. Radiation and Environmental Biophysics 45, 203–214.

Ulanovsky A, Pröhl G, Gómez-Ros J M, 2008. Methods for calculating dose conversion coefficients for terrestrial and aquatic biota. Journal of Environmental Radioactivity 99, 1440–1448.

UNSCEAR, 1996. Sources and effects of ionizing radiation. Report to the General Assembly. New York: United Nations. (UN Sales Publication E.96.IX.3.)

US DOE, 2002. A graded approach for evaluating radiation doses to aquatic and terrestrial biota. Technical Standard DoE-STD-1153-2002, U.S. Deptartment of Energy, Washington, DC.

US EPA, 2008. Child-specific exposure factors handbook (Final report). EPA/600/R-06/096F, U.S. Environmental Protection Agency, Washington, DC.

US EPA, 2011. Exposure factors handbook. EPA/600/R-09/052F, U.S. Environmental Protection Agency, Washington, DC.

Valmari A, 1977. Torrläggningsfrågor på myrjordar. Nordisk Jordbrugsforskning 59, 640–643.

Velasco H R, Ayub J J, Belli M, Sansone U, 2006. Interaction matrices as a first step toward a general model of radionuclide cycling: application to the 137Cs behavior in a grassland ecosystem. Journal of Radioanalytical and Nuclear Chemistry 268, 503–509.

Vidstrand P, Follin S, Öhman J, 2014. SR-PSU Hydrogeological modelling. TD13 – Periglacial climate conditions. SKB P-14-06, Svensk Kärnbränslehantering AB.

von Post L, Granlund E, 1926. Södra Sveriges torvtillgångar. 1. (The supply of peat in southern Sweden). Stockholm. (Sveriges geologiska undersökning C 335) (In Swedish.)

Welinder S, Pedersen E A, Widgren M, 1998. Det svenska jordbrukets historia. Band 1. Jordbrukets första femtusen år: 4000 f. Kr. – 1000 e. Kr. Stockholm: Natur och Kultur/LT. (In Swedish.)

Werner K, Johansson P-O, Brydsten L, Bosson E, Berglund S, Tröjbom M, Nyman H, 2007. Recharge and discharge of near-surface groundwater in Forsmark. Comparison of classification methods. SKB R-07-08, Svensk Kärnbränslehantering AB.

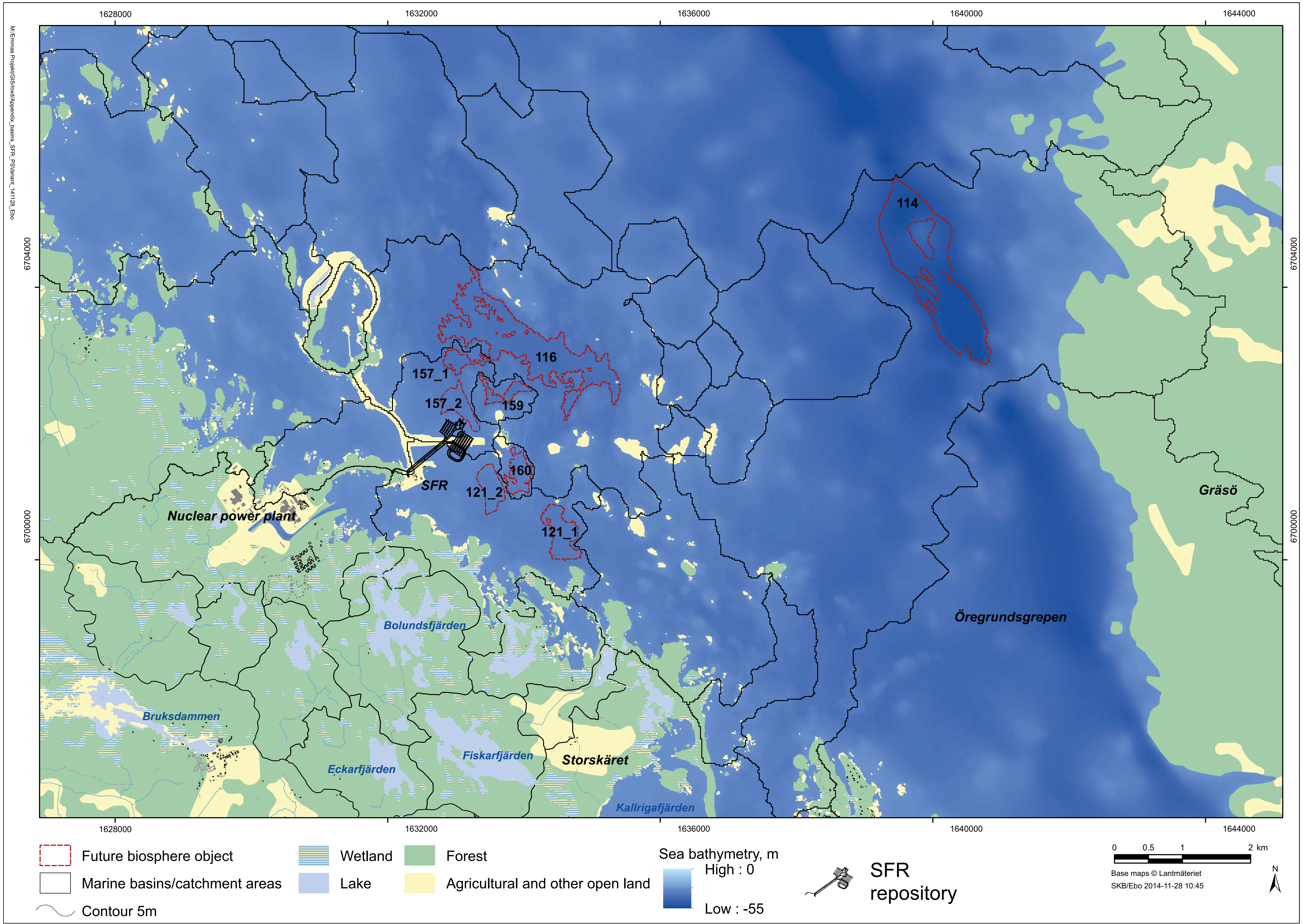
Werner K, Hamrén U, Collinder P, 2010. Vattenverksamhet i Forsmark (del I). Bortledande av grundvatten från slutförvarsanläggningen för använt kärnbränsle. SKB R-10-14, Svensk Kärnbränslehantering AB. (In Swedish.)

Werner K, Sassner M, Johansson E, 2013a. Hydrology and near-surface hydrogeology at Forsmark – synthesis for the SR-PSU project. SR-PSU Biosphere. SKB R-13-19, Svensk Kärnbränslehantering AB.

Werner K, Norville J, Öhman J, 2013b. Meteorological, hydrological and hydrogeological monitoring data from Forsmark – compilation and analysis for the SR-PSU project. SR-PSU Biosphere. SKB R-13-20, Svensk Kärnbränslehantering AB.

Öhman J, Vidstrand P, 2014. SR-PSU Bedrock hydrogeology. TD12 – Water-supply wells in rock. SKB P-14-05, Svensk Kärnbränslehantering AB.

Öhman J, Follin S, Odén M, 2014. SR-PSU Hydrogeological modelling. TD11 – Temperate climate conditions. SKB P-14-04, Svensk Kärnbränslehantering AB.


1628000
1632000
1636000
1640000
1644000
6704000
6700000
114
116
157_1
157_2
159
160
121_2
121_1
SFR
Nuclear power plant
Gräsö
Öregrundsgrepen
Bolundsfjärden
Bruksdammen
Eckarfjärden
Fiskarfjärden
Storskäret
Kallrigafjärden
Future biosphere object
Marine basins/catchment areas
Contour 5m
Wetland
Lake
Forest
Agricultural and other open land
Sea bathymetry, m
High : 0
Low : -55
SFR repository
0 0.5 1 2 km
Base maps © Lantmäteriet
SKB/Ebo 2014-11-28 10:45
N

Appendix 2

Terms and acronyms in SR-PSU Biosphere

Table A2-1. Terms and acronyms used is the SR-PSU biosphere assessment.

Term/acronym	Definition/description
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-PSU terminology, a basin is the drainage area of a biosphere object (cf. below) minus the drainage area of any upstream object. When the basin is below sea level, the basin equals the biosphere object.
BCC	Biosphere calculation case. The BCCs are used for the biosphere part of the radionuclide transport model in the SR-PSU safety assessment.
Biosphere	The part of the environment normally inhabited by living organisms. In the context of safety assessments usually more constrained to the surface (see *surface ecosystem*).
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.
CC	Calculation case. CCs are used in the main safety assessment calculations. Biosphere calculation cases (*BCC*, cf. above) are mapped to these main calculation cases.
Climate case	SR-PSU describes a set of 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. CR values are used to calculate uptake of radionuclides by biota and are defined as the element-specific concentration ratios 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.
DEM	Digital elevation model. The DEM describes the topography and bathymetry of the modelled area. It 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.
Deterministic analysis	Analysis using single numerical values for key parameters (taken to have a probability of one), which leads to a single value for the result.
Discharge points/locations	Locations/areas where groundwater reaches the ground surface. In the safety assessment context, these terms refer to discharge of groundwater that has passed though the repository volume in the bedrock and hence could carry radionuclides to the surface.
DM	Drained-mire farmers. DM refers to a self-sustained industrial agriculture in which wetlands are drained and used for agriculture (both crop and fodder production). It is one of four land use variants considered in SR-PSU for assessment of the most exposed group.
Dose	Dose, as used in SR-PSU, 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 $\mu Gy\ h^{-1}$.
Ecolego tool	Computer software used to model radionuclide transport.
Ecosystem model	Conceptual or mathematical representation of an ecosystem, divided into compartments, and its included processes.
Effective dose	Effective dose or effective dose equivalent is a measure of dose designed to reflect the risk associated with the dose. It is 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,* which 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 and filter feeders.
GP	Garden-plot households. GP refers to a type of household that is self-sustained with respect to vegetables and root crops produced through small scale horticulture. It is one of four land use variants considered in SR-PSU for assessment of the most exposed group.
Geosphere	Those parts of the lithosphere not considered to be part of the *biosphere*. In safety assessments usually used to distinguish the subsoil and bedrock below the depth affected by normal human activities, in particular agriculture, from the soil that is part of the *biosphere*.

Term/acronym	Definition/description
Glacial cycle	Used in climate descriptions to denote a period of c. 120,000 years that includes both a glacial, e.g. the Weichselian, and an interglacial.
Heterotroph	Organism that uses organic compounds produced by autotrophs.
HG	Hunter-gatherers. HG refers to a community that uses the undisturbed surface ecosystems as living space and to obtain food. It is one of four land use variants considered in SR-PSU for assessment of the most exposed group.
Hydrodynamic model	In SR-PSU, the hydrodynamic model is the flow model of the sea part of the considered model area, and gives outputs of annual mean flows between adjacent marine basins and water retention times for each individual basin.
Hydrological model	The SR-PSU hydrological modelling includes conceptual and mathematical modelling of surface, near-surface and bedrock water flows. The SR-PSU hydrological modelling utilises GIS, as well as the MIKE SHE and DarcyTools numerical modelling tools.
IM	Interaction matrix. The IM is a tool used to ensure that all relevant processes affecting transport and accumulation of radionuclides in the biospehre are considered in the assessment.
Infilling	Infilling describes the combined process of sedimentation and organogenic deposition, which turns lakes into wetlands.
IO	Infield-outland farmers. IO refers to a self-sustained agriculture in which infield farming of crops is dependent on nutrients from wetlands for haymaking (outland). It is one of four land use variants considered in SR-PSU for assessment of the most exposed group.
K_d	Element-specific soil/liquid partition coefficient defined as the ratio between the elemental concentrations in the solid and liquid phases.
LDF	Landscape dose conversion factor. The LDF is a radionuclide-specific dose conversion factor, expressed in Sv/y per Bq/y, which represents the mean annual effective dose to a representative individual from the most exposed group, resulting from a unit constant release rate to the biosphere of a specific radionuclide. This means that the LDF relates a unit release rate to dose.
LDM	Landscape development model. The LDM is 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*.
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-PSU, the most exposed group refers to the group of individuals subjected to the highest exposure during any time period.
NEP	Net ecosystem production. NEP is the sum of gross primary production and ecosystem respiration.
NHB	Non-human biota. SR-PSU includes an assessment of the effects of potential future radionuclide releases on NHB.
NPP	Net primary production. The balance between gross primary production and plant respiration.
Probabilistic analysis	Mathematical analysis of stochastic (random) events or processes and their consequences. Since the input is described in stochastic terms, also the output is stochastic (e.g. in the form of probabilities or distributions).
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). The radionuclide model utilises the Ecolego modelling tool.
Regolith	All matter overlying the bedrock is collectively denominated regolith. This includes both minerogenic and organogenic deposits, as well as anthropogenic landfills.
RDM	Regolith depth and stratigraphy model. The RDM interpolates observation points of analysed vertical distribution of regolith into a three-dimensional model of regolith extension.
RLDM	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 output is the regolith distribution and thickness of different strata at the studied time steps.
SDM	Site descriptive model. The SDM is a multi-disciplinary description of the studied site, including both qualitative and quantitative information, which is based on both direct observations and modelling studies.
SFR	The existing final repository for short-lived radioactive waste.
SR-PSU	The safety assessment of the existing SFR facility (SFR 1) and its planned extension (SFR 3).
Sub-catchment	In the present context defined the drainage area of a biosphere object minus the drainage area of the inlets to the object.
Surface ecosystem	In the safety assessment context, surface ecosystem refers to the part of the analysed system that is above the bedrock, with all its abiotic and biotic processes and features.
Terrestrialisation	The transfer of an aquatic ecosystem (marine or limnic) to a terrestrial ecosystem.
Watershed	In the present context defined as the drainage area of a biosphere object.

Appendix 3

Description of methods used to generate future landscapes

Variant 2 represents a development in which all areas that can be cultivated are used as arable land, (Section 5.4.3) and was therefore modelled at a more detailed temporal resolution than the other four variants. The potential landscape development is presented as 41 snapshots between 8500 BC and 40,000 AD. The Forsmark area was completely covered by the Baltic Sea from 8500 BC to 2000 BC and this period is only shown for two time steps in the resulting animation described later. For the following period, the landscape development for variant 2 was produced in 500-year time steps from 1500 BC to 15,000 AD and in 5,000-year time steps from 15,000 AD to 40,000 AD.

The landscape development for variants 1 and 3 was produced for four time steps: 2000, 3000, 5000 and 20,000 AD. Variant 4 was illustrated with one snapshot at 20,000 AD, which was in accordance with the expected timing of a potential permafrost period in the *early periglacial climate case*. Landscape development for the extended global warming (variant 5) was illustrated by the time steps 3000, 5000 and 20,000 AD. The landscape development for variants 1, 2, 3 and 5 was produced using data from the RLDM for the *global warming climate case* and for variant 4 using data from the RLDM for the *early periglacial climate case* (Brydsten and Strömgren 2013).

All GIS-calculations were carried out using ArcGIS 9.3. Most of the data were produced in ESRI raster format using cell size of a 20 metres. The geographical properties necessary for the modelling of the landscape development variants are described in Chapter 5. Nine different types of data were necessary for the first step of the modelling (Table A3-1). The calculations were performed using "Map Algebra" in the "Spatial Analyst" extension and the "Spatial Analyst Tools" in "Arc Toolbox". For these calculations, the cells representing different data in the raster layers were assigned unique numeric codes (Table A3-1).

Data from the RLDM were used to produce raster layers representing the landscape from 1500 BC to 10,500 AD for the *global warming climate case* (Brydsten and Strömgren 2013). All regolith for each time step were added on the bedrock surface and a DEM was calculated for each time step. The ArcGIS Hydrological model was used to fill local depressions with regolith to the levels of the thresholds. All cells below 0 m were calculated as sea and consequently the remaining cells as land. From the raster layers representing land, new layers were produced showing 20 m cells situated one metre or more above sea level.

The raster layer referring to till was produced from the RLDM (Brydsten and Strömgren 2013) for the time step 8500 BC and was originally produced by the use of site data when modelling regolith depth and stratigraphy (RDM) (Sohlenius et al. 2013b). Glaciofluvial deposits and artificial fill from the RLDM were added to the raster layer referring to till, since these deposits are assumed to have similar properties to till in the landscape modelling (hereafter these deposits are called "till and similar deposits").

Table A3-1. Different types of data and the codes for denoting different categories within maps used in the Map Algebra calculations of the landscape development.

Description of data used in the calculations (numeric codes within parentheses)	Reference
Land area (1000000) and other areas (0)	(Brydsten and Strömgren 2013)
Land area 1 m above sea level (500000) and other areas (0)	(Brydsten and Strömgren 2013)
Arable land (100000) and other areas (0)	(Brydsten and Strömgren 2013)
Non-arable land (1), (10) and other areas (0)	(Brydsten and Strömgren 2013)
Till and similar deposits (10) and other areas (0)	(Sohlenius et al. 2013b)
Bedrock outcrops (1) and other areas (0)	(Brydsten and Strömgren 2013)
Wetlands (4000) and other areas (0)	(Brydsten and Strömgren 2013)
Lake development (wetland within original extension of lake (400), lake (500), and other areas (0))	(Brydsten and Strömgren 2013)
Infilled former lakes (50000) and lakes (0)	(Brydsten and Strömgren 2013)

Raster layers referring to bedrock outcrops were calculated for every time step to 6500 AD using the RLDM (Brydsten and Strömgren 2013). For every time step all raster layers referring to regolith were added on the bedrock surface, resulting in a DEM. The bedrock surfaces were subtracted from the DEMs and all 20 m cells with a value equal to zero were defined as outcrops. After 6500 AD the distribution of outcrops does not change.

Raster layers referring to arable land were calculated for all time steps. Raster layers referring to marine and lacustrine postglacial deposits were added for every time step until 7000 AD, after which time no deposition or erosion occurs. These layers represent clay gyttja and were multiplied using a compaction factor of 0.25 (Grolander 2013). Wetlands (i.e. peat) from the RLDM (Brydsten and Strömgren 2013) were added for every time step and multiplied using a compaction factor of 0.34 (Grolander 2013). The raster layers for the compacted deposits were added to layers from the RLDM representing glacial clay. Areas where the total thickness of glacial clay and compacted clay gyttja and peat is 0.5 m or more were modelled as arable land. From 7000 AD, the same raster layer was used for glacial clay since no more erosion or accumulation occurs. A raster layer referring to clayey till with a low frequency of boulders (from Hedenström and Sohlenius 2008) was added to the raster layers referring to arable land. The raster layers referring to non-arable land were classified either using the numeric code for till or the code for bedrock outcrops.

Wetlands and data showing succession of lakes used in the landscape development modelling were produced in the RLDM. The *early periglacial climate case* is characterised by lower rates of succession compared with the other cases (Brydsten and Strömgren 2013). All present lakes not modelled in the RLDM are small and shallow and consequently are assumed to be instantaneously filled with regolith already at 2000 AD. The calculation of peat accumulation in these lakes is described in Brydsten and Strömgren (2013).

The nine raster layers described in Table A3-1 were used to model different types of ecosystems. For that, "Single Output Map Algebra" in "Model Builder" was used for all time steps. For some ecosystems, the same raster layers were used for all time steps, whereas for other ecosystems new raster layers were used for almost every time step (see Table A3-2). New raster layers had to be used since the terrestrial area and distribution of lakes and wetlands are changing through time. The modelling procedure is exemplified in Figure A3-1 for the time step 2500 AD. Raster layers referring to lakes were not used in the first time steps, since no lakes had developed at that time.

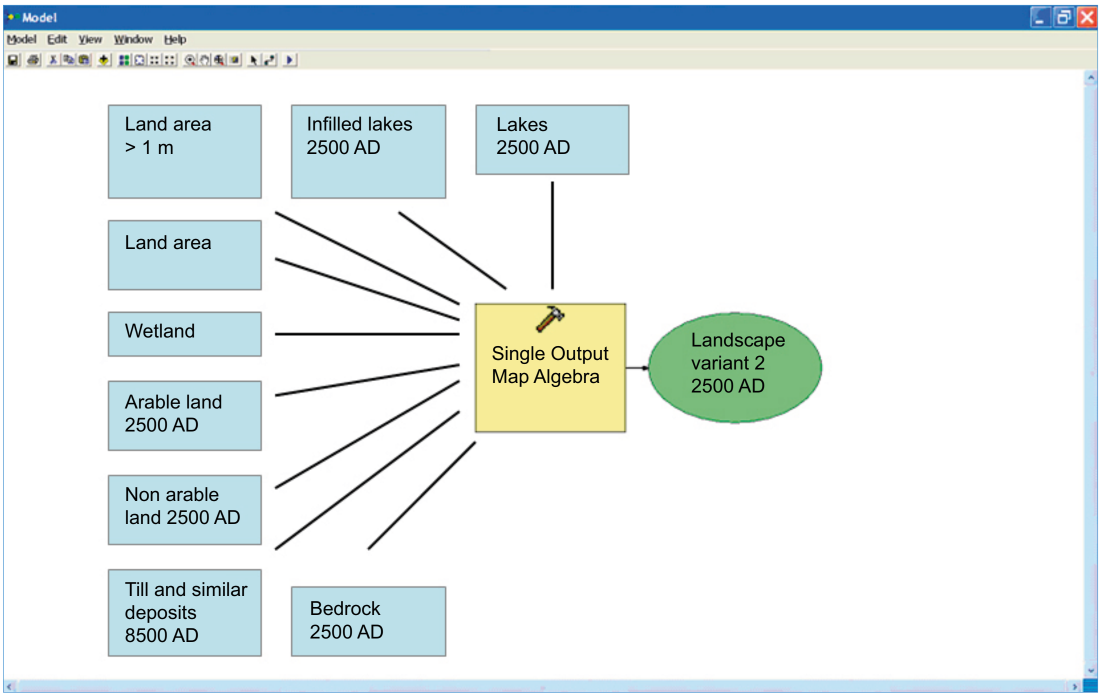


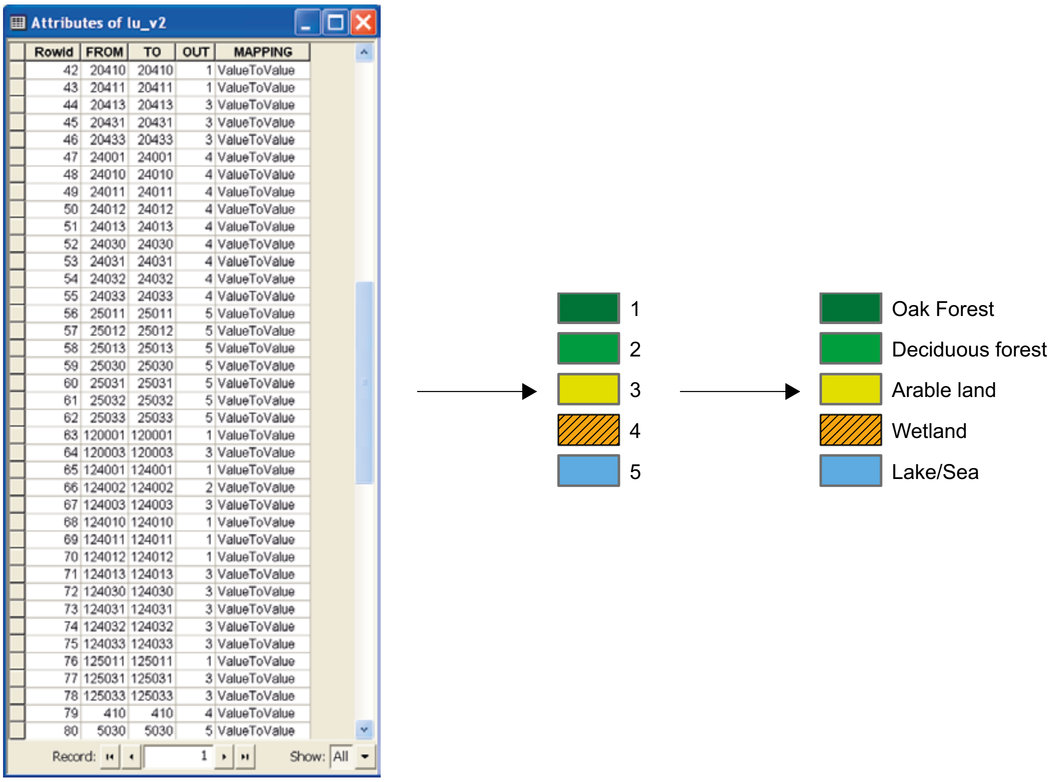
Figure A3-1. *Schematic illustration of the addition of nine raster layers used in the landscape development (variant 2) for the time step 2500 AD using "Single Output Map Algebra" in "Model Builder".*

Input data to the landscape modelling for all time steps are summarised in Table A3-2. The Forsmark area was completely covered by the Baltic Sea before 1500 BC and therefore no information is shown in Table A3-2 for times earlier than 1500 BC. However, this period is shown for two time steps in the resulting animation described later, using different raster layers for the sea for the two time steps.

Raster layers with, in total, 116 unique numeric codes were produced in the "Map Algebra" calculations. These unique numeric codes were used for ecosystem classification in variant 2. The numeric codes were reclassified to five ecosystem types using a reclassification table and the "Spatial Analyst Tools". In Figure A3-2, the procedure for the reclassification and the resulting legend are illustrated.

Table A3-2. Data used in the Map Algebra calculations of the landscape development (variant 2) from –1500 AD to 40,000 AD. For some ecosystems the same raster layer was used for all time steps or from a certain time step and onwards (O), for other ecosystems new raster layers were used for every time step (X).

Time step (year AD)	Land area > 1 m	Land area	Arable land	Non arable land	Till and similar deposits	Bedrock outcrops	Wetlands	Lake succession	Former lakes
–1500	X	X	X	X	O	X	O		
–1000	X	X	X	X	O	X	O		
–500	X	X	X	X	O	X	O		
0	X	X	X	X	O	X	O		
500	X	X	X	X	O	X	O		
1000	X	X	X	X	O	X	O		
1500	X	X	X	X	O	X	O	X	
2000	X	X	X	X	O	X	O	X	
2500	X	X	X	X	O	X	O	X	
3000	X	X	X	X	O	X	O	X	X
3500	X	X	X	X	O	X	O	X	X
4000	X	X	X	X	O	X	O	X	X
4500	X	X	X	X	O	X	O	X	X
5000	X	X	X	X	O	X	O	X	X
5500	X	X	X	X	O	X	O	X	X
6000	X	X	X	X	O	X	O	X	X
6500	X	X	X	X	O	X	O	X	X
7000	X	X	X	X	O	O	O	X	X
7500	X	X	X	X	O	O	O	X	X
8000	X	X	X	X	O	O	O	X	X
8500	X	X	X	X	O	O	O	X	X
9000	X	X	X	X	O	O	O	X	X
9500	X	X	X	X	O	O	O	X	X
10,000	X	X	X	X	O	O	O	X	X
10,500	X	X	X	X	O	O	O	X	X
11,000	X	O	X	X	O	O	O	X	X
11,500	O	O	X	X	O	O	O	X	X
12,000	O	O	X	X	O	O	O	X	X
12,500	O	O	X	X	O	O	O	X	X
13,000	O	O	X	X	O	O	O	X	X
13,500	O	O	X	X	O	O	O	X	X
14,000	O	O	X	X	O	O	O	X	X
14,500	O	O	X	X	O	O	O	X	X
15,000	O	O	X	X	O	O	O	X	X
20,000	O	O	X	X	O	O	O	X	X
25,000	O	O	X	X	O	O	O	X	X
30,000	O	O	X	X	O	O	O	X	X
35,000	O	O	X	X	O	O	O	X	X
40,000	O	O	X	X	O	O	O	X	X



Attributes of lu_v2

Rowid	FROM	TO	OUT	MAPPING
42	20410	20410	1	ValueToValue
43	20411	20411	1	ValueToValue
44	20413	20413	3	ValueToValue
45	20431	20431	3	ValueToValue
46	20433	20433	3	ValueToValue
47	24001	24001	4	ValueToValue
48	24010	24010	4	ValueToValue
49	24011	24011	4	ValueToValue
50	24012	24012	4	ValueToValue
51	24013	24013	4	ValueToValue
52	24030	24030	4	ValueToValue
53	24031	24031	4	ValueToValue
54	24032	24032	4	ValueToValue
55	24033	24033	4	ValueToValue
56	25011	25011	5	ValueToValue
57	25012	25012	5	ValueToValue
58	25013	25013	5	ValueToValue
59	25030	25030	5	ValueToValue
60	25031	25031	5	ValueToValue
61	25032	25032	5	ValueToValue
62	25033	25033	5	ValueToValue
63	120001	120001	1	ValueToValue
64	120003	120003	3	ValueToValue
65	124001	124001	1	ValueToValue
66	124002	124002	2	ValueToValue
67	124003	124003	3	ValueToValue
68	124010	124010	1	ValueToValue
69	124011	124011	1	ValueToValue
70	124012	124012	1	ValueToValue
71	124013	124013	3	ValueToValue
72	124030	124030	3	ValueToValue
73	124031	124031	3	ValueToValue
74	124032	124032	3	ValueToValue
75	124033	124033	3	ValueToValue
76	125011	125011	1	ValueToValue
77	125031	125031	3	ValueToValue
78	125033	125033	3	ValueToValue
79	410	410	4	ValueToValue
80	5030	5030	5	ValueToValue

Record: 1 Show: All

Figure A3-2. *Schematic illustration of the reclassification procedure of a raster layer with unique numeric codes (fields "FROM" and "TO") to the five ecosystems used in variant 2 (field "OUT").*

In the next step of the landscape modelling procedure (variant 2), raster surfaces produced in the "Map Algebra" calculations were recalculated according to the following criteria:

- Surfaces with arable land, pine forest on bedrock and wetland less than 2,400 m^2 become mixed coniferous forest.
- Wetland outside lake extensions bordering arable land becomes mixed coniferous forest.

From 3000 AD when the first lakes are filled with peat, and onwards, a model processed in 43 steps constructed in "Model Builder" was used for these calculations. A model processed in 28 steps was constructed and used for the time steps before 3000 AD when no lakes were filled with regolith. After these models were run only small manual corrections (a few 20 m cells) were necessary to fulfil the rules set above.

For the modelling of variant 1 (a land use similar to the present), the raster layers produced for variant 2 for the time steps 2000, 3000, 5000, and 20,000 AD were used. Variant 1 differs from variant 2 in that only regolith suitable for cultivation having an area of more than 10,000 m^2 (1 ha) is used as arable land. Furthermore, peat is not used as arable land and the former lakes are consequently not cultivated. A model processed in 28 step constructed in "Model Builder" was used for these calculations. After the model was run only small manual corrections (a few 20 m cells) were necessary to fulfil the criteria for variant 1.

Raster layers produced for variant 1 were used for the modelling of variant 5 (a land use similar to the present for the *extended global warming climate case*). Since other forest types are assumed in this variant, a reclassification was done (Figure A3-3).

In variant 5 no shoreline displacement is assumed between 2000 and 3000 AD due to rising global sea level. The shoreline displacement is thereafter assumed to continue at the same rate as for the *global warming climate case* (which means that shoreline displacement is delayed by 1,000 years compared to the *global warming climate case*). In the climate modelling, this delay has been estimated to c. 1,200 years (**Climate Report**), but due to the temporal resolution of 500-year steps in the landscape modelling the delay was approximated to occur during two time steps.

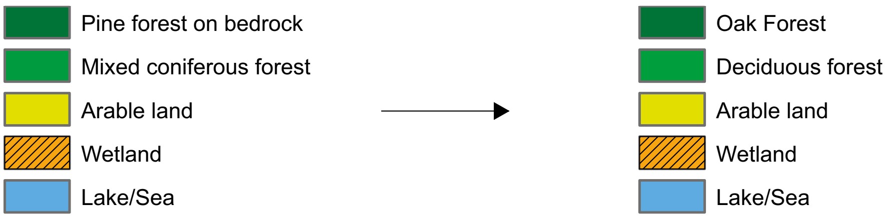


Figure A3-3. *Schematic illustration showing how the ecosystem classification in variant 1 was transformed to the one used in variant 5.*

The raster layer for 2000 AD for variant 1 was therefore assumed to correspond to 3000 AD for variant 5. Accordingly, the raster layer for 4000 AD in variant 1 corresponds to 5000 AD in variant 5. After 10,500 AD no sea exists in the area and the distribution between land and water in variant 5 is consequently not different from the other variants.

However, the lake development for the raster layers used in variant 1 could not be used for all time steps in variant 5 since the succession of lakes continues even though the shoreline displacement is delayed. For lakes present at 2000 AD the same lake development could be used. Thereafter, the lake development is delayed 1,000 years in variant 5 due to the delay in shoreline displacement. Also for 20,000 AD the lake development should be delayed by 1,000 years in variant 5, but since lake development was only modelled for 15,000 and 20,000 AD we chose to use the lake development for 20,000 AD from variant 1 instead.

In the modelling of variant 3 (development unaffected by humans), the raster layers produced for variant 2 for the time steps 2000, 3000, 5000, and 20,000 AD were used again. Variant 3 differs from variant 2 in that no arable land exists and no wetlands are ditched. The succession of wetlands and lakes is therefore only affected by natural processes. The wetlands outside the lake extensions and data from lakes used for variant 2 were added to these raster layers once more and a reclassification was performed according to the criteria for variant 3 (Table A3-3). In the animation showing the permafrost landscape (variant 4) the raster layers from variant 3 were reclassified to variant 4 using the reclassification shown in Figure A3-4.

The raster layers referring to the five different landscape developments (variants 1–5) were used to produce maps for animations. In these animations, other GIS-data were added (e. g. the present shoreline). These GIS-data and the adjustments made for these animations are saved in ArcGis-projects. The ArcGis projects and a short description of the data used are stored in the SR-PSU data storage (https://svn.skb.se/trac/projekt/browser/SFR/SR-PSU/Landscape), and can be made available upon request.

Table A3-3. Data used in the "Map Algebra" calculations for variant 3. For some data the same data was used for all time steps (O), for other data new raster layers were used for every time step (X).

Time step (Year AD)	Landscape development variant 2	Wetland outside lake extension	Former lakes	Reclassification table
2000	X	O	X	O
3000	X	O	X	O
5000	X	O	X	O
20,000	X	O	X	O

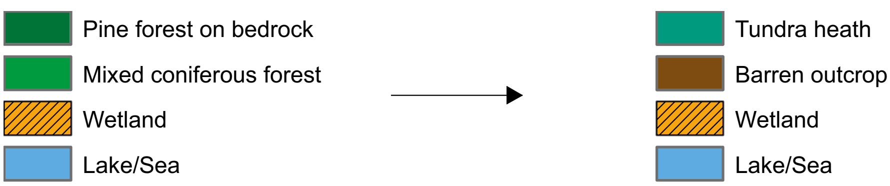


Figure A3-4. *Schematic illustration showing how the ecosystem classification in variant 3 was transformed to the one used in variant 4.*

Appendix 4

LDF data used in comparisons with earlier assessments

Table A4-1 shows the LDFs calculated within the SR-PSU biosphere assessment (see Chapter 10), and the corresponding LDFs from the earlier SAR-08 and SR-Site safety assessments. The comparison between SR-PSU and earlier LDF values is illustrated in Figure 10-1.

Table A4-1. LDFs for radionuclides that were previously analysed in the SAR-08 or SR-Site safety assessment and in the present safety assessment. Note that SR-PSU LDFs were calculated to match those of the previous safety assessments, either as a mean values from probabilistic simulations (SAR-08, Bergström et al. 2008) or from best estimates of parameter values (SR-Site, Avila). For the comparison the maximum from the ecosystem and the well (weighted by p_{well} = 0.1, SKB 2008b) LDFs were used for SAR-08, and the LDF for the interglacial period for SR-Site. For further details and a discussion of the comparison, see Section 10.4.

Radionuclide	Probabilistic		Best estimate	
	SR-PSU	SAR-08	SR-PSU	SR-Site
Ac-227	1.0E–11		1.0E–11	8.0E–12
Ag-108m	7.6E–14	1.0E–12	5.4E–14	7.1E–13
Am-241	1.7E–12	1.3E–11	1.7E–12	1.5E–12
Am-243	3.8E–12	6.1E–12	2.0E–12	1.5E–12
C-14	2.8E–14	1.7E–13	7.9E–15	5.4E–12
Ca-41	1.6E–12		6.2E–14	9.9E–14
Cl-36	3.4E–12	1.5E–12	7.5E–13	5.8E–13
Cm-244	1.0E–12		1.0E–12	8.7E–13
Cm-245	4.0E–12		2.2E–12	1.6E–12
Cm-246	3.0E–12		2.0E–12	1.6E–12
Cs-135	1.7E–12	5.8E–11	2.0E–13	4.0E–14
Ho-166m	2.3E–14	3.0E–13	2.1E–14	5.9E–14
I-129	3.6E–11	1.7E–11	8.0E–12	6.5E–10
Mo-93	1.5E–11	4.5E–13	5.5E–12	
Nb-94	6.7E–14	6.4E–13	3.8E–14	4.0E–12
Ni-59	8.4E–14	2.3E–14	2.9E–14	7.4E–14
Np-237	2.6E–12	3.0E–11	1.3E–12	4.8E–11
Pa-231	2.2E–11		8.4E–12	8.1E–12
Pb-210	6.2E–12		6.0E–12	5.1E–12
Pd-107	5.8E–14		1.9E–14	6.7E–15
Po-210	1.0E–11		1.0E–11	8.9E–12
Pu-239	1.1E–11	1.6E–11	2.7E–12	1.9E–12
Pu-240	5.9E–12	1.6E–11	2.4E–12	1.9E–12
Pu-242	1.3E–11	4.1E–12	2.8E–12	1.9E–12
Ra-226	1.4E–11		4.3E–12	3.8E–12
Se-79	7.9E–13	7.5E–12	3.0E–13	1.2E–09
Sm-151	8.5E–16		8.5E–16	7.2E–16
Sn-126	3.4E–13	2.5E–12	2.0E–13	2.5E–11
Tc-99	3.8E–13	5.1E–14	1.7E–13	9.0E–13
Th-229	9.1E–12		5.9E–12	3.6E–12
Th-230	5.1E–12		2.4E–12	1.3E–11
Th-232	6.0E–12		2.6E–12	1.7E–12
U-233	2.3E–11		5.9E–12	2.5E–12
U-234	2.2E–11		5.7E–12	3.6E–12
U-235	2.2E–11		5.7E–12	2.8E–12
U-236	2.2E–11		5.5E–12	1.9E–12
U-238	2.2E–11		5.4E–12	1.9E–12
Zr-93	5.2E–13	6.9E–14	1.8E–13	2.8E–14