R-14-02

Handling of biosphere FEPs and recommendations for model development in SR-PSU

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November 2015

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ISSN 1402-3091
SKB R-14-02
ID 1459251

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Keywords: FEP, Exposure pathway, Irrigation, Peat and wood combustion, Draining, Forms of carbon, CH_4, CO_2, Sensitivity of water fluxes, Model calibration, C-12, C-14.

Abstract

This report is a background report of the long-term safety assessment SR-PSU of SFR. It describes the handling of biosphere Features, Events and Processes (FEPs) in the assessment, an updated exposure pathway analysis and studies of specific topics related to the radionuclide transport modelling of the biosphere. The identified issues have been explored either by developing the conceptual understanding using information in the literature or by alternative modelling and reccomendations for handling of the different topics in the safety assessment SR-PSu has been given.

The systematic presentation of SR-PSU biosphere FEPs provides a roadmap to how and where they are handled in the modelling. In the biosphere interaction matrix (presented in SKB 2013), 10 physical components, 6 variables and 45 processes are identified as important for a safety assessment for a repository at Forsmark. These are shortly described providing information on how they have been included in the modelling of the biosphere in the present safety assessment SR-PSU.

The aim of the exposure pathway analysis is to identify a set of potentially relevant exposure pathways for humans and non-humna biota, as a prerequisite of the long-term safety assessment of SFR. This is done by systematically identifying and excluding pathways that are not significant for long-term safety based on the characteristics and habits of future inhabitants, as well as the characteristics of the area potentially receiving radionuclides from the repository. The exposure pathways are then related to a set of most exposed groups identified based on potential land use variants and assumptions on future societies.

Irrigation of food items with water containing radionuclides originating from the repository is a potential exposure pathway. In Sweden today, irrigation is not very common. Nevertheless, in this report, different options are discussed for the irrigation of drained peat land and a garden plot and it is concluded that watering of drained peat land with an embanking system is more convenient than a technology based on sprinkler irrigation. Moreover, calculaitons are provided on potential amounts of water that could be needed to sustain and maximize plant growth in e.g. a garden plot irrigated with water.

The combustion of peat and/or wood containing radionuclides originating from the repository may be an exposure pathway. Combustion by a power plant and a household are discussed. The maximum dose rates for the peat-fueled power plant were at most 25% of the maximum dose rates in the case of the peat and wood combusting household. Therefore, it is recommended that peat and wood combustion by a household is included as an exposure pathway in the evaluation of human exposure in the safety assessment.

Wetlands are a sink for carbon and other elements because of the continuous accumulation of peat. They can therefore potentially also accumulate radionuclides originating from the repository. A close examination of the transformation of wetland to agricultural land by draining is presented to underpin assumptions in the radionuclide transport modelling performed for the assessment.

Advective water fluxes are the main driver for radionuclide transport in the ecosystems considered in SR-PSU. The sensitivity of water fluxes obtained from hydrological modelling with respect to the discretization and parametrisation of stratigraphic features is explored by comparing alternative modelling. The comparison shows that the the variation of the thickness of layers in the hydrological model may have a minor impact than changing their conductive properties (sandy soil versus clay). Various differences were also found comparing different delineations of biosphere object 157_2.

In order to study the performance of the radionuclide transport model for the biosphere, and to be able to calibrate that model, it was applied to simulate transport of stable carbon (C-12). The model results were compared with empirical estimates. The comparison was done for an existing lake (Lake Fiskarfjärden) and a future lake of importance for the SR-PSU assessment (biosphere object 157_1 which was populated with data from areal measures form comparable systems today). In general, the agreement between model results and empirical estimates was good. One parameter that describes the exchange of carbon over the water/atmosphere interface in the mire (the piston velocity) could be adjusted to better fit the measured concentrations of dissolved carbon in the surficial peat layer.

Overall, this iterative work of exploring assumptions and their implications in the radionuclide modelling has, helped to better understand the degree of caution in the assumptions underpinning the assessment and by clarifying and documenting the assessment procedure.

Contents

1 Introduction

This report, which relates to the latest safety assessment for the SFR facility, describes the handling of identified biosphere Features, Events and Processes (FEPs) in such an assessment, provides an updated exposure pathway analysis, and gives an underpinning to assumptions in the radionuclide model. A number of FEPs in the biosphere have been identified and described in SKB (2013). These are important for processes such as the development of surface ecosystems, for transport and accumulation of radionuclides in those surface ecosystems, and for exposure of humans and biota. The list of important FEPs in SKB (2013) was produced particularly in relation to a geological repository for spent nuclear fuel at the Forsmark site, but has also been regarded as complete for the biosphere part of the safety assessment for the SFR repository. This report contains a structured description of how the identified important biosphere FEPs are handled specifically in the SR-PSU assessment. The aim of the report is also to describe a number of issues (uncertainties) that were investigated during the project to facilitate and support model development.

When conducting the safety assessments SAR08 (SKB 2008b), SR-Site (SKB 2011), and the present SR-PSU, various issues requiring specific consideration have been identified during the work and by feedback from external reviews. These issues have been further explored either by developing the conceptual understanding using information in the literature or by alternative modelling. The developmental work in this report includes reviewing assumptions and their implementation in the radionuclide model in order to understand the degree of conservatism implied. Furthermore, the different safety assessments have different source terms, e.g. spent nuclear fuel and low-level waste, which introduces different sets of radionuclides and concentrations of radionuclides in the modelled releases and thereby requires adjustments in the radionuclide modelling. For example, C-14 is a key radionuclide in the SR-PSU assessment and there was a need for a review of the handling of C-14 in the radionuclide transport model to make sure that it was appropriate for use in SR-PSU.

Overall this iterative work of exploring assumptions and their implications in the radionuclide modelling has in some cases resulted in changes in the radionuclide model, whereas in other cases change has not been considered necessary. This report presents both conceptual developments and alternative modelling approaches. Issues closely related to ecosystem functioning are presented and discussed in this report, whereas other issues are presented in the dedicated reports on hydrology and landscape modelling (e.g. Werner et al. 2013a, b, Brydsten and Strömgren 2013) or in the Biosphere synthesis report (SKB 2014a).

Thus, the major aims of this report are the following.

- Provide a roadmap as to where in the SR-PSU Biosphere assessment the FEPs have been handled and document systematically how this has been done. The intention of the documentation on how the FEPs has been handled is to give a brief overview and not to provide details, this is dealt with in other reports (e.g. Saetre et al. 2013, Werner et al. 2013, Brydsten and Strömgren 2013).
- Provide an exposure pathway analysis and show how the exposure pathways can be mapped to the most exposed groups of humans.
- Underpin assumptions made in the development of the modelling of the biosphere.
- Report results from alternative modelling approaches to investigate issues related to uncertainties in radionuclide transport modelling.

1.1 Background

The final repository for short-lived radioactive waste (SFR) is used for the final disposal of low- and intermediate-level operational waste from Swedish nuclear facilities. SFR is located in Forsmark in northern Uppland in the immediate vicinity of the Forsmark nuclear power plants (Figure 1-1). SKB plans to extend SFR to host waste from the decommissioning of the nuclear power plants and other nuclear facilities. Additional disposal capacity is needed also for operational waste from the nuclear power units that are in operation, since their operational life-times have been extended compared with what was originally planned.

The SFR repository includes waste vaults underground together with buildings above ground that include a number of technical installations. The existing facility (SFR 1) comprises five waste vaults with a disposal capacity of approximately 63,000 m^3. The extension (SFR 3[1]) will have a disposal capacity of 108,000 m^3 in five new waste vaults plus one new vault for nine boiling water reactor pressure vessels, see Figure 1-2. The waste vaults of SFR 1 are covered by about 60 metres of granitoid rock, c 3–7 metres of regolith and c 3–4 metres of seawater (Sohlenius et al. 2013). The planned extension SFR 3 will function in the same way as the existing repository, but the rock vaults will be situated at c 120 metres depth. Forsmark is situated in an area with post-glacial uplift and shoreline displacement, and with time (some 1,000 years from now) the sea will have withdrawn from the site.

As a part of the license application for the extension of SFR, the Swedish Nuclear Fuel and Waste Management Company (SKB) has undertaken 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.

This report originates from the sub-project of SR-PSU for the assessment of the biosphere system, called SR-PSU Biosphere. The purpose of the project SR-PSU Biosphere is to assess radiological consequences to humans and the environment from potential radionuclide releases from SFR for time spans of up to 100,000 years after closure contributing to the demonstration of compliance of the repository system with regulatory requirements. A major task in this assessment is the treatment of the inherent uncertainties associated with the prediction of future development of the site and of exposure pathways over this time frame.

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

1. Identification of features, events, and processes (FEPs) 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 of 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). Thus, 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.

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[1] The extension is called SFR 3 since the name SFR 2 was used in a previous plan in which it was proposed to build vaults adjacent to SFR 1 for disposal of reactor core components and internal parts. The current plan is to dispose of this waste in a separate repository.

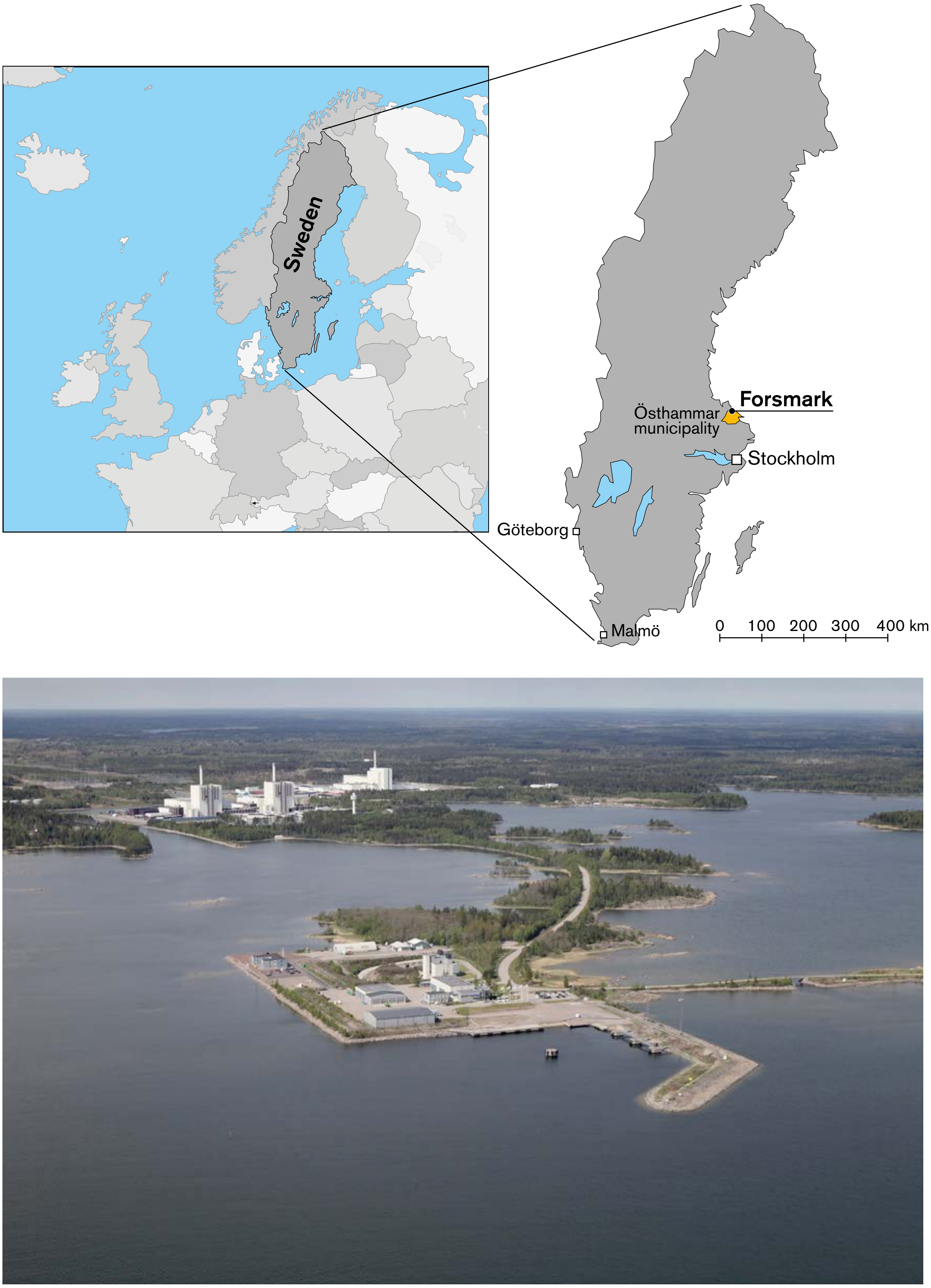

***Figure 1-1.** Location of Forsmark and the surface part of the SFR facility in the Forsmark harbour.*

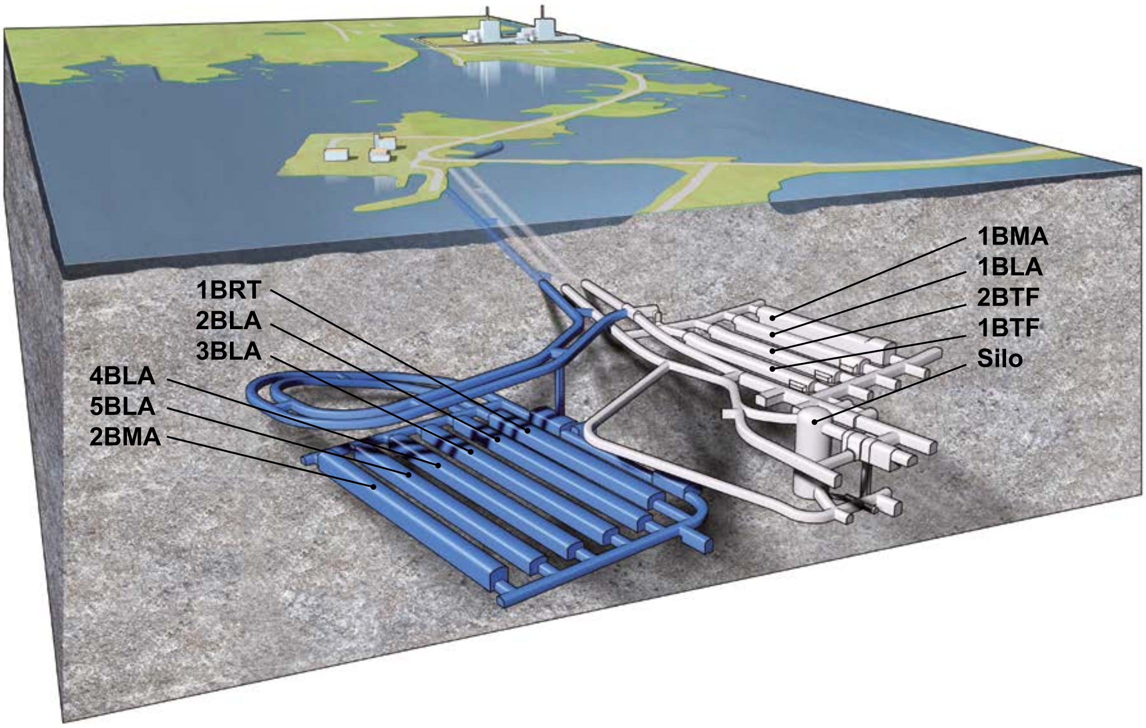

Figure 1-2. *A schematic illustration of SFR. The grey part is the existing repository (SFR 1) and the blue part is the planned extension (SFR 3). The waste vaults in the figure are the silo for intermediate-level waste, 1–2BMA vaults for intermediate-level waste, 1–2BTF vaults for concrete tanks, 1–5BLA vaults for low-level waste and the 1BRT vault for reactor pressure vessels.*

1.2 Report hierarchy in SR-PSU

SR-PSU is reported in a series of SKB reports, which includes a main report, here referred to as SR-PSU Main report (SKB 2014b), and a set of primary references. These include, among others, the reports denoted as Climate report (SKB 2014c), Radionuclide transport report (SKB 2014d), FEP report (SKB 2014e), FHA report (SKB 2014f) and Biosphere synthesis report (SKB 2014 a) in the SR-PSU reporting. In addition to these primary references, the safety assessment is based on a large number of background reports and other references. The present report is a background report to the Biosphere synthesis report (SKB 2014a) and the FEP report (SKB 2014e). A schematic illustration of the safety assessment documents is shown in Figure 1-3.

Major relationships between the background biosphere reports and the primary references are shown in Figure 1-4. However, although not shown in the figure, the present report on important processes is related to all of the other background reports on the biosphere. Table 1-1 presents the background reports produced within SR-PSU Biosphere. For the background reports, conventional references are used in the text (e.g. "Strömgren and Brydsten (2013)" for the DEM report).

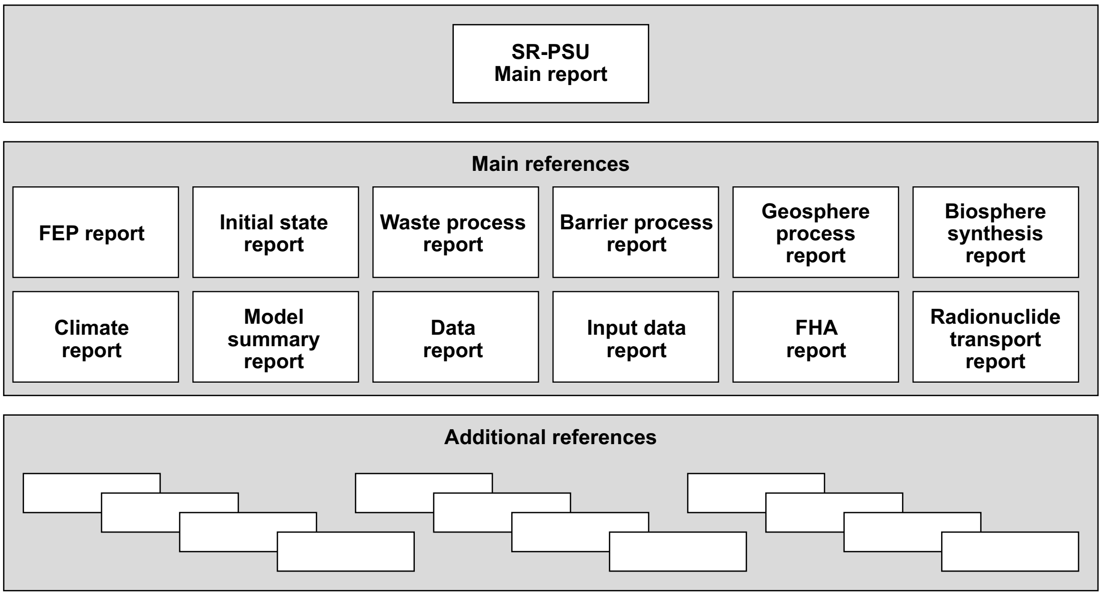

Figure 1-3. *The hierarchy of the SR-PSU Main report (SKB 2014b), Main references and additional references underpinning the SR-PSU long-term safety assessment. The additional references either support the Main report or any of the Main references. The present report belong to the additional references that is a background report to the Biosphere synthesis report (SKB 2014a), but also provides information to the FEP report (SKB 2014e).*

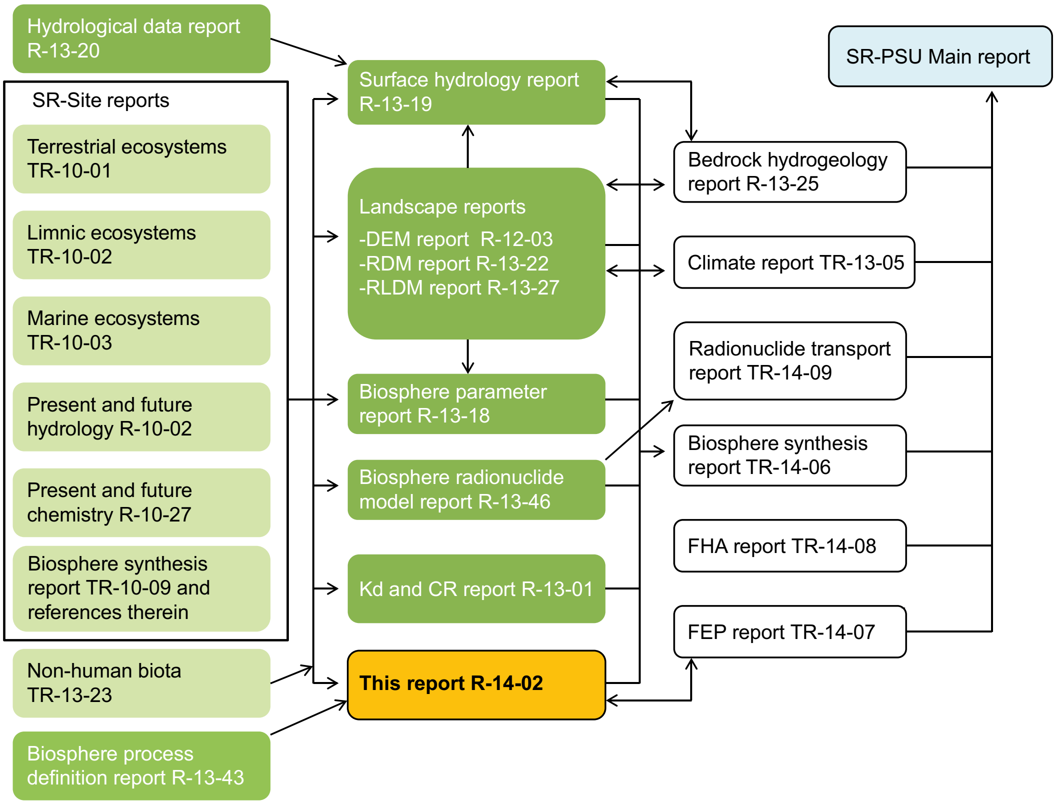

Figure 1-4. *Major relationship between reports produced in the SR-PSU Biosphere project (dark green boxes). The present report is marked in orange and bold. Supporting documents produced within other biosphere projects at SKB are marked in light green, whereas other reports in the SR-PSU project are shown in white except for the SR-PSU Main report (SKB 2014b), which is shown in blue. Please not that interdependencies exist between most biosphere and although only the relations to the FEP report and Biosphere synthesis report are visible in the figure, the present report is related to all of the other background reports of the biosphere; e.g. the present report is a major input to the radionuclide model report R-13-46.*

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

Report number	Full title
R-12-03	Digital elevation model (DEM) of Forsmark. SR-PSU Biosphere.
R-13-01	K_d and CR used for transport calculations in the biosphere in SR-PSU.
R-13-18	Biosphere parameters used in radionuclide transport modelling and dose calculations in SR-PSU.
R-13-19	Hydrology and near-surface hydrogeology at Forsmark – synthesis for the SR-PSU project. SR-PSU Biosphere.
R-13-20	Meteorological, hydrological and hydrogeological monitoring data from Forsmark – compilation and analysis for the SR-PSU project. SR-PSU Biosphere.
R-13-22	Depth and stratigraphy of regolith at Forsmark. SR-PSU Biosphere.
R-13-27	Landscape development in the Forsmark area from the past into the future (8500 BC – 40,000 AD).
R-13-43	Components, features, processes and interactions in the SR-PSU biosphere modelling.
R-13-46	The biosphere model for radionuclide transport and dose assessment in SR-PSU.
R-14-02	Handling of biosphere FEPs and recommendations for model development in SR-PSU. The present report.

1.3 This report

1.3.1 Content and structure of this report

This report covers the handling of identified FEPs in SR-PSU, an exposure pathway analysis, and description of assumption and uncertainties in the radionuclide transport model used for the biosphere.

As stated in the background to the report, large amounts of site-specific information have been collected in order to describe transport and accumulation of elements in the biosphere at the site (e.g. Site descriptive model, Lindborg 2008) and information from the present and previous safety assessments (SAR08 and SR-Site) has been used to identify topics that need to be evaluated for their relevance in a safety case. Issues closely related to ecosystem functioning are presented and discussed in this report, whereas others are presented in the dedicated reports on hydrology and landscape modelling (e.g. Werner et al. 2013, Strömgren and Brydsten 2013) or radionuclide transport (e.g. the modified atmosphere models described in Saetre et al. 2013b). The identified issues are related to three major areas of model development: 1) exposure pathways, 2) land-use, and 3) model calibration and sensitivity analyses (Table 1-2).

The outline of the report is set out below.

Chapter 1: This chapter gives a background and describes the context of the report.

Chapter 2: This chapter summarises the handling of biosphere FEPs in the safety assessment SR-PSU.

Chapter 3: This chapter reports on the exposure pathway analysis performed for SR-PSU in which exposure pathways for humans were identified and mapped to one of the land-use variants that have been identified as bounding cases to assess doses to most exposed humans.

Chapter 4: This chapter includes a review of irrigation practice in Sweden today as well as a discussion of its potential application in the Forsmark area based on the historical use.

Chapter 5: This chapter describes implications for exposure to radiation from peat and wood combustion using peat and wood that contain radionuclides.

Chapter 6: This chapter is a review of factors important for describing the utilisation of mires for agricultural purposes, the process of draining such mires and how they develop over time.

Chapter 7: This chapter describes sensitivity simulations of water fluxes that were made with the purpose of studying the effects of the horizontal and vertical model discretization, i.e. the model layer thicknesses and the lateral extent of the modelled object.

Chapter 8: This chapter describes how the radionuclide transport model used for modelling transport and accumulation of radionuclides in the biosphere was calibrated using stable carbon (C-12).

Chapter 9: This chapter comprises a summary of the report.

Table 1-2. Issues addressed in this report as related to four major areas of development, the biosphere modelling context and the ecosystems to which the issues relate.

Area of development	Issue	Biosphere model	Ecosystem	Chapter in this report
Exposure pathways	Exposure pathway analysis	Dose calculations	All ecosystems	3
Land-use	Irrigation of agricultural land	Radionuclide transport model	Terrestrial	4
	Peat and wood combustion	Dose calculations	Terrestrial	5
	Draining of wetland to form agricultural land	Radionuclide transport model	Terrestrial	6
Model calibration and sensitivity analysis	Regolith discretisation and area delineation	Hydrological modelling, Radionuclide transport model	Aquatic, Terrestrial	7
	Model calibration with C-12	Radionuclide transport model	Aquatic, Terrestrial	8

1.3.2 Participating experts

This report was edited by Anders Löfgren, Sara Grolander, Ben Jaeschke, Sven Keesmann, and Eva Andersson. The authors that have contributed to the writing of the different chapters are presented in Table 1-3. The report has also been reviewed by Mike Thorne, and Ulrik Kautsky. However, the work done within the SR-PSU Biosphere project has been conducted by a number of people from various disciplines. 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. Their contribution to the identification and understanding of important FEPs has been essential for putting this chapter together. The project members in alphabetic order, their roles and affiliations are listed in Table 1-4.

Table 1-3. The authors who have directly contributed with text to the different chapters in this report.

Chapter	Authors
2 FEP-handling	S. Grolander, E. Andersson, A. Löfgren
3 Exposure pathway analysis	T. Hjerpe, A. Löfgren, B. Jaeschke
4 Irrigation on agricultural land	A. Löfgren
5 Peat and wood combustion	K. Stenberg, V. Rensfeldt
6 Draining of peatland	G. Sohlenius, A. Löfgren, P Saetre
7 Sensitivity of water fluxes	M. Sassner, S Keesmann
8 Model calibration	A. Löfgren, P. Saetre, E. Andersson, P.-A. Ekström

Table 1-4. 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.
Fredrik Hartz, Hartz Technology	GIS analysis and landscape development.
Thomas Hjerpe, Facilia AB	Handling of FEPs (features, events and processes).
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 modelling.
Tobias Lindborg, SKB	Site modelling and landscape development.
Anders Löfgren, EcoAnalytica	Terrestrial ecosystems.
Sara Nordén, SKB	Non-human biota.
Veronica Rensfeldt, Facilia AB	K_d and CR analysis.
Peter Saetre, SKB	Radionuclide model development, data evaluation, synthesis.
Mona Sassner, DHI Sverige AB	Hydrological modelling.
Gustav Sohlenius, SGU	Regolith and future land use.
Kristofer Stenberg	Modelling of combustion.
Viktor Smide, Hartz Technology	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.

2 Handling of biosphere FEPs in SR-PSU

In SKB (2013), biosphere features, events and processes (FEPs) important for radionuclide transport and accumulation in the biosphere and exposure of humans and non-human biota are identified and defined. An interaction matrix (IM) for the biosphere is also presented in SKB (2013). In the IM, the biosphere is divided into 10 physical components (surrounded by 2 boundary components), 6 variables (features) acting on the physical components and 50 processes whereby the physical components can affect each other. The FEPs identified as important and having to be considered in a safety assessment for a geological repository at Forsmark are included in several modelling activities in the biosphere assessment in SR-PSU. The mapping of components, variables and FEPs to the different biosphere model activities is summarised in Table 2-1. In Section 2.1, the modelling activities in SR-PSU Biosphere are briefly described. The following sections include descriptions of where and how the identified components (Section 2.2), variables (Section 2.3), and processes (Section 2.4) are handled within the SR-PSU safety assessment. However, a detailed description of the modelling activities is not given in this report but in the specific report for each modelling activity (see Section 2.1 for references). Likewise the relationships between components and FEPs are described in detail in SKB (2013) and only the resulting IM is shown in Appendix A, and relationships between variables and processes are specified and displayed in SKB's FEP database.

Table 2-1. Mapping of components, variables and FEPs to different modelling activities in SR-PSU Biosphere. Components, variables and processes are numbered as in the SKB FEP database CompBio = Components of the biosphere, VarBio = Variables of the biosphere, and Bio = Process of the biosphere. Aqua = Aquatic ecosystem, Mire = Wetland ecosystem, Agri = Agricultural system, NHB = non-human biota, K_d/CR = sorption/desorption value and concentration ratios.

		Radionuclide model					**Supporting activity**						
		Transport modelling			**Dose calculations**				**Ecosystem-specific parameters**				
Components, variables and processes		**Aqua**	**Mire**	**Agri**	**Humans**	**NHB**	**Landscape modelling**	**Hydrological modelling**	**Aqua**	**Mire**	**Agri**	**K_d/CR**	**Human NHB**
Components													
CompBio01	Geosphere				X		X	X					
CompBio02	Regolith	X	X	X	X	X	X	X	X	X	X	X	
CompBio03	Water in regolith	X	X	X	X	X	X	X	X	X	X	X	
CompBio04	Surface water	X	X	X	X	X	X	X	X			X	
CompBio05	Gas and local atmosphere	X	X	X	X	X		X	X	X	X		
CompBio06	Primary producers	X	X	X	X	X	X	X	X	X	X	X	
CompBio07	Decomposers					X						X	X
CompBio08	Filter Feeders					X			X			X	X
CompBio09	Herbivores				X	X			X	X		X	X
CompBio10	Carnivores				X	X			X	X		X	X
CompBio11	Humans				X				X	X	X		X
CompBio12	External conditions	X	X	X	X	X	X	X	X	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	
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			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

Components, variables and processes		Radionuclide model					Supporting activity						
		Transport modelling			Dose calculations				Ecosystem-specific parameters				
		Aqua	Mire	Agri	Humans	NHB	Landscape modelling	Hydrological modelling	Aqua	Mire	Agri	K_d/CR	Human NHB
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		
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					

2.1 Biosphere modelling activities in SR-PSU

SR-PSU includes a large number of modelling activities. All modelling activities are shown in the Assessment Model Flow chart (AMF; Appendix B) where the biosphere modeling activities are marked green. A short description of the modelling activities in the biosphere is given below, whereas a full description is given in other reports (listed in Table 2-2).

The **Radionuclide transport modelling** is used to calculate transport and accumulation of radionuclides in biosphere objects with the endpoint being concentrations of radionuclides in environmental media over time. From these concentrations in environmental media calculated with the radionuclide transport model, doses to humans and dose rates to non-human biota are calculated in the **Dose calculations**. Both the radionuclide transport model and the dose calculations are dependent on a number of input parameters from the Forsmark landscape. The landscape changes over time due to the shoreline evolution since the last glaciation and due to ecosystem succession in which lakes are transforming to wetlands (See SKB 2014a for futher description). The **Landscape modelling** provides information on landscape geometries over time. The transport of radionuclides in the radionuclide transport model is mainly mediated via water flows. The **Hydrological modelling** provides information on site-specific water flows for different time points (i.e. marine, lake and terrestrial stages of the landscape). The **Ecosystem-specific parameters** include supporting modelling and calculations that provide parameters for the radionuclide transport model and dose calculations. The **Ecosystem-specific parameters** cover a large range of parameters covering both chemistry and biology in the ecosystems as well as parameters realted to human characteristics. Examples of ecosystem-specific parameters are primary production and mineralization within the ecosystems, sorption coefficients and uptake ratios (K_d and CR) and dose coefficients. Site-specific data from the site investigations have as far as possible been utilised both for describing parameters and specifying parameter values. It is not possible to predict parameter values for a fully dynamic future ecosystem in detail. Instead, data from the site and nearby ecosystems are used as natural analogues for the future ecosystems. This is based on the assumption that all relevant interactions among species and between organisms and the abiotic environment are contained in these analogue ecosystems.

The biosphere modelling activities are listed in Table 2-2 together with links to references to the reports where each modelling activity is thoroughly described and to the activities in the SR-PSU Assessment Model Flow chart (AMF). The AMF gives an overview of all the modelling activities in the assessment and are presented in Appendix B.

2.2 Biosphere components

Ten physical components of the biosphere and two boundary components are identified as important in SKB (2013). How these components are included in the safety assessment modelling activities is described in this section. If a component is not relevant or has little influence on the model outcome it is marked "not included" for that model activity.

2.2.1 Regolith

Mapping. SKB R-13-43 Section 4.1; SKB FEP database: CompBio02.

Definition. Regolith is composed of weathered rock debris covering the rock beneath it, as well as glacial and postglacial deposits, newly formed soils and sediments including dead organic material. In addition, in the SKB definition the surface of rock outcrops is included.

Radionuclide model

Radionuclide transport modelling. Each layer of regolith is represented by (one or more) compartments in the radionuclide transport model. The topmost compartments consist of sediments in the aquatic ecosystem and peat in the terrestrial ecosystem. The oxygenated top regolith component is divided into two compartments: one represents radionuclides adsorbed on solids or dissolved in pore water (water in regolith, see Section 2.2.2), and one represents radionuclides in organic matter. Underlying the sediments or peat is a component of post-glacial sediments, this component is also divided into two compartments, one representing radionuclides adsorbed on solids/dissolved in pore water and one representing radionuclides in organic matter. Older deposits underlying the postglacial sediments primarily consist of till and glacial clay, and are implemented as two distinct compartments.

Table 2-2. The biosphere modelling activities in which components, variables and processes are handled are listed here with a mapping to AMF activities and references to the reports where detail descriptions are given.

Safety assessment modelling activity	Activity and short description	Reference	AMF activities
Radionuclide transport modelling	Radionuclide transport model for the biosphere results in radionuclide concentrations in environmental media.	Saetre et al. 2013b	• RN transport and Dose
Dose calculations	Dose calculations for humans and non-human biota by using results from the radionuclide transport model.	Saetre et al. 2013b	• RN transport and Dose
Landscape modelling	Digital elevation model (DEM) describes the elevation of the present landscape.	Strömgren and Brydsten 2013	• Landscape development, • Biosphere object identification
	The regolith depth model (RDM) describes depth and stratigraphy of regolith in Forsmark.	Sohlenius et al. 2013	
	Regolith lake development model of Forsmark from past to present (RLDM) describes regolith depth in future lakes.	Brydsten and Strömgren 2013	
	Landscape development model (LDM) identifies the biosphere objects (areas where radionuclides may enter the biosphere), describes the development of the biosphere objects and gives input parameters to the radionuclide transport model.	SKB 2014a (Biosphere synthesis report)	
Hydrological modelling	Syntheses of present and future hydrology at Forsmark are used to give input parameters to the radionuclide transport model.	Werner et al. 2013	• Surface hydrology • Well investigation
Ecosystem-specific parameters	K_d and CR used for transport calculation in the biosphere in SR-PSU. Gives input parameters to the radionuclide transport modeling.	Tröjbom et al. 2013	• K_d/CR in biosphere
	Biosphere parameters used in radionuclide transport modelling and dose calculations. Describes calculation of ecosystem parameters such as primary production and mineralisation, human characteristics (need of food) and dose coefficients.	Grolander 2013	• Ecosystems parameters and dose coefficients • Site-specific data • Input data

Dose calculations: External exposure from the ground is included in dose calculations for humans. The upper regolith (top regolith component) is also considered as a habitat for non-human biota and the concentration of radionuclides in the upper regolith therefore contributes to the dose rate to those organisms that live either on or in the upper regolith.

Supporting activities

Landscape modelling. The regolith depth model describes the type and depth of regolith in present Forsmark. The landscape development model simulates the regolith distribution for the future Forsmark landscape, separated into glacial clay, post-glacial clay of lacustrine and limnic origin, and peat.

Hydrological model. The regolith layers are included in the hydrological model. See also discussion on regolith properties and hydrological pathways in Chapter 8 of this report.

Ecosystem-specific parameters. Different regolith properties are defined for different compartments e.g. porosity, density, degree of water saturation and mineralisation rate. Also site observations of bioturbation depths are used to define the upper regolith layer. Soild/liquid distribution coefficients (K_d) are used to model sorption of radionuclides in the regolith.

2.2.2 Water in regolith

Mapping. SKB R-13-43 Section 4.2; SKB FEP database: CompBio03.

Definition. Water in regolith is the pore water in the saturated and the unsaturated zone of the regolith. Frost and ice are also included. Water in wells are included, but deep wells drilled into the geosphere are included in the bounding component 'geosphere'.

Radionuclide model

Radionuclide transport modelling. The transport of radionuclides is driven by the flows of water in the regolith. The radionuclides within the regolith compartments are assumed to be either absorbed to the solid fraction of the regolith compartment or to be dissolved in the water in the regolith. The distribution between the dissolved and sorbed fractions is modelled using solid/liquid distribution coefficients (K_d). A dug well (i.e. withdrawing water from the regolith) is included in the radionuclide transport model; the water from this well is used for irrigation of the household garden plot.

Dose calculations. Water from a dug well is included in the dose calculation where the doses from food products derived from livestock consuming the water and from drinking water by humans are considered. Upper regolith (including water in regolith) is also considered as a habitat for non-human biota and the concentration of radionuclides in the upper regolith therefore contributes to dose rates to those organisms inhabiting the regolith.

Supporting activities

Landscape modelling. Water in regolith is considered in the biosphere object identification activity where wetness index is used to delineate wetland objects.

Hydrological modelling. The water flows in the saturated and unsaturated zone of the regolith compartments are calculated in the hydrological modelling. The quantified water flows between regolith compartments are used to parameterise the radionuclide model.

Ecosystem-specific parameters. Solid/liquid distribution coefficients (K_d) are used to model the dissolved concentrations of radionuclides in water in regolith. The pore water content is described for agricultural land, which is the only ecosystem where the regolith is not assumed to be always saturated.

2.2.3 Surface Waters

Mapping. SKB R-13-43 Section 4.3; SKB FEP database: CompBio04.

Definition. Surface water component is here defined as water on the Earth's surfaces, collecting on the ground, or in streams, rivers, wetlands, lakes, open water, and oceans, as opposed to water in rock, regolith or atmosphere. Rainwater on rock surfaces, snow and ice on land and on water, as well as droplets on e.g. vegetation are included in surface water.

Radionuclide model

Radionuclide transport modelling. Surface water is included in the radionuclide model in marine basins, lakes and streams. Surface water includes both dissolved elements and compounds and particulate matter within the water. Dissolved and adsorbed radionuclides are represented with one compartment, and the inventory is portioned assuming equilibrium conditions (K_d approach). To account for the consideration that the radionuclide concentration in refractory organic particulate matter may not necessarily be in equilibrium with the surface water, a compartment representing radionuclides (including C-14) stored in organic matter is implemented.

Dose calculations. Surface water is ingested by humans and livestock and contributes to radiation doses to humans. Surface water is also considered as a habitat for non-human biota and the concentrations of radionuclides in surface waters therefore contributes to dose rates to those species living in/on surface waters.

Supporting activities

Landscape modelling. The development of surface water in the landscape over time is described by the landscape development model.

Hydrological modelling. Essentially the connections between all different sources of surface water and groundwater are described by the hydrological modelling. For the time periods when submerged conditions prevail, inter-basin water flows are modelled. For the time periods when the landscape has risen above sea-level, surface-water flows (stream and overland flows) are modelled.

Ecosystem-specific parameters. Characteristics of the surface waters in Forsmark are included in the parameters for the radionuclide transport model. Solid/liquid partitioning coefficients (K_d values) are used to assess sorption of radionuclides onto particulate matter within the surface waters.

2.2.4 Gas and local atmosphere

Mapping. SKB R-13-43 Section 4.4; SKB FEP database: CompBio05.

Definition. Gas and local atmosphere includes the local atmosphere and gas in regolith and in water in regolith as well as gas bubbles in surface water. Gas flow and gas composition are included in this element which, therefore, includes wind and the content of particulates in the local atmosphere, i.e. water droplets, pollen, dust etc. The local atmosphere is defined as the layer of the atmosphere above the studied area that participates in gas exchange with the studied area. It is surrounded by the atmosphere, which is a boundary to the biosphere system.

Radionuclide model

Radionuclide transport modelling. As part of the SR-PSU safety assessment, SKB has developed a new conceptual and numerical model of the atmosphere, recognising a need to distinguish between different layers of the atmosphere (see Saetre et al. 2013b). However, the dynamics in the atmosphere are fast, and the exchanges with the upper atmospheric layers are much greater in magnitude than the exchanges with surface waters. Thus, for modelling purposes, the atmosphere can be treated as a sink (or source) in the ecosystem compartment model, and radionuclide concentrations of volatile radionuclides in the local atmosphere are calculated using a steady state solution.

Dose calculations. Exposure to gas in the atmosphere is included in the estimation of doses to humans and dose rates to non-human biota.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. The local atmosphere, in terms of evapotranspiration, is an important factor affecting the local water balance.

Ecosystem-specific parameters. Gas exchanges and the characteristics of the local atmosphere are defined by ecosystem-specific parameters.

2.2.5 Primary producers

Mapping. SKB R-13-43 Section 4.5; SKB FEP database: CompBio06.

Definition. Primary producers are autotrophic organisms able to use sunlight or the oxidation of inorganic compounds as an energy source to synthesise organic compounds from inorganic carbon sources. Primary producers include green plants, algae and autotrophic bacteria.

Radionuclide model

Radionuclide transport modelling. Primary producers are included as an explicit model compartment.

Dose calculations. Primary producers are in many cases the most important food source for humans and herbivores, and are consequently an important constituent in the dose calculations, e.g. in describing exposures due to radionuclide transfers from hay from wetlands to animal products or from ingestion of cultivated crops. Dose rates to different primary producers is also considered within the non-human biota dose assessment.

Supporting activities

Landscape modelling. The development of reed and peat in shallow bays and lakes is described by this model. This ingrowth is driven by the growth of primary producers and the accumulation of organic matter.

Hydrological modelling. Primary producers affect the water balance by processes such as root uptake and transpiration, which are included in the modelling.

Ecosystem-specific parameters. Primary producers are described in terms of biomass and net primary production over time. Uptake of radionuclides by primary producers is modelled using element-specific concentration ratios (CR).

2.2.6 Decomposers

Mapping. SKB R-13-43 Section 4.6; SKB FEP database: CompBio07.

Definition. Decomposers are organisms (bacteria, fungi or animals) that feed on dead plant and animal matter and break down complex organic compounds into carbon dioxide, water and inorganic compounds. Examples of decomposers are bacteria, soil-fauna such as earthworms and some species of aquatic benthic fauna.

Radionuclide model

Radionuclide transport modelling. Decomposers are important for the decomposition and thereby transport of radionuclides bound in the organic fraction to inorganic fractions of regolith compartments. However, the amounts of radionuclides stored in decomposers and other biota are small compared with other compartments of the biosphere and therefore, although the process of decomposition is considered, the decomposers themselves are not included in the radionuclide transport model.

Dose calculations. Dose rates to decomposers are calculated within the non-human biota dose assessment.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Element-specific concentration ratios for decomposers are assigned to assess activity concentrations in the decomposers for the non-human biota dose assessment. Characteristics (as size and shape) of decomposers are included in the dose calculations.

2.2.7 Filter feeders

Mapping. SKB R-13-43 Section 4.7; SKB FEP database: CompBio08.

Definition. Filter feeders are aquatic organisms that feed on particulate organic matter and small organisms (phytoplankton and zooplankton) filtered out by circulating the water through the animal's system. Filter feeders include a wide range of animals such as bivalves (e.g. mussels), sponges, crustaceans (e.g. shrimps) and even whales.

Radionuclide model

Radionuclide transport modelling. The amounts of radionuclides stored in filter feeders and other biota are small compared with other compartments of the biosphere and therefore the filter feeders themselves are not included in the radionuclide transport model.

Dose calculations. Dose rates to filter feeders are calculated within the non-human biota dose assessment.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Filter feeders are not explicitly included in the transport or dose calculations for humans, but are a part of the food web in aquatic ecosystems and may affect parameter estimates related to particulate matter concentrations and decomposition, this is considered indirectly by using site–specific data. In addition, element-specific concentration ratios for filter feeders are assigned to assess activity concentrations in the filter feeders for the non-human biota dose assessment.

2.2.8 Herbivores

Mapping. SKB R-13-43 Section 4.8; SKB FEP database: CompBio09.

Definition. Herbivores are animals that feed on primary producers, i.e. plants, algae and autotrophic bacteria. Omnivores are functionally a mix of herbivores and carnivores and are included both here and in carnivores (see below). Examples of herbivores include some species of insects, rodents, fish and larger mammals.

Radionuclide model

Radionuclide transport modelling. The amounts of radionuclides stored in herbivores and other biota are small compared with other compartments of the biosphere and therefore the herbivores themselves are not included in the radionuclide transport model.

Dose calculations. Herbivores contribute to doses to humans since domestic animals, fish and game is a part of the human diet. Dose rates to herbivores are also calculated within the non-human biota assessment.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Herbivores are not explicitly included in the transport calculations for humans, but are a part of the food web in terrestrial and aquatic ecosystems and may affect parameter estimates related to e.g. biomass and net primary production. Element-specific concentration ratios used for estimation of concentrations of radionuclides in herbivores are used in the dose calculations. In addition, amounts of herbivores in the biosphere objects available as a food resurce to humas are considered in the dose assessment.

2.2.9 Carnivores

Mapping. SKB R-13-43 Section 4.9; SKB FEP database: CompBio10.

Definition. Carnivores are animals that feed on other animals. Omnivores are functionally a mix of herbivores and carnivores and are included both here and in herbivores (see above). Examples of carnivores include some species of insects, birds, fish and mammals.

Radionuclide model

Radionuclide transport modelling. The amounts of radionuclides stored in carnivores and other biota are small compared with other compartments of the biosphere and therefore the carnivores are not included in the radionuclide transport model.

Dose calculations. Carnivores (e.g. piscivorous fish like perch and pike) contribute to dose to humans as a part of the human diet. Dose rates to carnivores are calculated within the non-human biota assessment.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. The presence of carnivores in terrestrial and aquatic ecosystems may to some extent affect the estimates of different parameters, this is included indirectly by using site-specific data. The effect is expected to be small in the area around Forsmark. This is due to the small and sometimes negligible population sizes of larger carnivores. Element-specific concentration ratios are used for estimation of concentrations of radionuclides in carnivores that are used in the dose calculations. In addition, amounts of carnivores in the biosphere objects available as a food resurce to humas are considered in the dose assessment.

2.2.10 Humans

Mapping. SKB R-13-43 Section 4.10; SKB FEP database: CompBio11.

Definition. Humans are defined as human beings living in the affected area. This includes the number of persons and also their activities at the site e.g. fishing, water pumping and releases of chemicals and water, as well as agriculture, irrigation and construction (terrestrial).

Radionuclide model

Radionuclide transport modelling. The component 'humans' is not included into the radionuclide transport model although human actions are considered and affect the radionuclide transport modelling results (e.g. draining and cultivating wetlands).

Dose calculations. The radiation doses to humans, i.e. to representative members of critical groups, are calculated. Several possible human communities are identified in an exposure analysis (Chapter 3). The doses to individuals in these different communities are modelled within the dose model.

Supporting activities

Landscape modelling. Not included. Humans may affect the landscape, e.g. by draining and cultivating the land. However, this is considered in the landscape model in terms of processes performed by humans and the actual humans are not considered in the landscape model e.g. the numbers of humans are not included in the model.

Hydrological modelling. Not included. Humans may affect the hydrological fluxes, e.g. by damming a water body or utilising a well. However, this is considered in the hydrological modelling by specific processes performed by humans and the actual humans are not considered in the hydrological model e.g. the number of humans is not included in the model.

Ecosystem-specific parameters. Parameters describing the human communities living in the affected area are defined. For example, numbers of individuals, ingestion rates of different food stuffs and water, and time spent working on contaminated land are defined.

2.2.11 Boundary components

The geosphere and external conditions are not defined as components of the biosphere they are considered to be boundary components in the biosphere assessment.

Geosphere

Mapping. SKB R-13-43 Section 4.11.1; SKB FEP database: CompBio01.

Definition. Geosphere is the bedrock surrounding the repository. It also includes deep groundwater and gases present in the saturated zone in the bedrock. Thus, deeply drilled wells are included.

Radionuclide model

Radionuclide transport modelling. The geosphere is not included in the radionuclide transport model of the biosphere.

Dose calculations. The geosphere is not included in the radionuclide model of the biosphere. However, the dose contribution from a geological well situated in the geosphere is included.

Supporting activities

Landscape modelling. The bedrock is included as a boundary condition in the landscape modelling.

Hydrological modelling. The hydrological modelling includes bedrock down to a depth of 150 meters.

Ecosystem-specific parameters. Not included.

External conditions

Mapping. SKB R-13-43 Section 4.11.2; SKB FEP database: CompBio12.

Definition. External conditions are all external factors that affect the local conditions considered within the biosphere interaction matrix or that are affected by the biosphere identified in the matrix. External conditions include those relating to surrounding ecosystems and the atmosphere above and beyond the lateral boundaries of the local atmosphere. They also include global conditions such as global climate and solar insolation.

Radionuclide model

Radionuclide transport modelling. External conditions are included in the radionuclide transport model, e.g. by considering different climate conditions in different climate cases. Climate cases defined in the SR-PSU Climate Report (SKB 2014c) are used to simulate effect of different possible future climate developments and the handling of these in the biosphere modelling is described in SKB (2014a) and in Saetre et al. (2013b).

Dose calculations. Climate affects the behavior of humans and therefore also the dose calculations.

Supporting activities

Landscape modelling. Climate is considered in the landscape modelling and alternative developments are described for different climate evolutions (See SKB 2014a and Brydsten and Strömgren 2013).

Hydrological modelling. Different climate cases are used to investigate the effects of climate on hydrological flows. A warmer/wetter climate relative to the present day and permafrost conditions are modelled.

Ecosystem-specific parameters. Many of the parameter values that are used are dependent on climate. Therefore, alternative parameter values are used for different climate conditions in the biosphere calculations.

2.3 Biosphere features (variables)

A feature is here defined as a property, function, condition or attribute affecting a biosphere component or affecting the *rate or direction* of a process interaction between two components. The features included in the biosphere IM represent the internal characteristics of the components and can affect the internal characteristics of a principal diagonal element of the IM or can affect the internal characteristics of a process included in an off-diagonal element, but cannot by itself be an off-diagonal element. If a feature is not relevant or has little influence on the model outcome it is marked "not included" for that model activity.

2.3.1 Geometry

Mapping. SKB R-13-43 Section 5.1; SKB FEP database: VarBio01.

Definition. Geometry includes geometric descriptions of the landscape such as topography and bathymetry, depth and volume of regolith, peat, water etc. The feature also includes the geometry of organisms, i.e. the shape, surface area and volume of organisms. In addition, geometry includes the amount of a component.

Radionuclide model

Radionuclide transport modelling. The biosphere objects included in the radionuclide model are defined by the geometries of the overall object, water bodies and regolith layers. In addition, the geometries of the different components are taken into account in parameterising the radionuclide transport model.

Dose calculations. The geometry is considered in the dose calculations, e.g. the number of human inhabitants in a biosphere object and the amount of food produced from a biosphere object depend on its size. The non-human biota included in the dose assessment are defined by shape, volume and surface area.

Supporting activities

Landscape modelling. Time-dependent geometries of landscape elements are defined by the landscape development modelling.

Hydrological modelling. Topography, bathymetries, regolith distribution and depth at each time step are accounted for in the MIKE SHE water-flow modelling.

Ecosystem-specific parameters. Ecosystem-specific parameters are used to define the thickness of the regolith layers, amounts and biomass of primary producers etc. The size, shape and surface area of organisms are ecosystem-specific and are used in dose calculations for non-human biota.

2.3.2 Material composition

Mapping. SKB R-13-43 Section 5.2; SKB FEP database: VarBio02.

Definition. Material composition includes chemical composition (e.g. concentrations of minerals and nutrients) as well as physical features such as grain size and porosity.

Radionuclide model

Radionuclide transport modelling. The chemical composition of the regolith and water compartments is included in the radionuclide transport modelling, for example organic matter content, concentration of dissolve inorganic carbon and particulate matter content are taken into account.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Physical composition is identified based on the distribution of different regolith layers in the landscape.

Hydrological modelling. Grain sizes and porosities of regolith layers are used in the hydrological modelling when calculating flows.

Ecosystem-specific parameters. Element-specific solid/liquid partitioning coefficients (K_d values) and concentration ratios (CR) are used to calculate sorption on soils and particulate matter and uptake by biota. These parameters are dependent on the chemical composition of the regolith/water compartments and therefore the material composition is included indirectly by applying site-specific K_d and CR values. The material composition of regolith (hard or soft bottoms, nutrient content etc) may affect the type and amounts of primary producers. This is assumed to be indirectly included in the parameters for biomass and production in the radionuclide model, since these parameters are based on site data in which the effect of this parameter is included. The porosity, grain size and pore water content are also included as parameters.

2.3.3 Radionuclide inventory

Mapping. SKB R-13-43 Section 5.3; SKB FEP database: VarBio03.

Definition. Radionuclide inventory include radionuclides and their activities in all physical and biological components of the biosphere system in question (i.e. in all components of the interaction matrix described in Section 2.2).

Radionuclide model

Radionuclide transport modelling. The inventory of radionuclides is included in compartments of the radionuclide transport model.

Dose calculations. The calculated inventory of radionuclides is used in estimating doses to humans and dose rates to non-human biota.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Not included.

2.3.4 Stage of succession

Mapping. SKB R-13-43 Section 5.4; SKB FEP database: VarBio04.

Definition. Stage of succession is a feature used in the biosphere IM to determine the development of ecosystems. The landscape in Forsmark is continuously developing due to the ongoing shore line displacement and there is an ongoing succession of ecosystems from marine to limnic to terrestrial.

Radionuclide model

Radionuclide transport modelling. The succession of the landscape is included in the radionuclide model by explicit representation of the transition from aquatic to terrestrial ecosystems, and by transforming areas into agricultural land.

Dose calculations. The stage of succession affects human land use and therefore also the effective exposure pathways. It also affects what kinds of habitat that is available for non-human biota and therefore also affects the dose rate calculations to non-human biota.

Supporting activities

Landscape modelling. Development of sea basins, lakes and mires is included in the landscape development model.

Hydrological modelling. Hydrological modelling is performed for three time steps to cover the succession from marine through limnic to fully terrestrial conditions and thereby includes the stage of succession.

Ecosystem-specific parameters. Stage of succession affects whether marine, limnic or terrestrial biota are present in the biosphere objects. Moreover, it affects the geometry of the biosphere object, thereby also affecting biomass, net primary production and type of biota. The continuous subsidence of drained wetland is included. Stage of succession also affects the number and characteristics of the human population present in the area.

2.3.5 Temperature

Mapping. SKB R-13-43 Section 5.5; SKB FEP database: VarBio05.

Definition. Temperature is the well-defined physical property. Temperature has an impact on whether water is liquid or solid, chemical reaction rates and equilibria, and temperature affects living conditions for primary proucers, fauna and humans. In SKB's IM, temperature is related only to the temperature in the physical components of the system of interest.

Radionuclide model

Radionuclide transport modelling. Climate cases are used in the radionuclide model to assess the effects of different temperatures on the transport of radionuclides in the landscape.

Dose calculations. Climate is considered in the dose calculations as agriculture is not assumed possible during periglacial conditions. Likewise, the biota present are dependent on climate.

Supporting activities

Landscape modelling. The landscape development model describes the landscape in a warmer and a colder climate than at the present day, as well as under present-day conditions.

Hydrological modelling. Air-temperature data are used in the hydrological modelling.

Ecosystem-specific parameters. Temperature is included in the calculation of gas exchange. Alternative parameter values for a number of ecosystem-specific parameters are used for periglacial and extended global warming conditions.

2.3.6 Water composition

Mapping. SKB R-13-43 Section 5.6; SKB FEP database: VarBio06.

Definition. Water composition comprises dissolved elements and compounds, colloids and suspended particles (including dead organic matter).

Radionuclide model

Radionuclide transport modelling. Water composition is included in the radionuclide model by parameter values defining particulate matter content and dissolved inorganic carbon.

Dose calculations. Water composition is indirectly included in the dose calculations for both humans and non-human biota, as water is an exposure pathway and includes particulate matter in the water.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Water composition is considered directly in terms of parameter values for dissolved inorganic carbon and particulate matter. It is also included in the calculation of other parameters such as pH and salinity, and in the calculation of exchange across the air/water interface. Element-specific solid/liquid partitioning coefficients (K_d values) and concentration ratios (CR) are used to calculate sorption on particulate matter and uptake by aquatic biota are dependent on the chemical composition of the water compartments. Therefore, the water composition is included conceptually by applying site-specific K_d and CR values for model parameterisation.

2.4 Biosphere processes

In total, 50 processes were identified as potentially important for ecosystem functioning, landscape development, and for transport and accumulation of elements and radionuclides in the biosphere. Of these, 45 have been identified as requiring consideration for a geological repository at Forsmark (SKB 2013). These 45 processes are included in the safety assessment in different ways. In this section, a description is given as to where the processes have been considered in the safety assessment modelling.

Five processes of the 50 potentially important processes are classified as not important to the safety assessment. These five processes are Movement (animal locomotion in surface water), Change of pressure (pressure change in air or water above a surface), Loading (force caused by the weight of material that affects the underlying rock), Irradiation (the process whereby an object is exposed to ionising radiation and absorbs energy, not to be confused with exposure which is included), and Radiolysis (the disintegration of molecules caused by radionuclide decay). For discussion and motivation for excluding the five processes, see SKB (2013). If a process is not relevant or has little influence on the model outcome it is marked “not included” for that model activity.

2.4.1 Bioturbation

Mapping. SKB R-13-43 Section 6.1.1; SKB FEP database Bio01.

Definition. Bioturbation is the mixing of particles in both aquatic and terrestrial regolith by plants, animals, bacteria and fungi.

Radionuclide model

Radionuclide transport modelling. Bioturbation is explicitly accounted for in agricultural ecosystems in the radionuclide transport model, where inventories from upper regolith layers are initially mixed into one biologically active cultivated layer when drained mire and lacustrine sediments are cultivated. Bioturbation is also explicitly accounted for in aquatic ecosystems. When the depth of the upper sediment layer is reduced due to 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.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. The depth of the upper regolith in aquatic ecosystems is defined as the upper oxygenated layer, i.e. the same as the bioturbation depth. The ploughing depth defines the bioturbated zone in agriculture land.

2.4.2 Consumption

Mapping. SKB R-13-43 Section 6.1.2; SKB FEP database Bio02.

Definition. Consumption is the ingestion of matter by organisms (particulate matter and other organisms).

Radionuclide model

Radionuclide transport modelling. Consumption by decomposers is handled in the process decomposition (see Section 3.3.3). Consumers are not part of the radionuclide transport model as a separate compartment, but they affect the flux of organic matter from primary producers (which are included as a compartment) to regolith. The flux from primary producers to regolith is included in the aquatic and terrestrial parts of the radionuclide transport model, where non-mineralised net primary production (the amount being dependent on consumption, death, decomposition, excretion and particle release) is deposited on surface regolith layers.

Dose calculations. Consumption by humans is accounted for in the dose calculations. The consumption by game and domestic animals (cows) is also accounted for in the dose calculations for humans. Consumption is also accounted for in the dose calculations for non-human biota.

Supporting activities

Landscape modelling. Consumption has an impact on ingrowth (a function of primary production of biomass that is indirectly affected by consumption, death and decomposition) in shallow bays and lakes, which is accounted for in the landscape development model by using site data where the process in indirectly included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. It is mainly consumption by herbivores that is expected to have an effect on the ecosystem-specific parameters (See Section 3.1.7 to 3.1.9). The consumption by herbivores is indirectly included in the estimates of biomass and NPP and the amount of primary production that contributes to the organic pool of the regolith. Parameters defining consumption by cows and humans are used as input parameters for the dose calculations.

2.4.3 Death

Mapping. SKB R-13-43 Section 6.1.3; SKB FEP database Bio03.

Definition. Death is the transfer of organisms from living compartments to a dead organic matter pool.

Radionuclide model

Radionuclide transport modelling. Death leads to litter fall which is included in the radionuclide transport model. The flux from primary producers to regolith is included in the aquatic and terrestrial parts of the radionuclide transport model in which non-mineralised net primary production (the amount being dependent on consumption, death, decomposition, excretion and particle release) is deposited on surface regolith layers.

Dose calculations. Not included.

Landscape modelling. Ingrowth (a function of primary production, death and decomposition) in shallow bays and lakes is described in the landscape development model.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Death of organisms is considered in the transfer of organic matter from biota to regolith, where the fraction of primary producers that remains after initial consumption and mineralisation contributes to undecomposed organic matter in the different environmental media.

2.4.4 Decomposition

Mapping. SKB R-13-43 Section 6.1.4; SKB FEP database Bio04.

Definition. Decomposition is the disintegration of dead organic matter by decomposers.

Radionuclide model

Radionuclide transport modelling. Decomposition is included in all ecosystems in the radionuclide transport model as a flux from the organic to the inorganic fraction of the regolith (explicitly included as a mineralization rate). Decomposition is also included in the radionuclide transport model as it affects the flux from biota to regolith. The flux from primary producers to regolith is included in the aquatic and terrestrial parts of the radionuclide transport model where non-mineralised net primary production (the amount are dependent on consumption, death, decomposition, excretion and particle release) is deposited on surface regolith layers.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Peat ingrowth in lakes is described as a function of primary production, death and decomposition. Decomposition occur when peat lands are drained and the resulting subsidence is included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Decomposition of organic matter is represented by mineralisation rates for the different physical components (upper regolith, postglacial deposits and particulate matter in water) used in the radionuclide model.

2.4.5 Excretion

Mapping. SKB R-13-43 Section 6.1.5; SKB FEP database Bio05.

Definition. Excretion is the release of elements and compounds from organisms to the surrounding media.

Radionuclide model

Radionuclide transport modelling. Excretion is represented in the radionuclide transport model in terms of the flux from biota to regolith. The flux from primary producers to regolith is included in the aquatic and terrestrial parts of the radionuclide transport model where non-mineralised net primary production (the amount being dependent on consumption, death, decomposition, excretion and particle release) is deposited on surface regolith layers.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Excretion from organisms is considered in the transfer of organic matter from biota to regolith in the radionuclide model where the fraction of primary production that remains after initial consumption and mineralisation contributes to undecomposed organic matter in the different environmental media. The excretion of elements may also affect respiration, and the composition of atmosphere and water. By using site-specific data, the effects of excretion are assumed to be indirectly included in parameter values where water chemistry is important, e.g. as with the excretion or uptake of CO_2 affecting pH values. CR values depend on uptake, excretion and sorption/desorption. CR values are based on site data where all of these processes are indirectly included in all ecosystem types.

2.4.6 Food supply

Mapping. SKB R-13-43, Section 6.1.6; SKB FEP database: Bio06.

Definition. Food supply is the production of food and the process by which it is made available to consumers. Primary producers, animals and dead organic matter may be utilised as food sources by other organisms and thereby comprising a supply of food to consumers.

Radionuclide model

Radionuclide transport modelling. Food supply is not directly modelled in the radionuclide transport model, but results from the radionuclide transport model (e.g. concentrations in food items that can be calculated from the environmental media modelled) are used in the dose calculations. Losses of radionuclides associated with harvest are cautiously ignored in the radionuclide transport model.

Dose calculations. The food supply from biosphere objects modelled in the radionuclide transport model are considered in the dose calculations In the dose calculations, four exposure variants are identified to explicitly address uncertainties in *food supply* related to humans: hunter-gatherer, inland-outfield farmers, drained mire farmers and garden plot farmers.

Supporting activities

Landscape modelling. Habitats providing food supply, as agricultural land, mires and lakes, are identified within the landscape model.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Productivities of edible plants and animals are used to calculate the food supply from agricultural lands, lakes and mires.

2.4.7 Growth

Mapping. SKB R-13-43 Section 6.1.7; SKB FEP database Bio07.

Definition. Growth is the generation of biomass by organisms.

Radionuclide model

Radionuclide transport modelling. Growth is not explicitly modelled but is indirectly included by the use of parameters from the landscape modelling and in the ecosystem-specific parameters dependent on the process (see description below).

Dose calculations. Not included.

Supporting activities

Landscape modelling. Ingrowth of reed is the first step of terrestrialisation of lakes and shallow bays and is described in the landscape development model.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Growth of biota may dilute the radionuclide concentration in the biota. For most calculation cases biomass is assumed to be in steady state. However, for estimating the effects of irrigation, growth of primary producers is considered in the parameter that describes the loss of intercepted elements due to processes such as growth.

2.4.8 Habitat supply

Mapping. SKB R-13-43 Section 6.1.8; SKB FEP database Bio08.

Definition. Habitat supply is when organisms or abiotic components of the environment provide a substrate or shelter for other organisms.

Radionuclide model

Radionuclide transport modelling. Habitat supply is not explicitly modelled, but is indirectly included by the use of parameters from the landscape modelling and in the ecosystem-specific parameters dependent on the process (see description below).

Dose calculations. For the dose calculations for non-human biota, the habitat of the organisms is considered. For dose calculations for humans, the habitat is used to define both human behaviour and the exposure pathways.

Supporting activities

Landscape modelling. A number of habitats are followed during landscape development this is accounted for in the delineation of the landscape (i.e. when determining the surface area of the potentially contaminated biosphere object).

Hydrological modelling. Not included.

Ecosystem-specific parameters. The available habitats within the biosphere objects are included in the calculation of aquatic biomasses and production parameters used in the radionuclide model (e.g. the area and depth of photic zone are considered). The habitat is not differentiated within the mire and agricultural ecosystems, but for these ecosystems the biomass is assumed to be homogenous and only vary in proportion to the area of the ecosystem. For dose rate calculations applicable to non-human biota, parameters describing the occupancy of organisms in different habitats are used.

2.4.9 Intrusion

Mapping. SKB R-13-43 Section 6.1.9; SKB FEP database Bio09.

Definition. Intrusion is defined here as the process whereby organisms (including humans) enter the repository by for example locomotion, drilling or growth.

Radionuclide model

Radionuclide transport modelling. Intrusion by drilling a well into the repository or into a downstream area from the repository where release from the repository could lead to elevated concentrations of radionuclides (Well interaction area) are considered in the radionuclide transport model by a special biosphere calculation case (BCC5, see Section 7.4.5 in SKB 2014a) where water from the well is used for drinking and irrigation of a garden plot. Intrusion is further considered in the Future human action report (SKB 2014f). These aspects are not part of the biosphere component of the assessment.

Dose calculations. Estimation of doses from ingestion of well water and doses from the use of well water for irrigation are included in the dose calculations.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Parameters defining the amount of water ingested and used for irrigation are used to assess the effects of an intrusion well.

2.4.10 Material supply

Mapping. SKB R-13-43 Section 6.1.10; SKB FEP database Bio10.

Definition. Material supply is the amount of material that is available for human utilisation for purposes other than feeding.

Radionuclide model

Radionuclide transport modelling. Material supply is not calculated in the radionuclide transport modelling.

Dose calculations. Doses from using material (peat/wood, manure and seaweed) are included in the dose calculations for humans and consideration is taken as to whether the amount of peat/wood available in the biosphere objects is enough to meet the needs of the population (this is done by using parameters from the landscape model).

Supporting activities

Landscape modelling. Identification of different regolith and water resources, areas suitable for forestry, peat cutting, and animal husbandry is done within the landscape model.

Hydrological modelling. Not included.

Ecosystem-specific parameters. The amounts of peat, wood, manure and seaweed needed are defined by human habits (see Material use), but the supply is defined by the ecosystems in the biosphere objects which is dependent on ecosystem parameters together with landscape parameters. From the agricultural ecosystem, the amount of manure from animals is supplied.

2.4.11 Particle release/trapping

Mapping. SKB R-13-43 Section 6.1.12; SKB FEP database Bio12.

Definition. Particle release/trapping is the release of particles from organisms to the environment, or the trapping of particles in the environment by organisms.

Radionuclide model

Radionuclide transport modelling. Particle release is represented in the radionuclide transport model by the flux from biota to regolith. The flux from primary producers to regolith is included in the aquatic and terrestrial parts of the radionuclide transport model, where non-mineralised net primary production (the amount being dependent on consumption, death, decomposition, excretion and particle release) is deposited on surface regolith layers.

Dose calculation. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Particle release from organisms is considered in the transfer of organic matter from biota to regolith, where the fraction of primary producers that remains after initial consumption and mineralisation contributes to undecomposed organic matter in the different environmental media. The particulate content of surface waters and in the atmosphere is represented by parameter values in the radionuclide transport model and this content is implicitly affected by particle trapping by and release from organisms. Since the parameter values relating to particulate concentration used in the radionuclide model are based on site data, the effects of particle trapping/release are indirectly included in the parameter values.

2.4.12 Primary production

Mapping. SKB R-13-43 Section 6.1.13; SKB FEP database Bio13.

Definition. Primary production (which here refers to gross primary production) is the total fixation of inorganic carbon by primary producers.

Radionuclide model

Radionuclide transport modelling. Fixation of carbon is included in radionuclide transport model as plant uptake in the aquatic and terrestrial parts of the radionuclide transport model. Net primary production also drives litter respiration/release and litter production.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Peat ingrowth in lakes which is modelled in the landscape model is a function of primary production, death and decomposition.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Primary production in terrestrial and aquatic ecosystems is parameterised in the radionuclide transport model. In addition, primary production is used in calculations of the amounts of edible food arising from aquatic, terrestrial and agricultural systems (see Section 2.4.6)

2.4.13 Stimulation/inhibition

Mapping. SKB R-13-43 Section 6.1.14; SKB FEP database Bio14.

Definition. Stimulation/inhibition occurs when a component influences another component positively or negatively, e.g. biota may compete for space and thereby inhibit each other affecting both biomass and production.

Radionuclide model

Radionuclide transport modelling Biological communities are treated as being in equilibrium with stimulation and inhibition implicitly taken into account. Also, the level of detail required in modelling to represent stimulation/inhibition is not compatible with the model resolution of the radionuclide transport model and so stimulation/inhibition is not explicitly included in the radionuclide transport model.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Stimulation/inhibition is considered in the landscape modelling by using site data that implicitly take into account stimulation/inhibition and thereby the effects of this process are indirectly included. For example, ingrowth is inhibited by greater water depth, sedimentation is affected by fetch and depth, cultivation of regolith is dependent on soil depth, and too small a depth of regolith may inhibit humans from utilising an area for agricultural purposes.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Stimulation/inhibition is captured by applying site-specific parameter values whereby the effect of stimulation/inhibition is indirectly included.

2.4.14 Uptake

Mapping. SKB R-13-43 Section 6.1.15; SKB FEP database Bio15.

Definition. Uptake is the incorporation of elements or water from the surrounding media by organisms (including humans). It includes drinking, inhalation and transfer through the skin, but ingestion is treated under consumption.

Radionuclide model

Radionuclide transport modelling. In aquatic ecosystems, plants uptake of dissolved radionuclides from the surrounding water is explicitly included. In mire ecosystems, plant uptake of radionuclides from the upper soil layers (root uptake) and from the canopy atmosphere (through leaves) is explicitly included. Atmospheric dry deposition is implicitly included in root uptake modeled using empiric CR values (see belove).

Dose calculations. Uptake by crops and domestic animals and directly by humans is included in dose calculations for humans. Uptake is also taken into account in the dose calculations for non-human biota.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Uptake of radionuclides by non-human biota is modelled by using CR parameter values that are affected by several processes (among others uptake). Since CR values are based on site data all of these processes are indirectly included. The amount of water uptake needed by humans is an input parameter to the dose calculations. In addition, by using site data effects of uptake are assumed to be indirectly included in parameter values where the effects of such uptake on chemistry are important, e.g. the uptake of CO_2 affecting pH.

2.4.15 Anthropogenic release

Mapping. SKB R-13-43 Section 6.2.1; SKB FEP database Bio16.

Definition. Anthropogenic release is the emission of a substance into the air or water, or the deposition of a substance on land, also including release of water and energy (heat) mediated by humans.

Radionuclide model

Radionuclide transport modelling. Release of radionuclides due to fertilisation with contaminated wetland hay and irrigation with contaminated water are explicitly included in agricultural ecosystems in the radionuclide transport model. The former for the infield-outland farmer exposure variant and the latter for the garden plot exposure variant of agricultural systems.

Dose calculations. Doses caused by anthropogenic releases due to fertilisation, combustion of peat and wood, and irrigation are included in the dose calculations to humans.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Parameters describing irrigation with water containing radionuclides, fertilisation with manure and seaweeds containing radionuclides and combustion of peat and wood are used to assess anthropogenic releases.

2.4.16 Material use

Mapping. SKB R-13-43 Section 6.2.2; SKB FEP database Bio17.

Definition. Material use is human utilisation of the environment for purposes other than feeding (see "Consumption"), drinking (see "Uptake") and water use.

Radionuclide model

Radionuclide transport modelling. The use of manure and seaweed for fertilisation is addressed in the radionuclide transport model.

Dose calculations. The dose from utilising peat and wood for combustion is addressed in the dose calculations.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Parameters describing the use of peat/wood for combustion and parameters describing the fertilisation of agricultural soils are used.

2.4.17 Species introduction/extermination

Mapping. SKB R-13-43 Section 6.2.3; SKB FEP database Bio18.

Definition. Species introduction/extermination is the introduction or extermination of species to/from the repository site by human activities.

Radionuclide model

Radionuclide transport modelling. Biological communities are treated as being in equilibrium. Modelling of species introduction and/or extermination would require a long-term representation of community structure, but with open boundaries allowing flows of organisms from a wider ecological context, i.e. detailed modelling on a large scale. Thus, species introduction or extermination would require representation at a level of detail that is not compatible with model resolution and it is not explicitly included in the radionuclide transport model.

Dose calculations. Species introduction is considered in the dose calculations. When mires are transformed to agricultural land, crops are introduced to the biosphere objects. It is also assumed that crayfish are introduced in the area in order to cautiously consider possible exposure pathways for humans from aquatic ecosystems. Species that are currently not present in Forsmark are included in non-human biota dose calculations.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Crayfish are assumed to be introduced into the area in order not to underestimate possible food sources in the future and parameter values for crayfish biomass and production are estimated from other crayfish locations in the County. Parameters of crop biomass and production are estimated for agricultural land.

2.4.18 Water use

Mapping. SKB R-13-43 Section 6.2.4; SKB FEP database Bio19.

Definition. Water use is the amount of water used by humans for purposes other than drinking. Examples of water use are energy production, irrigation, sewage flushing, washing clothes, showering. Loss in the supply chain (e.g. leakage from pipes), which is not strictly a use, needs also to be taken into account.

Radionuclide model

Radionuclide transport modelling. Irrigation is included in the radionuclide model for the garden plot exposure variant.

Dose calculations. Effects of irrigation are considered in the garden plot exposure variant.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Types and rates of water use by future, self-sustaining communities are estimated and used as parameter values.

2.4.19 Consolidation

Mapping. SKB R-13-43, Section 6.3.2. SKB FEP database: Bio21.

Definition. Consolidation is any process whereby loosely aggregated, soft, or liquid soil materials become firm and coherent rock; it includes the compaction of regolith.

Radionuclide model

Radionuclide transport modelling. Compaction of regolith during draining of a mire is included in the radionuclide transport model.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Compaction of peat is defined by parameter values for the regolith in agricultural systems.

2.4.20 Element supply

Mapping. SKB R-13-43 Section 6.3.3; SKB FEP database Bio22.

Definition. Element supply is the amount of elements and substances from a reservoir that are available for humans and other organisms. Here the definition includes, in addition to elements, dissolved or gaseous compounds that are available for uptake by organisms.

Radionuclide model

Radionuclide transport model. The amounts of radionuclides released to the biosphere are assumed to be small in mass terms relative the abundance of naturally occurring elements, and have no effect on supply of elements. Nutrient availability in the physical components (element supply) may limit the production of primary producers and thereby affect the transport of radionuclides to biota. However, providing this level of detail on element supply is not compatible with the level of detail included in the model. Therefore, element supply is not included in the radionuclide transport model, but is instead considered in specifying values of the underlying ecosystem parameters.

Dose calculations. Not included.

Supporting activities

Landscape modelling. The landscape model identifies the location of different ecosystems with specific properties affecting element supply, so element supply is dependent on the results from the landscape modelling.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Element supply is important for organism productivity. By using site data or data from analogue locations (e.g. other lakes in the nearby area, or similar wetland types in Sweden) for situations that are projected to occur at the site in the future, the effects of element supply on production under ambient conditions is indirectly included. For aquatic organisms, oxygen may become limiting during winter and minimum depths of aquatic ecosystems to enable fish and crayfish populations to exist are used as input parameters to the dose calculation. Element supply also affects the site-specific K_d and CR values (see Tröjbom et al. 2013).

2.4.21 Phase transitions

Mapping. SKB R-13-43 Section 6.3.5; SKB FEP database Bio24.

Definition. Phase transitions are changes between different states of matter: solid, liquid and gas.

Radionuclide model

Radionuclide transport modelling. Effects of pase transitions are explicitly accounted for in mire, agricultural and aquatic ecosystems when modelling gas exchange between surface water (including pore water) and the atmosphere.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Phase transitions are considered in the hydrological modelling through the representation of processes such as evapotranspiration and ice coverage.

Ecosystem-specific parameters. Ecosystem-specific parameters are used to model the effects of phase transitions. Carbon may exchange between dissolved and gas phases and piston velocities are used to quantify such gas exchanges. During the period of ice coverage of lakes, the phase transition from liquid to solid water is addressed in the calculation of appropriate parameter values for other system characteristics.

2.4.22 Physical properties change

Mapping. SKB R-13-43 Section 6.3.6; SKB FEP database Bio25.

Definition. In this context, physical properties change is limited to changes in volume and density, and/or the viscosity of water. Other physical properties e.g. colour, electric charge, length, pressure, are not included.

Radionuclide model

Radionuclide transport modelling. Soil properties (porosity and density) change when mire regolith is drained and cultivated in the radionuclide transport model. The properties of sediments change when sea basins are transformed into lakes.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Different porosities are applied for different regolith types in the hydrological modelling.

Ecosystem-specific parameters. The compaction of different regolith layers after drainage is included by parameterisation of resulting regolith characteristics. Changes in viscosity and salinity are included in parameter values dependent on physical properties change, e.g. viscosity and salinity change between sea and lake stages (affecting, e.g. piston velocity).

2.4.23 Reactions

Mapping. SKB R-13-43 Section 6.3.7; SKB FEP database Bio26.

Definition. In this context, the term 'reaction' is limited to chemical reactions, excluding weathering, decomposition and photosynthesis (treated as separate processes).

Radionuclide model

Radionuclide transport modelling. Reactions lead to transfer of radionuclides from one medium to another in the radionuclide transport model. The equilibrium concentration ratio between solid and liquid phases (K_d) and the concentration ratios between organisms and its surrounding media (CR) include the outcome of chemical reactions. Also modelled in the radionuclide transport model is the reaction that gives an equilibrium of CO_2 concentrations across the air/water interface.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. There are a vast number of reactions going on in the biosphere of which many are indirectly included in the site data used for parameterisation. For example, parameters related to the equilibration of CO_2 are used. Empirical K_d and CR values include a vast number of reactions, the sum effect of these reactions is captured by the K_d and CR values.

2.4.24 Sorption/desorption

Mapping. SKB R-13-43, Section 6.3.8; SKB FEP database: Bio27.

Definition. Sorption is the process whereby dissolved substances adhere to surfaces or are absorbed by particles (e.g. soil or sediment particles), whereas desorption is the reverse process, whereby substances are released. Sorption includes adsorption, partitioning and absorption, as the end result of all these sub-processes is the association of substances with particles.

Radionuclide model

Radionuclide transport modelling. Sorption/desorption leads to transfer of radionuclides from one medium to another in the radionuclide transport model. Sorption is included by use of ecosystem-specific parameters (K_d).

Dose calculations. Sorption/desorption is considered in the dose calculations for humans (e.g. sorption to skin) and to non-human biota by the use of CR values which take into account the sorption of radionuclides.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Solid/liquid partitioning coefficients (K_d) are used to model sorption/desorption. Concentration ratios (CR) used to model uptake by biota also depend on sorption/desorption. Both K_d and CR values are as far as possible based on site data where effects of sorption/desorption processes are included in the measurements.

2.4.25 Water supply

Mapping. SKB R-13-43 Section 6.3.9; SKB FEP database Bio28.

Definition. Water supply is the flux of water that can be utilised by organisms, including humans, in the ecosystem. The supply of water to organisms may be utilised for drinking, and humans may also use the water for other purposes, for example irrigation of crops.

Radionuclide model

Radionuclide transport modelling. The water supply is not explicitly modelled in the radionuclide transport model, but the concentrations of radionuclides in water resources are modelled and used in the dose calculations (see below).

Dose calculations. Water supply is addressed in the dose calculations, were consideration is taken of available water resources in the landscape for different exposed populations (e.g. some populations can utilise drilled wells whereas others are assumed to only be able to use surface water resources. The actual amount water used is considered in the processes uptake and water use.

Supporting activities

Landscape modelling. The landscape model identifies the location of potential sea bays, lakes and streams in the landscape that can be used for humans as water resources and that can be simulated in the dose assessment.

Hydrological modelling. Capacities of future ground- and surface-water are estimated using hydrogeological properties data and hydrological modelling.

Ecosystem-specific parameters Human needs for water (uptake and water use) are parameterised for different exposure variants and compared against water supply in the landscape.

2.4.26 Weathering

Mapping. SKB R-13-43 Section 6.3.10; SKB FEP database Bio29.

Definition. Weathering is the disintegration and decomposition of rock and regolith into smaller pieces. Weathering can be chemical, mechanical and/or biological.

Radionuclide model

Radionuclide transport modelling. Weathering is not explicitly modelled; instead the effect of weathering is included in empirical parameter values, e.g. K_d values.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Leaching of radionuclides from the drained mire may be characterized as a type of weathering. The DIC concentrations in the mire and the regolith (used as parameter values in the radionuclide transport model) are, to a large extent, a result of the dissolution of calcite. Weathering can also affect sorption/desorption processes; these effects are included in the empirical K_d values.

2.4.27 Wind stress

Mapping. SKB R-13-43 Section 6.3.11; SKB FEP database Bio30.

Definition. Wind stress is a mechanical force generated by the wind and affecting surfaces in the biosphere.

Radionuclide model

Radionuclide transport modelling. Wind stress is not explicitly included in the radionuclide transport model, but it is indirectly included by the use of landscape and ecosystem parameters that depend on wind stress.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Fetch (determined by wind stress) is a factor that determines where the accumulation of glacial and postglacial clay occurs.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Wind stress is important for the exchange of gas across the air-water interface and its effect is included in the values selected for piston velocity, which is one of the parameters used to calculate this exchange in the radionuclide transport model.

2.4.28 Acceleration

Mapping. SKB R-13-43 Section 6.4.1; SKB FEP database Bio31.

Definition. Acceleration is the change, either positive or negative, in velocity of a gas, liquid or solid body over time and/or the rate and direction of velocity change.

Radionuclide model

Radionuclide transport modelling. Acceleration is not explicitly included in the radionuclide transport model, but it is considered by the use of hydrological parameter values that are dependent on this process.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Residence times in marine basins are assessed by an approach which takes into account the changes in velocities due to variable bathymetry.

Ecosystem-specific parameters. Not included.

2.4.29 Convection

Mapping. SKB R-13-43 Section 6.4.2; SKB FEP database Bio32.

Definition. Convection is here defined as the transport of a substance (e.g. water) or a conserved property (e.g. temperature) in a liquid or gas. The definition includes convective and advective transport as well as diffusive transport.

Radionuclide model

Radionuclide transport modelling. Water exchange between sea basins and down-stream advection, vertical groundwater advection, pore water diffusion and degassing are included in the radionuclide model. Convection is included implicitly in expressions for atmospheric equilibrium concentrations. Atmospheric transport is also addressed for volatile radionuclides.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. The starting point for the exposure pathways analysis is that groundwater contaminated by releases from the repository reaches the surface environment. Particle tracking is performed to estimate travel times in the groundwater of both rock and regolith. Advective water flows between regolith layers are modelled. Water exchanges between marine basins are also modelled.

Ecosystem-specific parameters. The main aspects of transport in the radionuclide transport model are modelled with hydrological parameters (given by the hydrological modelling). However, gas exchange across the air/water interphase is modelled by the use of a piston velocity which is parameterised for the different ecosystems.

2.4.30 Covering

Mapping. SKB R-13-43 Section 6.4.3; SKB FEP database Bio33.

Definition. Covering is the process whereby something, such as ice or vegetation, covers a surface and thereby reduces the incoming light, as well as reducing the exchange of gases and particles between the surface and the atmosphere.

Radionuclide model

Radionuclide transport modelling. Covering is included in the transition of a lake to a mire (ingrowth). The effect of covering is also addressed where ice-cover is accounted for in ecosystem parameter values for degassing and gas uptake.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Covering is considered in the landscape modelling as lake in-growth by reed expansion.

Hydrological modelling. Ice-cover of lakes and sea bays is included in the hydrological modelling.

Ecosystem-specific parameters. Ice cover affects the exchange of gases across the water/air interface. Periods of ice coverage in lakes and marine basins are considered in setting the parameter values used to calculate exchanges across the air-water interface.

2.4.31 Deposition

Mapping. SKB R-13-43 Section 6.4.4; SKB FEP database Bio34.

Definition. Deposition is the transfer of a material or an element due to gravitation to a surface of any kind. The process thereby includes both sedimentation and atmospheric precipitation. Atmospheric precipitation occurs as dry deposition or wet deposition (rain, snow and hail).

Radionuclide model

Radionuclide transport modelling. Deposition is modelled as sedimentation in aquatic ecosystems and as litter production flux in mires. Precipitation is implicitly included in the modelling of hydrological flows.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Sedimentation of organic and inorganic matter on sea and lake bottoms is included in the landscape modelling.

Hydrological modelling. Precipitation is included in the hydrological modelling.

Ecosystem-specific parameters. The amount of dead organic matter that is not immediately degraded contributes to deposition on the ground which is parameterised for the aquatic and mire ecosystems.

2.4.32 Export

Mapping. SKB R-13-43 Section 6.4.5; SKB FEP database Bio35.

Definition. Export is the process whereby something (e.g. organisms, water, gas, elements, compounds, heat or emigrating humans) is transported out of the model domain.

Radionuclide model

Radionuclide transport modelling. Export is included in the radionuclide transport model in several ways; radionuclide fluxes associated with flows of water and gas including sea basin exchanges and down-stream water flows out of biosphere objects, and radionuclide fluxes associated with leaching and degassing. Dilution of radionuclides, through movement of solid matter or biological populations out of the model area, is cautiously neglected in the radionuclide transport model.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Export of sediment out of the marine basins is included in the landscape modelling.

Hydrological modelling. Runoff out of the modelled biosphere objects is included in the hydrological modelling.

Ecosystem-specific parameters. Not included.

2.4.33 Import

Mapping. SKB R-13-43, Section 6.4.6; SKB FEP database: Bio36.

Definition. Import is the process whereby something (e.g. organisms, water, gas, elements, compounds, heat or immigrating humans) is transported into the model domain.

Radionuclide model

Radionuclide transport modelling. Import is included in the radionuclide transport model in several ways; radionuclides enter the biosphere object through groundwater discharge (release) or groundwater uptake, sea basin exchange, surface water from upstream objects and gas uptake. See anthropogenic release for additional source terms to agricultural ecosystems.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Import of sediment into the marine basins is included in the landscape modelling.

Hydrological modelling. Surface-water flow across the model-area boundary is accounted for in the hydrological modelling.

Ecosystem-specific parameters. Not included.

2.4.34 Interception

Mapping. SKB R-13-43, Section 6.4.7; SKB FEP database: Bio37.

Definition. Interception covers here the fraction of wet and dry deposition of elements that is retained (intercepted) on vegetation and does not immediately infiltrate into the ground or take part in subsurface transport or runoff processes.

Radionuclide model

Radionuclide transport modelling. Effects of intercepted radionuclides from irrigation are included in the Garden plot variant as leaf retention.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Interception is calculated by the hydrological model.

Ecosystem-specific parameters. Parameters describing interception of elements on vegetation after irrigation and the following decrease in activity concentration with time due to the effects of wind, rain and growth are included in the radionuclide model.

2.4.35 Relocation

Mapping. SKB R-13-43, Section 6.4.8; SKB FEP database: Bio38.

Definition. Relocation is the transfer of solid matter and sessile organisms from one point to another, which can be mediated by erosion, landslides, or human activities such as digging and soil transport.

Radionuclide model

Radionuclide transport modelling. Relocation of organic matter through fertilisation (manure and seaweed) is a source term in the infield-outland agriculture exposure variant. The erosion of glacial and postglacial sediments is indirectly included in the radionuclide transport model by applying parameter values derived from the landscape modelling.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Erosion of glacial and postglacial sediments is included in the landscape modelling.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Parameters describing fertilisation by manure and seaweed are used in the model.

2.4.36 Resuspension

Mapping. SKB R-13-43, Section 6.4.9; SKB FEP database: Bio39.

Definition. Resuspension is the process by which material that has been deposited on a surface is reconveyed into the overlying media.

Radionuclide model

Radionuclide transport modelling. Resuspension of radionuclides from upper sediment is explicitly included in the radionuclide transport model.

Dose calculations. Resuspension of fine particulate matter in dust is addressed in exposure/dose calculations.

Supporting activities

Landscape modelling. Resuspension is taken into account in the calculation of the growth of sediment thickness.

Hydrological modelling. Not included.

Ecosystem-specific parameters. A parameter defining resuspension rate for aquatic ecosystems is used in the radionuclide model.

2.4.37 Saturation

Mapping. SKB R-13-43, Section 6.4.10; SKB FEP database: Bio40.

Definition. Saturation is defined here as the change in the water content of the regolith.

Radionuclide model

Radionuclide transport modelling. Saturation is not explicitly modelled in the radionuclide transport model, but is indirectly considered by the use of parameters derived from the underlying hydrological model where the process is included (see below).

Dose calculations. Not included.

Supporting activities

Landscape modelling. Saturation is considered in biosphere object identification.

Hydrological modelling. Water saturation of the regolith is calculated by the hydrological model.

Ecosystem-specific parameters. Regolith layers of sea, lake and mire ecosystems are assumed to be saturated. A parameter defining the amount of water contained in the pores of soils that can be used for cultivation is used in the agricultural part of the radionuclide transport model.

2.4.38 Radioactive decay

Mapping. SKB R-13-43, Section 6.5.1; SKB FEP database: Bio41.

Definition. Radioactive decay is a fundamental process that affects all radioactive (unstable) nuclides. The decay leads to a reduction in activity of a nuclide due to radioactive transformation. Radionuclides decay to other radionuclides or stable nuclides.

Radionuclide model

Radionuclide transport modelling. Radioactive decay of a radionuclide's inventory is proportional to its inventory, whereas its ingrowth is proportional to the inventory of the parent nuclide.

Dose calculations. Short-lived radionuclides are treated as being in secular equilibrium and the dose contributions of progeny nuclides are included in the dose coefficient of the parent nuclide, in this way the combined effect of radionuclides in decay chains are considered in the dose calculations. For long-lived radionuclides, members of decay chains are treated explicitly in the dose calculations.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Half-lives are used to model the radioactive decay of radionuclides.

2.4.39 Exposure

Mapping. SKB R-13-43, Section 6.5.2; SKB FEP database: Bio42.

Definition. Exposure is here meant as the process whereby living or dead organisms/matter are exposed to alpha, beta, gamma or neutron radiation. Exposure can either be external exposure from sources outside the body or internal exposure from sources inside the body.

Radionuclide model

Radionuclide transport modelling. Exposure is not included in the radionuclide transport model.

Dose calculations. Internal and external exposures are calculated from the radionuclide concentrations in food and the environment, both to humans and to non-human biota. An exposure pathway analysis has been conducted and four different land use variants have been identified and used as bounding cases to assess doses to the most exposed groups of humans and dose rates to the most exposed non-human biota.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Several kinds of dose coefficients are parameterised, e.g. for ingestion, inhalation, absorption by non-human biota.

2.4.40 Heat storage

Mapping. SKB R-13-43, Section 6.5.3; SKB FEP database: Bio43.

Definition. Heat storage (heat capacity) is the ability of materials (solids, gases, or liquids) to store thermal energy.

Radionuclide model

Radionuclide transport modelling. Heat storage is not included in the radionuclide transport model, but the heat storage capacities of water in its various phases are considered in ecosystem-specific parameters as described below.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. In aquatic and mire ecosystems heat storage in the water affects the abundance and type of biota, i.e. heat storage dampen the effect of large temperature changes in the air. By using site data on the abundance and types of organisms, this process is indirectly included in parameter values for biomasses used in the radionuclide transport model. Temperature is also directly included in calculation of each radionuclide's solubility coefficient and the piston velocity used in the radionuclide transport model.

2.4.41 Light-related processes

Mapping. SKB R-13-43, Section 6.5.5; SKB FEP database: Bio45.

Definition. Light-related processes are those that involve light entering the biosphere (insolation) and processes associated with this, i.e. absorption, scattering and reflection. Light-related processes do not include photosynthesis, which is treated as a biological process (see *primary production*).

Radionuclide model

Radionuclide transport modelling. Not included, but indirectly considered by the use of ecosystem parameters that take this process into consideration.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Light is considered by use of site data (and thereby present light conditions for primary producers in the different ecosystems) in the calculation of the primary production parameters that are used in the radionuclide transport model.

2.4.42 Radionuclide release

Mapping. SKB R-13-43, Section 6.5.7; SKB FEP database: Bio47.

Definition. Radionuclide release is the release of radionuclides from a repository for solid radioactive waste via the geosphere to the biosphere.

Radionuclide model

Radionuclide transport modelling. The radionuclide release from the repository is the source term for radionuclide transport model. See also Import and Anthropogenic release above.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Not included.

Hydrological modelling. Not included.

Ecosystem-specific parameters. Not included.

2.4.43 Change in rock-surface location

Mapping. SKB R-13-43, Section 6.6.1; SKB FEP database: Bio48.

Definition. Change in rock-surface location refers to vertical changes in the rock-surface location due to tectonic, isostatic rebound or repository induced changes.

Radionuclide model

Radionuclide transport modelling. The effects of land upheaval on geometries, regolith depths and associated processes is accounted for in several time-dependent landscape and hydrological parameters used, but not explicitly modelled, in the radionuclide transport model.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Change in rock-surface location is described by the shore-line displacement in the landscape model.

Hydrological modelling. The rock surface elevation at each time step is accounted for in the hydrological modelling.

Ecosystem-specific parameters. Not included.

2.4.44 Sea-level change

Mapping. SKB R-13-43, Section 6.6.2; SKB FEP database: Bio49.

Definition. Sea-level change is the rise and fall of the sea level relative to the land surface. For sea-level change caused by land upheaval (see Bio48 above).

Radionuclide model

Radionuclide transport modelling. Natural fluctuations in sea-level change due to e.g. frequency and magnitude of storms are not explicitly included in the radionuclide transport model but are included in landscape parameter values describing the start and end of threshold effects at lake isolation.

Dose calculations. Not included.

Supporting activities

Landscape modelling. Sea-level change is described by the shore-line displacement in the landscape model. The sea-level of the model area is defined by landscape geometry parameters used in the radionuclide transport model.

Hydrological modelling. The sea level at each time step is accounted for in the hydrological modelling.

Ecosystem-specific parameters. Not included.

2.4.45 Thresholding

Mapping. SKB R-13-43, Section 6.6.3; SKB FEP database: Bio50.

Definition. Thresholding is the occurrence and location of topographical thresholds that delimit water bodies in height.

Radionuclide model

Radionuclide transport modelling. Thresholds are not modelled in the radionuclide transport model, but are considered by the use of landscape parameters defining the locations of sea basins and lakes.

Dose calculations. Not included.

Supporting activities

Landscape modelling. The thresholds of the landscape are defined in the landscape model. Thresholding is an important factor that is used to identify sea bays and lakes.

Hydrological modelling. Lake thresholds at each time step are accounted for in the hydrological modelling.

Ecosystem-specific parameters. Not included.

3 Exposure pathways analysis

An exposure pathway is defined by IAEA (2007) as ‘a route by which radiation or radionuclides can reach humans and cause exposure’. SSM (2008) (SSMFS 2008:37, general advice) defines an exposure pathway in more detail as: the migration of the radioactive substances from a repository to a place where human beings are present, or where an organism covered by the environmental protection regulations is present. This includes dispersion in the geological barrier, transport with water and air flows, migration within ecosystems, and uptake in human beings or non-human biota in the environment. Humans can be exposed through several exposure pathways due to different ways of utlising the landscape. Figure 3-1 illustrate potential exposure pathways for humans utlising an area with discharge from a repository.

SSM gives guidance on how to handle exposure pathways in relation to biosphere conditions and protection of the environment (SSM 2008).

- The future biosphere conditions for calculations of consequences for human beings and the environment should be selected in agreement with the assumed climate state. Unless it is clearly inconsistent, however, today’s biosphere conditions at the repository and its surroundings should be evaluated, i.e. agricultural land, forest, wetland (mire), lake, sea or other relevant ecosystems. Furthermore, consideration should be taken to land uplift (or subsidence) and other predictable changes.
- The risk analysis can include a limited selection of exposure pathways, although the selection of these should be based on an analysis of the diversity of human use of environmental and natural resources which can occur in Sweden today. Consideration should also be taken to the possibility of individuals being exposed to combinations of exposure pathways within and between different ecosystems.

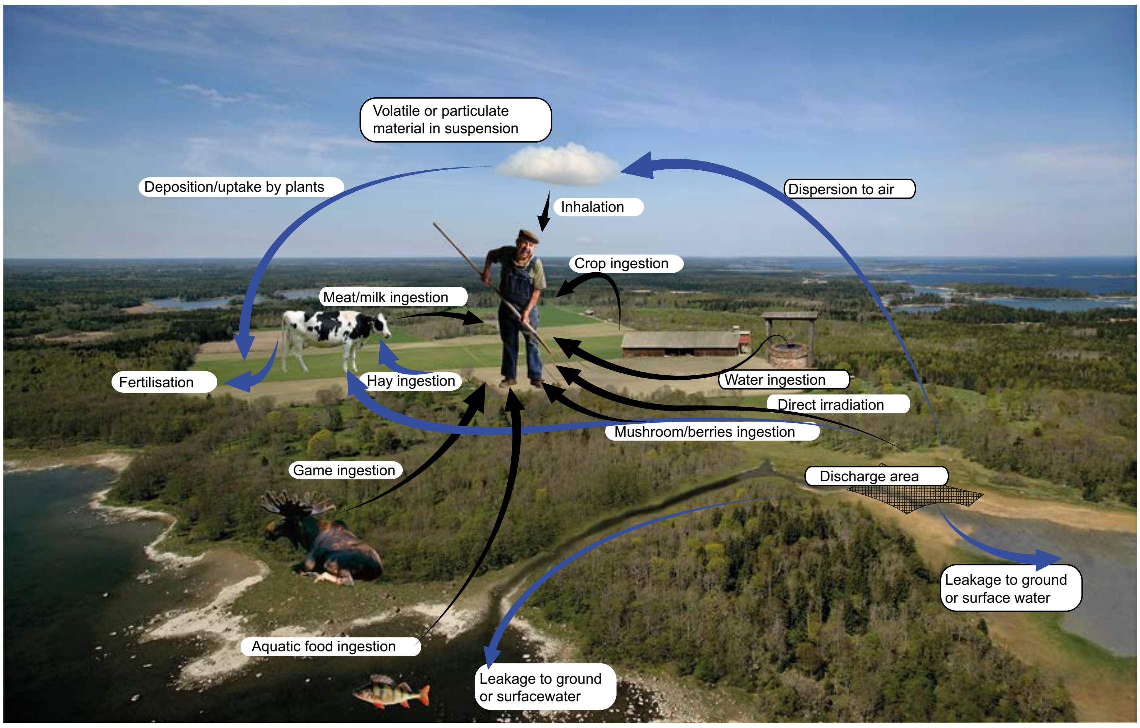

Figure 3-1. *Potential exposure pathways.*

Due to the long time-scales considered for evaluating the safety of disposal of long-lived solid radioactive waste, the characteristics and habits of future inhabitants, as well as the characteristics of the contaminated area, can only be based on a number of assumptions (cf. ICRP 1998). The assumed habits should reflect all relevant pathways of exposure and, as far as can be ascertained, be reasonable and sustainable with respect to the considered area, as well as human physiological requirements (ICRP 2006). By identifying environmental media accessible to humans and with a high potential for radionuclide accumulation, and then considering human behaviour that would lead to the greatest exposure from utilising such contaminated natural resources, a framework can be developed for identifying the most exposed group.

In previous safety assessments a systematic approach was applied with the use of a interaction matrix for identification of transport and accumulation of radionuclides and exposure of humans and biota (see Chapter 2). A range of exposure patwyas was identified in the previous safety assessments and included for the exposure evaluation of the most exposed group. In this chapter potential exposure pathways, relevant for the long-term safety of a geological disposal facility are described in another structured way. An analysis of the exposure pathways is performed in order to identify and exclude pathways that are not significant for long-term safety. The potential exposure pathways are then related to a set of potentially most exposed groups identified based on potential land use variants and habits of different societies. The first few subsections describe the analysis of exposure pathways in the biosphere that is relevant for humans. Exposure pathways to non-human biota are discussed in Section 3.5.

3.1 Methodology

The methodology for exposure pathway analyses applied here is based on the methodology for evaluating exposure pathways presented by the Agency for Toxic Substances and Disease Registry (ATSDR 2005). The goal of the ATDSR exposure pathway evaluation is to identify likely site-specific exposure situations and answer the questions: Is anyone at a given site exposed to environmental contamination? Under what conditions does this exposure occur? For the analysis it is convenient to divide the exposure pathway into five elements, as follows:

1 The **contaminant source or release**. Sources may include waste packages, drums, landfills, and many others which may release radionuclides into the environment.

2 **Environmental transport and fate**. Once released to the environment, radionuclides move through and across different media and may also be subject to transformations in their physical state and chemical form.

3 **Exposure points or area**. This is the specific location(s) where people, or non-human biota, might come into contact with a contaminated medium.

4 **Exposure route**. The route is the means by which people physically contact the radionuclides at the exposure point (e.g. by inhalation or ingestion)

5 Potentially **exposed populations**, i.e. populations that may come to be, or may have been, exposed to radiation.

For the scope of this report, element 1 is considered to be discharge of contaminated groundwater into the deep regolith layers from the geosphere, or pumping of contaminated water from a well. Element 2 is the transport of the released radionuclides from the deep regolith layers to environmental media on the surface, which also includes transport of well water to its point of use. The transport and fate of radionuclides in the biosphere is handled jointly through FEP analysis (Chapter 2), ecosystem descriptions (described in the ecosystem reports: Andersson (2010), Aquilonius (2010) and Löfgren (2010)), and biosphere transport modelling (Saetre et al. 2013b). Hence, the analysis starts at element 3, by identifying the exposure points and areas for underpinning the subsequent exposure route analysis.

3.2 Point or area of potential exposure and the environmental media

Identifying the potential exposure points or areas and the potential contaminated media at these locations is the starting point of the exposure pathway analysis performed here. Hydrogeological modelling has shown that contaminated groundwater from the present (SFR1) and planned (SFR3) repositories is likely to be discharged to the deep regolith layers of certain ecosystems, i.e. sea basins, lakes and wetland areas (SKB 2014a). Radionuclides will then be transported to surface waters and sediments, peat, and the atmosphere of the receiving ecosystems, and spread to other areas by, for example, surface and groundwater fluxes. Moreover, human inhabitants may drain and cultivate lake and mire sediments, use contaminated vegetation as fodder and fertilisers for agricultural soil, and irrigate a garden plot with contaminated water. For the purpose of this analysis, the types of exposure areas have been categorized into:

- **Terrestrial environment**. Comprising the sub-types: mire, agricultural land, garden plot.
- **Aquatic environment**. Comprising the sub-types: lake, river, stream and sea.

The relevant exposure points are expressed here by the different types of environmental media potentially contaminated by repository-derived radionuclides. The environmental media that need to be considered are atmosphere, regolith, water and non-human biota (primary producers and consumers). To better correspond with the sub-types of environments identified above, the environmental media are further distinguished. The environmental media and the types of environment in which they are relevant are presented in Table 3-1 for terrestrial environments and in Table 3-2 for aquatic environments.

Table 3-1. The environmental media for terrestrial environments and the types of environments in which they are relevant.

	Type of environment		
Environmental media	Arable land	Mire	Garden plot
Atmosphere – outdoor	X	X	X
Atmosphere – indoor	X	X	X
Regolith – soil	X		X
Regolith – peat	X	X	X
Well water	X		X
Primary producers	X	X	X
Consumers	X	X	

Table 3-2. The environmental media for aquatic environments and the types of environments in which they are relevant.

	Type of environment			
Environmental media	Lake	River	Streams	Sea
Atmosphere – outdoor	X	X	X	X
Surface water	X	X	X	X
Regolith – sediment	X	X	X	X
Primary proucers	X	X	X	X
Consumers	X	X	X	X

3.3 Exposure route analysis for humans

To establish a comprehensive set of exposure routes, the processes underpinning radiation exposures need to be selected. The processes by which individuals can be exposed to radionuclides in contaminated environmental media during different types of activities may be divided as follows:

- Through the respiratory tract (inhalation).
- Through the digestive tract (ingestion).
- External irradiation.
- Through the skin (dermal absorption).
- Direct introduction into the body (through traumatic entry of foreign material, or into open wounds).

In the context of a prospective dose assessment for a geological disposal facility at Forsmark, the first three processes in the above list are considered relevant. This is in line with international recommendations, where for example the IAEA states that the principal modes of exposure relevant to radiological exposure assessment are ingestion, inhalation and external irradiation (IAEA 2003). Exposure modes related to the skin and hair (transdermal transfer, adhesion to skin and hair) are considered negligible (IAEA 2003, SSI 1996). Moreover, the risk of exposure due to radionuclides entering directly into the body is considered negligible in comparison with exposure by ingestion of environmental media e.g. drinking water.

The three relevant modes of exposure (ingestion, inhalation and external irradiation) may now be combined with the environmental media in the identified points or area of potential release of contaminants (Section 3.2). This results in a comprehensive set of environmental media × exposure route combinations that are relevant for a geological disposal facility at Forsmark. These are called 'exposure route cases', and examples of human activities related to each case are given. Each exposure route case is then assessed for significance with respect to long-term safety (Section 3.3.1). For cases judged insignificant, the rationale behind the judgement is presented in detail in the following section (Section 3.3.2).

3.3.1 Exposure route cases

In total, 29 relevant exposure route cases were identified for terrestrial environments (Table 3-3), and the corresponding number for aquatic environments was 15 (Table 3-4). Note that this set included a few indirect exposure route cases, where radionuclides are transferred from one environmental medium to another. In total, 16 terrestrial and six aquatic cases were considered relevant, and these are further analyzed in the safety assessment. The rest of the cases were considered to present little or no risk compared with the included cases, and the rationale for their dismissal is discussed in the next section (Section 3.3.2).

Table 3-3. Exposure route cases in terrestrial environments (denoted Ter-1 to Ter-29) and examples of related activities. SKB IM gives the position in SKB's interaction matrix where the exposure route has been identified in present and previous assessments (see Appendix A). A recommendation for inclusion in further safety assessment is given in the last column.

Environmental media	Exposure route case		Related activities	SKB IM	Propagate
Atmosphere – outdoor	Ter-1	Inhalation of gases.[2]	All outdoor activities.	5:11	Yes
	Ter-2	Inhalation of dust.	All outdoor activities.	5:11	Yes
	Ter-3	External irradiation.	All outdoor activities.	5:11	No
Atmosphere – indoor	Ter-4	Inhalation of gases.[3]	All indoor activities.	5:11	No[4]
	Ter-5	Inhalation of dust.	All indoor activities.	5:11	No
	Ter-6	External irradiation.	All indoor activities.	5:11	No
Regolith – soil (inorganic)	Ter-7	Deliberate ingestion of soil.	Eating.	2:11	No
	Ter-8	Inadvertent ingestion of soil.	Eating, ploughing, digging, harvesting, gardening, playing, gathering, picnicking.	2:11	Yes
	Ter-9	External irradiation from the ground when staying outdoors.	All outdoor activities in terrestrial environments where there are soils.	2:11, 3:11	Yes
	Ter-10	External irradiation from the ground when staying indoors.	All indoor activities.	2:11, 3:11	No
Regolith – peat	Ter-11	Deliberate ingestion of peat.	Eating.	2:11	No
	Ter-12	Inadvertent ingestion of peat.	Eating, harvesting, gardening, playing, gathering, picnicking.	2:11	Yes
	Ter-13	External irradiation from the ground when staying outdoors.	All outdoor activities in mires.	2:11, 3:11	Yes
	Ter-14	External irradiation from the ground when staying indoors.	All indoor activities.	2:11, 3:11	No
	Ter-15	Indirect[1] contamination of the environment (inhalation of gas/dust).	Burning of peat.	2:11	Yes
	Ter-16	Indirect[1] contamination of soil.	Fertilisation with peat ash.	2:11	Yes
Well water	Ter-17	Ingestion of well water.	Drinking.	1:11, 3:11	Yes
	Ter-18	External irradiation from well water.	Bathing and showering.	1:11, 3:11	No
	Ter-19	Indirect[1] contamination of crops and soils.	Eating crops irrigated with well water.	1:11, 3:11	Yes
	Ter-20	Indirect[1] contamination of animals that drinks water.	Eating meat or other animal proucts (milk, kidney etc) from animals that have drunk well water.	1:11, 3:11	Yes
Primary producers	Ter-21	Ingestion of crops, berries and mushrooms.	Eating.	6:11	Yes
	Ter-22	External irradiation outdoors from radionuclides in the standing vegetation.	Outdoor activities in environments where there is vegetation.	6:11	Yes
	Ter-23	External irradiation indoors from stored vegetation.	Indoor activities in buildings where vegetation is stored.	6:11	No
	Ter-24	External irradiation indoors from vegetation used as building materials.	Indoor activities in buildings where vegetation, such as wood, is used as building materials.	6:11	No
	Ter-25	Indirect[1] contamination of the environment (inhalation of gas/dust).	Burning of wood and other vegetation.	6:11	Yes
	Ter-26	Indirect[1] contamination of soil.	Fertilisation with herbivore manure originating from fodder or ash from wood.	6:11	Yes
Consumers	Ter-27	Ingestion of consumers.	Eating	9:11, 10:11	Yes
	Ter-28	External irradiation outdoors from animals.	Human contact with animal (e.g. animal husbandry, riding, pets).	9:11, 10:11	No
	Ter-29	External irradiation indoors from animals.	Human contact with animal (e.g. animal husbandry, pets).	9:11, 10:11	No

[1] The exposure routes refer to the transfer of radionuclides from the environmental media to humans, except for the routes related to indirect contamination. Indirect exposure routes (pathways) are defined here as those that can lead to transfer of radionuclides from one environmental media to another environmental media or environment as result of human activities.

[2] Considered important for volatile radionuclides, e.g. C-14.

[3] Could be important for volatile radionuclides that could penetrate the house from the basement, emanate from building materials or released into the air when using household water.

[4] Considered to be included in the outdoor case, see text below.

Table 3-4. Exposure route cases in aquatic environments (denoted Aq-1 to Aq-15) and examples of related activities. SKB IM gives the position in SKB's interaction matrix where the exposure route has been identified in present and previous assessments (see Appendix A). A recommendation for inclusion in further safety assessment is given in the last column.

Environmental media	Exposure route case		Related activities	SKB IM	Propagate
Atmosphere – outdoor	Aq-1	Inhalation of gases	Swimming, boating, fishing.	5:11	No
	Aq-2	Inhalation of aerosols	Swimming, boating, fishing.	5:11	No
	Aq-3	External irradiation during immersion	Swimming, boating, fishing.	5:11	No
Surface water	Aq-4	Ingestion of surface water	Drinking.	4:11	Yes
	Aq-5	External irradiation during immersion	Swimming.	4:11	No
	Aq-6	External irradiation above water	Boating, fishing.	4:11	No
	Aq-7	Indirect[1] contamination of crops and soils	Eating crops irrigated with contaminated surface water.	4:11	Yes
	Aq-8	Indirect[1] contamination of animals that drinks contaminated water	Eating meat or other animal proucts (milk, kidney etc) from animals that have drunk contaminated surface water.	4:11	Yes[2]
Regolith – sediment	Aq-9	External irradiation from sediments	Sunbathing, fishing, picnicking, camping.	2:11	Yes
	Aq-10	Deliberate ingestion of sediments	Eating.	2:11	No
	Aq-11	Inadvertent ingestion of sediments	Sunbathing, fishing, picnicking, camping.	2:11	No
Primary producers	Aq-12	Ingestion of food	Eating	6:11	No
	Aq-13	Indirect[1] contamination of animals that eat freshwater primary producers.	Eating meat or other animal proucts (milk, kidney etc) from animals that have eaten contaminated food.	6:11	No
	Aq-14	Indirect[1] contamination of soils by fertilisation with aquatic primary producers.	Eating crops fertilised with contaminated aquatic primary producers.	6:11	Yes
Consumers	Aq-15	Ingestion of contaminated consumers.	Eating.	7:11, 8:11, 9:11, 10:11	Yes

[1] The exposure routes refer to the transfer of radionuclides from the environmental media to humans, except for the routes related to indirect contamination. Indirect exposure routes (pathways) are defined here as those that can lead to transfer of radionuclides from one environmental medium to another environmental medium or environment as a result of human activities.

[2] Ingestion of animal meat and milk from animals drinking freshwater from contaminated surface water should be considered as a pathway if it is likely to occur (EC 2002).

3.3.2 Cases or aspects considered insignificant for safety

Of the 44 cases listed in Tables 3-3 and 3-4, 22 are considered to be of little or no safety concern in the assessment of a geological repository. The justifications for excluding these exposure route cases are documented in this section. The potential relevance for safety is also discussed for four cases that were included in order to provide recommendations for the associated calculations.

External irradiation from atmosphere (Ter-3, Ter-6, Aq-3)

When a person is externally irradiated from a contaminated atmosphere, it is here assumed that the person is also exposed due to inhalation of the same air. The strategy to screen out these exposure route cases is to compare the external effective dose rate from the air and the internal effective dose rate due to inhalation of the air. If the external dose rate is less than 10% of the inhalation dose rate, for each radionuclide, it is considered that the exposure route related to external irradiation in atmosphere may be excluded from further analysis.

The external effective dose rate from air, E_{ext}, and the effective dose rate due to inhalation of air, E_{inh}, are calculated as:

$E_{\mathrm{subm}} = DC_{\mathrm{air\_ext}} \times O_{\mathrm{f}} \times C$ [Sv h^{-1}]

$E_{\mathrm{inh}} = DC_{\mathrm{inh}} \times IR \times O_{\mathrm{f}} \times C$ [Sv h^{-1}]

Where

$DC_{\mathrm{air\_ext}}$ (Sv h^{-1} per Bq m^{-3}) is the radionuclide-specific dose coefficient for external irradiation from air, (values are based on Eckerman and Ryman 1993, Table III.1, assuming all progeny are in secular equilibrium in the environment);

DC_{inh} (Sv Bq^{-1}) are the radionuclide-specific effective dose coefficients for inhalation of radionuclides for members of the public, (values are taken from ICRP 2012, Table G.1);

IR is the inhalation rate, here selected to be 1 m^3 h^{-1} (see Human characteristics in Grolander, 2013, Parameter report).

Q_{f} is the occupancy factor, i.e. the fraction of the time a person is exposed; (the value for Q_{f} does not affect the screening calculation); and

C is the activity concentration (Bq m^{-3}) in the air; (the value for C does not affect the screening calculation.

The ratios of external effective dose rates from air, E_{ext}, and the effective dose rates due to inhalation of air, E_{inh}, are plotted in Figure 3-2. The figure shows that the external dose rates are less than 10% of the inhalation dose rate for all radionuclides. The radionuclide with the highest external irradiation dose rate in comparison with inhalation dose is Co-60 (E_{ext} is 1.4% of E_{inh}). Two more radionuclides, Cs-134 and Sn-126, have an E_{ext} that is over 1% of E_{inh}.

Based on these results, the exposure routes related to external irradiation from the atmosphere can be excluded from further analysis in a safety assessment for a geological repository at the Forsmark site.

Inhalation of gases indoor (Ter-4)

Volatile radionuclides will be degassed from the water-air interface of biosphere objects (the mire and the lake, and from the drained mire). It is not considered plausible that any building will be situated at such location that will make them act as a potential container of volatile radionuclides originating from the biosphere object. The volatile gas that is modelled is CO_2, which will be more accurately represented under outdoor conditions in Ter-1.

Inhalation of dust indoor (Ter-5)

The exposure due to inhalation of dust originating from contaminated land is considered to be much higher outdoors (Ter-2) than indoors, because of the physical barrier buildings constitute and the resultant limited air-exchange that occurs between indoors and outdoors. This exposure pathway is screened out by making a conservative assumption on the time spent outdoors for the exposed population of hunters and gatherers (see below), who spend all their time outdoors, in contaminated areas.

Ingestion of regolith, deliberate or inadvertent (Ter-7, Ter-11, Aq-10, Aq-11)

The deliberate ingestion of soil by children does not need to be considered in assessments because this pathway is a recognised medical condition, known as pica, which tends to last for a relatively short time (EC 2002). Deliberate ingestion by adults, so called geophagy is typically the consumption of clay from known, usually uncontaminated sources (ATSDR 2001) and is therefore not considered. Exposure from inadvertent eating of aquatic sediments is regarded to be much less than from terrestrial sediments and would therefore be screened out by a calculation case using terrestrial sediments.

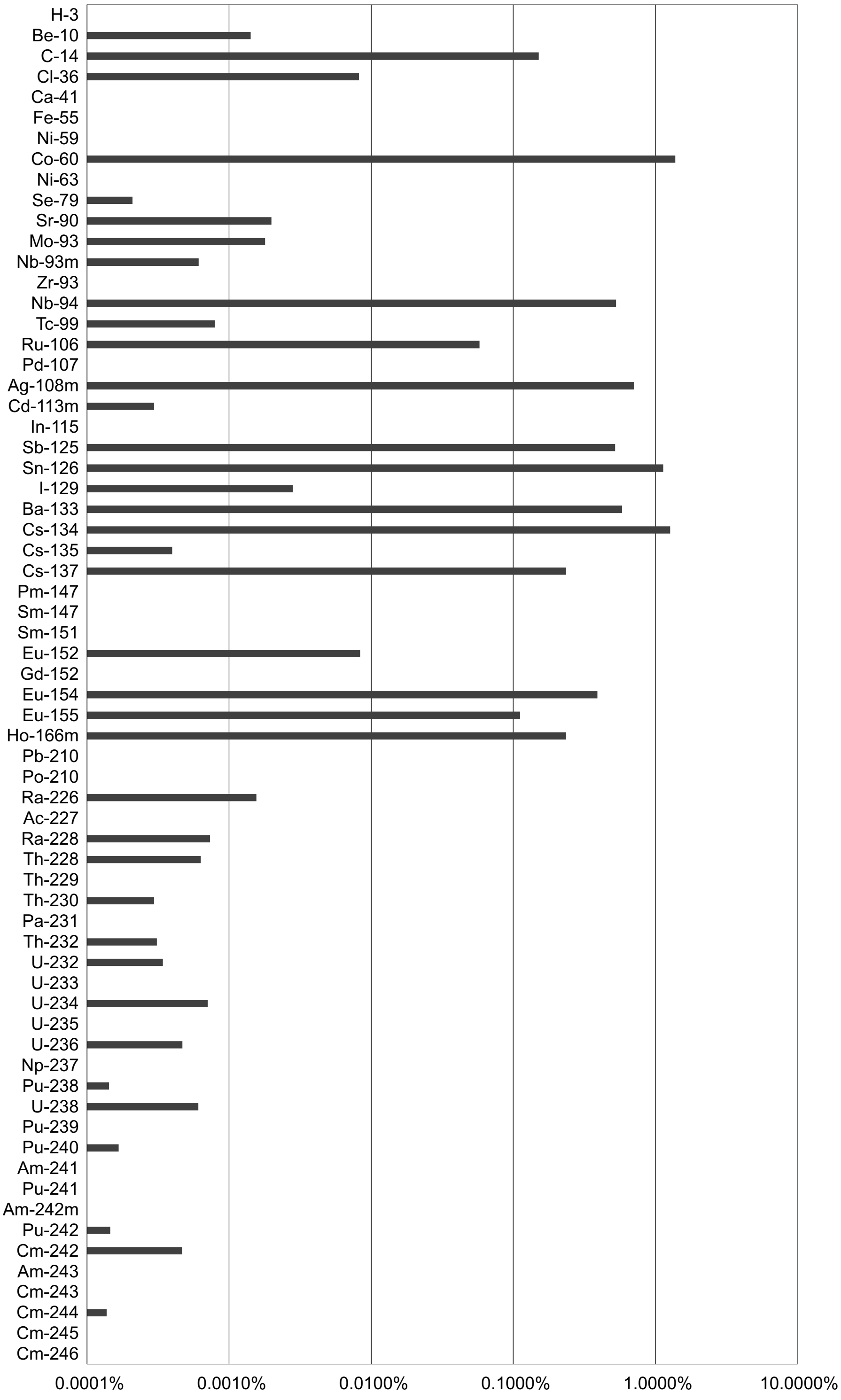

Figure 3-2. *The percentage of external effective dose rate from air,* E_{ext}*, relative to the effective dose rate due to inhalation of air,* E_{inh}*. The external effective dose rate from air is well below 10% of the effective dose rate due to inhalation of air.*

External irradiation from the ground when staying indoors (Ter-10, Ter-14)

The exposure from radionuclides in the ground is lower indoors than outdoors because of the shielding offered by the buildings. This exposure pathway is screened out by the conservative assumption that houses have no dose-reduction effect.

External irradiation from water (Ter-18, Aq-5, Aq-6)

The three exposure route cases are related to external irradiation due to usage of well water as household water, such as taking baths and showers (Ter-18), to use of surface waters for swimming (Aq-5) and exposure during activities above water, such as boating and fishing (Aq-6).

The strategy to screen out these exposure route cases is to compare their external effective dose rate to the internal effective dose rate due to ingestion of (the same) water. Hence, the assumptions are that a person drinks the same well that are used for taking baths and showers (Ter-18), or drinks the water from the same freshwater body where the swimming, boating and fishing activities (Aq-5 and Aq-6) are presumed to occur.

The dose coefficients for immersion in contaminated water can also be used to estimate the external effective dose rate above water (for example during boating activities) by applying a dose-reduction factor of 0.5 (Eckerman and Ryman 1993, p 189). If the external dose rate is less than 10% of the ingestion dose rate, for each radionuclide, it is considered that the exposure routes related to external irradiation from well water, during immersion in (surface) water and during activities above water may be excluded from further analysis. The external effective dose rate due to immersion in water, E_{imm}, activities above water, E_{above}, and the effective dose rate due to ingestion of water, E_{ing}, are calculated as:

$E_{\mathrm{imm}} = DC_{\mathrm{imm}} \times O_{\mathrm{f,bathing/swimming}} \times C$ [Sv year^{-1}]

$E_{\mathrm{above}} = DC_{\mathrm{imm}} \times 0.5 \times O_{\mathrm{f,boating}} \times C$ [Sv year^{-1}]

$E_{\mathrm{ing}} = DC_{\mathrm{ing}} \times IR_{\mathrm{W}} \times C$ [Sv year^{-1}]

Where

DC_{imm} (Sv year^{-1} per Bq m^{-3}) is the radionuclide-specific dose coefficient for external irradiation due to water immersion; values are based on Eckerman and Ryman (1993, Table III.2), assuming all progeny are in secular equilibrium in the environment;

DC_{ing} (Sv Bq^{-1}) is the radionuclide-specific effective dose coefficient for ingestion of radionuclides for members of the public; values are taken from ICRP (2012, Table F.1);

IR_{W} is the intake rate of drinking water, here selected to 0.73 m^3 year^{-1} (see Human characteristics in Grolander 2013).

$Q_{\mathrm{f,bathing/swimming}}$ is the occupancy factor for bathing or swimming, i.e. the fraction of the time a person is immersed in water (see discussion below for the used values);

$Q_{\mathrm{f,boating}}$ is the occupancy factor for boating and fishing, i.e. the fraction of the time a person spends above water (see discussion below for the used value); and

C is the activity concentration (Bq m^{-3}) in either the water or surface water; the value for C is irrelevant for the screening calculation.

The occupancy of bathing in well water is selected to 17 minutes per day (hence, $Q_{\mathrm{f,bathing}}$ is 1.2E–2); this is the value recommended by the US EPA (US EPA 2011, Table 16-1). The occupancy of swimming in surface waters is selected to 45 minutes per month (hence, $Q_{\mathrm{f,swimming}}$ is 1.0E–3); this is the value recommended by the US EPA for adults (US EPA 2011, Table 16-1). Consequently, the occupancy factor for bathing is higher and was therefore chosen to represent the exposure route of $\mathrm{E}_{\mathrm{imm}}$ in the calculations below. The occupancy for boating is assumed to be 20 hours per month (hence, $Q_{\mathrm{f,boating}}$ is 2.7E–2).

The ratios of external effective dose rates due to water immersion, E_{imm}, or being above water, E_{above}, and the effective dose rates due to water ingestion, E_{ing}, are plotted in Figure 3-3 (only water immersion due to bathing is included in the figure since the ratios are alwaus smaller for water immersion due to swimming). The figure shows that the external dose rates are less than 10% of the ingestion dose rate for all radionuclides. The radionuclide with the highest external irradiation dose in comparison with water ingestion dose are Nb-94, Ho-166m, Co-60, Ag-108m and Eu-154 (E_{imm} and E_{above} are about 4.5–6.5% of E_{ing}).

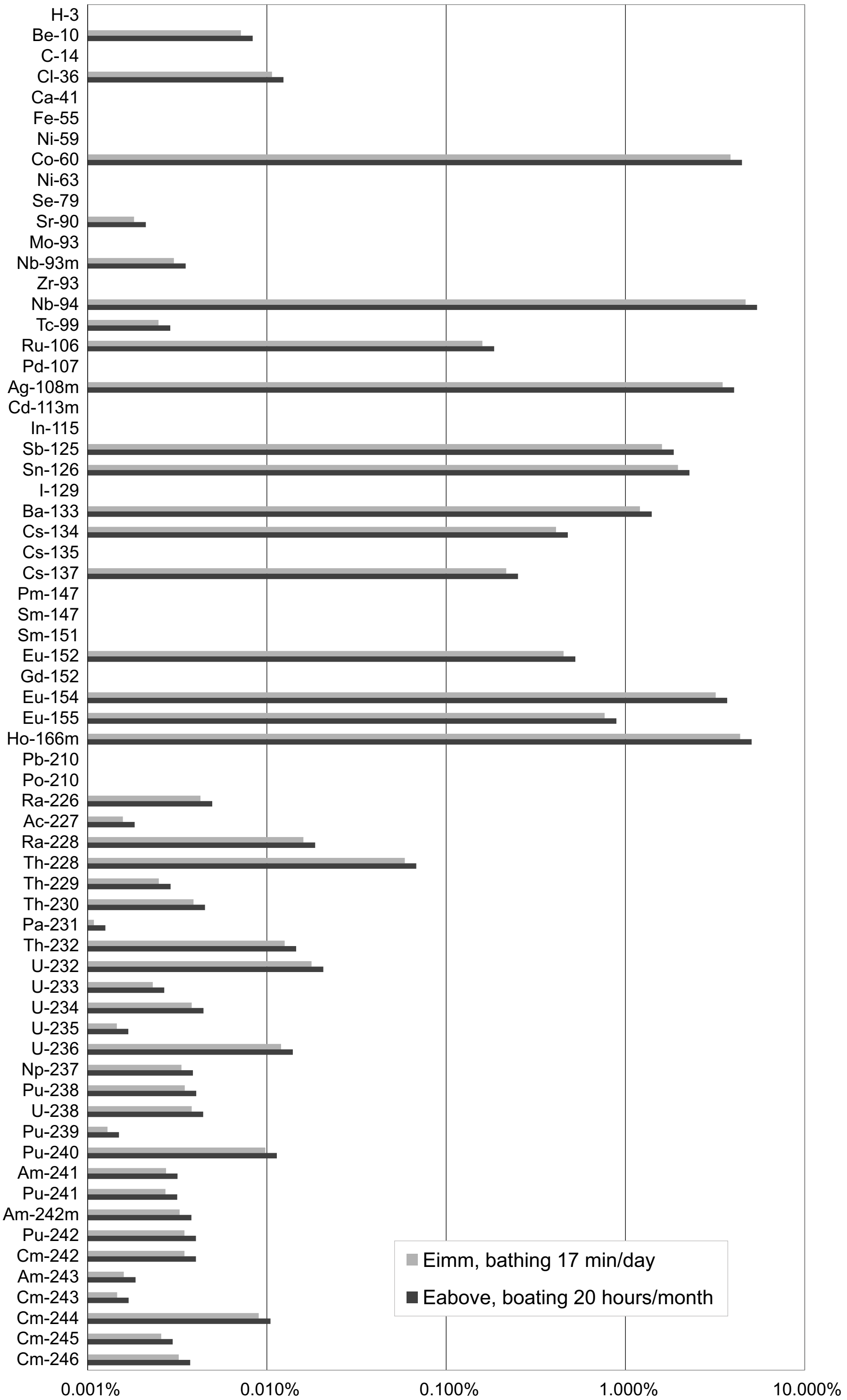

Figure 3-3. *The percentages of external effective dose rate due to bathing and boating relative to the internal effective dose rate due to ingestion of water.*

Based on these results, the exposure routes related to external irradiation from well water, during immersion in (surface) water and during activities conducted above water can be excluded from further analysis in a safety assessment for a geological repository at the Forsmark site.

Note: the strategy applied above for swimming in surface waters is not valid for swimming in sea water, since this is not used as drinking water. However, it is expected that activity concentrations in the Baltic Sea from a hypothetical release from a geological repository at Forsmark will be so low, due to fast dilution, that this exposure route will not be significant to safety.

External irradiation from terrestrial primary producers and consumers (Ter-23, Ter-24, Ter-28, Ter-29)

The external exposure of humans from primary producers and consumers is normally not considered in a long-term safety assessment for nuclear waste disposal. It is often considered that external irradiation from soil and sediment dominates over external irradiation from primary producers and animals (e.g. NWMO 2011, Section 3.3.04.01). However, some radionuclides, such as Cl-36 may reach high concentrations in the vegetation and the exposure route Ter-22 is used as a calculation case, which is also assumed to include Ter-23 and Ter-24. Human contact with animals is generally small and the ingestion of meat (Ter-27) is included in the analysis; therefore, the two exposure routes for external irradiation can be excluded from further analysis in a safety assessment for a geological repository at the Forsmark site.

Inhalation of gases and aerosols in aquatic environments (Aq-1, Aq-2)

Inhalation of gases during boating and swimming is generally an unimportant pathway (EC 2002). The doses from inhalation of re-suspended river-bank sediments are usually negligible (EC 2002). Inhalation of sea spray will generally only give a small contribution to dose in comparison with other potential exposure routes related to contaminated sea water, especially consumption of marine food.

Ingestion of aquatic primary producers (Aq-12)

If there were indications that local people would consume marine plants then the doses received from this pathway would form a significant proportion of the total dose received by an individual and would need to be considered (EC 2002). However, edible aquatic primary producers are not expected to be available in future freshwater and marine environments at the Forsmark site (Andersson 2010, Aquilonius 2010); hence, this exposure route case is assumed to be irrelevant.

Indirect contamination of animals that eat aquatic primary producers (Aq-13)

An indirect exposure route is defined here as one that can lead to transfer of radionuclides from one environmental medium to another environmental medium or environment as a result of human activities. A common way of sustaining cattle with winter fodder was to use hay from mires or shore meadows. Humans eating livestock that have been fed with aquatic plants or algae obtained from locations adjacent to the mire or the shore may be exposed to different concentrations and inventories of radionuclides than those eating meat from animals fed entirely from the terrestrial environment. This exposure route is included in the calculations.

3.4 Potentially exposed populations

The last element in the exposure pathway methodology concerns the selection of groups of persons who may potentially be exposed to radionuclides in environmental media in different exposure pathways. The principal objective of the disposal of solid radioactive waste is the protection of current and future generations from the radiological consequences of waste produced by the current generation, and that individuals and populations in the future should be afforded at least the same level of protection from actions taken today as is given to the current generation (ICRP 2007).

The concept of a *representative person* has been developed (ICRP 2006). The representative person, who will almost always be a hypothetical construct, receives a dose that is representative of the most highly exposed persons in the population. Here, the task of identifying relevant potentially exposed populations is equivalent to identifying the most highly exposed persons in the population from which the dose to the representative person can be assessed. This potential group of more highly exposed persons is below denoted the *most exposed group*.

The strategy applied here is to first identify population(s) related to certain types of societies, either modern or historical, that are suitable to use as a basis when identifying most exposed groups (Section 3.4.1). These populations should adequately represent the most exposed groups from any reasonable type of society. The identified societies, or more correctly, their most exposed groups, are then checked against the exposure route cases that are recommended to be propagated further in the safety assessment (Table 3-5). For exposure route cases not covered by the most exposed groups, additional situations leading to the exposure through certain routes are identified (Section 3.4.2).

3.4.1 Societies delimiting the most exposed group

In Saetre et al. (2013b) a method for identifying the most exposed group with respect to the potential exposure from a geological repository in Forsmark is described. Focus is on the intake of radionuclides via food and how human characteristics and habits affect this intake. In order to assess the intake from contaminated food, different possible uses of land and natural resources are considered, given the constraints set by human requirements for energy and nutrients and the physical landscape. Human requirements for energy and nutrients are not expected to change over time but the landscape is. Humans are constrained by the production from the site, i.e. the landscape determines possible land-use and number of people that can be suistanaied, and also which types of exposure pathways that are possible at a time. For example, when the area is submerged, only exposure from aquatic systems are possible and for terrestrial areas, only areas with a sufficient depth of regolith layers suitable for cultivation can be utilized for agriculture.

Assumptions on habits are drawn from self-sustained low- and higher-technology societies from prehistoric times to an industrial-age agrarian culture. Thus, the most exposed groups correspond to cultures and habits with high intake rates of food items with a high radionuclide concentration. It is considered that doses to representative persons based on these groups may serve as credible bounding doses to be used in the assessment of compliance with regulatory radiological protection criteria for the public.

Three types of society or land use variants have been identified to serve as the basis for the most exposed groups, encompassing the possible range of doses, with respect to exposure from groundwater contamination, when consumption of contaminated food is the primary source of exposure (Saetre et al. 2013a). These are: 1) hunters-gatherers, 2) infield-outland farmers, and 3) drained-mire farmers. They are described in detail in Saetre at al. (2013a), and briefly summarised below.

Hunter-gatherers

Remains from Mesolithic and Neolithic communities in Central Eastern Sweden have primarily been found from excavations at locations that were situated near the coastline at the time of settlement (Knutsson and Knutsson 2003). Stable isotope analyses of animal and human bones suggests that marine food was the dominant protein source for many Mesolithic settlements, and that this was also true for some coastal settlements well into the Neolithic period (Lidén et al. 2004; Fornander et al. 2008). During the middle Neolithic period, settlers with a marine diet co-existed with communities where the marine protein diet was clearly supplemented with terrestrial protein sources. The remains from these and other sites along the Swedish coast (e.g., Larsson 1988; Karsten and Knarrström 2003) are thought to reflect hunting-gathering communities, with foraging behaviours varying from a preference for marine prey, over a mixed diet, to a diet where protein was dominated by terrestrial game.

These hunting-gathering societies serve well as a local reference for the most exposed group with respect to radiation exposures from the natural environment and intakes of surface water and aquatic and terrestrial natural foods. Thus the exposure routes that was found relevant for a hunter and gatherer community included: inhalation of gas and dust (Ter-1, Ter-2), external irradiation from aquatic sediments, peat soils and mire vegetation (Aq-19, Ter-13, Ter-22), ingestion of surface water (Aq-4), ingestion of terrestrial (game, berries and mushrooms) and aquatic (fish) food (Ter-21, Ter-27, Aq-15) (Table 3-5).

Infield-outland farmers

Mires and wet meadows have been an important resource for animal fodder from the last millennium BC, and the dependence on willow and sedges probably increased with the development of efficient tools. Thus, a self-sufficient Iron-Age family may serve as a historical reference for the most exposed group with respect to exposure from wetland hay through infield-outland farming (Saetre et al. 2013b). This agrarian system was characterised by fertilised arable fields and enclosed meadows (infield) on the one hand and livestock grazing nearby pastures and forests (outlands) on the other hand. Hay making was also necessary to provide domestic animals with winter fodder.

Table 3-5. Exposure route cases screened-in for further analysis in the assessment and relevance for Hunter-gatherer, Infield-outland farmers and Drained-mire farmers.

Environmental media	Exposure route case		Hunter-Gatherer	Inland-Outfield	DM farmers	Garden plot household
Atmosphere – outdoor	Ter-1	Inhalation of gases	X	X	X	X
	Ter-2	Inhalation of dust	X	X	X	X
Regolith – soil (inorganic)	Ter-8	Inadvertent soil ingestion	–	–	–	X
	Ter-9	External irradiation from the ground when staying outdoors	–	X	–	X
	Aq-9	External irradiation from sediments e.g. fishing	X	–	–	–
Regolith – peat	Ter-12	Inadvertent peat ingestion	–	–	X	–
	Ter-13	External irradiation from the ground when staying outdoors	X	–	X	–
	Ter-15	Indirect[1] contamination of the environment (burning of peat) inhalation of gas/dust	–	–	–	X
	Ter-16	Indirect[1] contamination of the soil (peat ash) fertilisation	–	–	–	X
Well water	Ter-17	Ingestion of well water	–	X	X	X
	Ter-19	Indirect[1] contamination of crops and soils (irrigation)	–	–	–	X
	Ter-20	Indirect[1] contamination of animals that drinks water	–	X	X	
Surface water	Aq-4	Ingestion of surface water	X	X	X	X
	Aq-7	Indirect[1] contamination of crops and soils (irrigation)	–	–	–	X
	Aq-8	Indirect[1] contamination of animals that drinks contaminated water	–	X	X	–
Primary producers	Ter-21	Ingestion of crops, berries, mushrooms	X	–	–	–
	Ter-22	External irradiation outdoors from radionuclides in the standing vegetation	X	–	–	–
	Ter-25	Indirect[1] contamination of the environment (burning of wood) inhalation of gas/dust	–	–	–	X
	Ter-26	Indirect[1] contamination of soil (manure, wood ash)	–	X	–	X
	Aq-14	Indirect[1] contamination of soils by fertilisation with aquatic primary producers	–	–	–	X
Comsumers	Ter-27	Ingestion of terrestrial animals	X	X	X	–
	Aq-15	Ingestion of aquatic animals	X	–	–	–

[1] The exposure routes refer to transfer of radionuclides from the environmental media to humans, except for the routes related to indirect contamination. Indirect exposure routes (pathways) are defined here as those that can lead to transfer of radionuclides from one environmental medium to another environmental medium or environment as a result of human activities.

The key principle behind this agricultural system was to fertilise the arable land with the nutrients from meadows and pastures, by the use of animal manure as organic fertiliser. This basic principle more or less characterised agricultural practices in Scandinavia well into the 18th century (Welinder et al. 1998). In an Iron-Age infield-outland system, cattle would typically graze pastures and forest on solid ground, whereas hay would be collected from meadows on solid ground and from mires.

Thus, a self-sufficient Iron-Age agricultural community of two households are used as a model for the most exposed group with respect to exposure of radionuclides originating from the use of hay and manure for infield cultivation. Thus the exposure routes that was found relevant for an infield-outland farming community included: inhalation of gas and dust (Ter-1, Ter-2), external irradiation from cultivated soils (Ter-9), ingestion of surface water or water from a dug well (Aq-4, Ter-17), ingestion of crops, meat and dairy products (Ter-21, Ter-27) including exposure pathways for the livestock (Ter-20, Aq-8) (Table 3-5).

Drained-mire farmers

In the wake of the industrial revolution, agricultural practice changed dramatically during the 19th century in Sweden. Modern crop rotation replaced previous practices, the use of new species and improved crop types and animal breeds was established, and improved methods for fertilisation were introduced. The amount of arable land increased and the importance of meadows declined dramatically, as fodder was now primarily produced on arable land. During this period, the use of large-scale drainage to increase the land available for cultivation was first observed. At the turn of the 19th century, the majority of the farming population was found on self-sufficient small-scale farms, which are considered a good reference for the most exposed group with respect to exposure from draining and cultivating contaminated lake–mire systems (Saetre et al. 2013b). Although peat soils were traditionally used for fodder production, cereals (oats, barley, and in particular rye) and potatoes also grow well on organic soils, and thus it can cautiously be assumed that the most exposed group uses organic soils for production of all bulk food.

Thus, a self-sufficient agricultural community of two households that draines and cultivates a mire (or a lake-wetland complex) was used as a model for the most exposed group with respect to exposure of radionuclides that had accumulated in peat and regolith layers below. Thus the exposure routes that was found relevant for this farming community included: inhalation of gas and dust (Ter-1, Ter-2), inadvertent ingestion of, and external irradiation from, cultivated peat soils (Ter-12, Ter-13), ingestion of surface water or water from a dug or drilled well (Aq-4, Ter-17), ingestion of crops, meat and dairy products (Ter-21, Ter-27) including exposure pathways for the livestock (Ter-20, Aq-8) (Table 3-5).

Garden plot household

There are several possible pathways of exposure that are likely to affect a small group of future permanent residents, who are not necessarily self-sustained with respect to food production. These include for example irrigation (Aq-7), fertilization with sea weeds (Aq-14) or biofuel ash (Ter-16, Ter-26), and inhalation from combustion gases and fly ash of biofuel (Ter-15, Ter-25).

Large scale irrigation is little-used in Sweden today, and only 3–4% of the arable land is irrigated (Bergström and Barkefors 2004, Chapter 4 of this report, and Löfgren 2010). Moreover, it is mainly areas cultivated with potatoes and horticultural products that are irrigated, whereas irrigation of cereals or grassland is rare (Brundell et al. 2008). Thus, a household depending on small-scale horticulture may be considered to cover the exposure route cases concerning the irrigation of crops. It may be assumed that one family utilises contaminated water from a stream, a lake or a well. The water may be used for household water (i.e. drinking, cleaning, and bathing) as well as to irrigate a garden plot for production of vegetables and root crops. A garden plot household is a reasonable reference for a family that is self-sustained with respect to vegetables and root crops, and hence serves well as a reference for the most exposed group with respect to radionuclides from intake of irrigated crops and external exposure from soils contaminated due to irrigation.

There is a long history of coastal communities using seaweeds, in Sweden and many other countries, especially the large brown seaweeds, to fertilise nearby land. Wet seaweed is heavy so it is typically not carried far inland. Species of *Ascophyllum*, *Ecklonia* and *Fucus* are most commonly used (FAO 2003). They are today sold as soil additives and function as both fertiliser and soil conditioner. They have a suitable content of nitrogen and potassium. The large amounts of insoluble carbohydrates in brown seaweeds act as soil conditioners (improving aeration and soil structure, especially in clay soils) and have good moisture retention properties. At the late succession stage of a sea basin, when the water exchange is limited and activity concentrations in water and sea weeds are expected to peak, the production of algal biomass is limited, and only a fraction of this resource can be expected to be washed ashore locally. For example, given a fertilizer demand of 0.22 kgC per square meter and year (corresponding to $40 \cdot 10^3$ kg_{FW} per hectar, Grolander 2013) and assuming that 50% of algal net primary production in basin 157_2 can be harvested, algal fertilization could support approximately 1 hectar ($1 \cdot 10^6$ m^2) of arable land at the time before isolation (4000 AD). Thus it is to assumed that seaweeds will be used as fertiliser and mulch for horticultural production at the local household-scale. The most exposed group, based on garden plot cultivation, then also covers the exposure route case Aq-14 (indirect contamination of soils by fertilisation with aquatic primary producers).

Historically, peat has been used for heating houses (Liljegren 2010) and wood is still used for heating (Liss 2005, Stenberg and Rensfeldt 2014). The exposure route analysis results in a few cases related to the use of biofuels, where inhalation (Ter-15 and Ter-25, see also Section 3.3.1) and the use of ash as soil fertilisers (Ter-16 and Ter-26) are relevant exposure routes. To address these exposure routes, it is deemed reasonable to use characteristics of the garden plot household as a reference. The house may be assumed to be heated by combustion of biofuels, such as peat or wood, which may naturally lead to the direct exposure via inhalation of air contaminated by the radionuclides released when burning the biofuel. The most exposed group related to the exposure route cases Ter-16 and Ter-26 (indirect contamination of the environment from burning peat, wood or other vegetation) may thus be the family living in the heated house and using ash as fertiliser on the garden plot.

The soil of the garden plot was assumed to be a cultivated glacial deposits, which a have a high clay content and a god supply of base cations. Clay soils needs continuous conditioning such as digging, and addition of organic material/fertilisers to maintain a porous structure suitable for cultivation, but the small size of the garden plot would make this effort plausible for a small household. Moreover, clay soil has a high potential for accumulation of sorbing radionuclide, as indicated by a high Kd as compared to other regolith types (Tröjbom 2013). Thus the clay rich garden plot soil was also used to assess exposure from inadvertent soil ingestion (exposure route case of Ter-8).

In summary, garden plot cultivation covers eight unique exposure route cases, namely irrigation with well and surface water (Ter-19, Aq-7), fertilization with sea weeds (Aq-14) or ash (Ter-16, Ter-26), inhalation of fly ash and combustion gases from burning biomass fuel (Ter-15, Ter-26) and inadvertent ingestion of mineral rich soil (Ter-8). In addition to these exposure routes, this exposed group also share most of the exposure routes of inland-outfield farming communities (Table 3-5).

3.5 Exposure pathway analysis for other biota

The exposure pathway analysis for humans identified five different exposure routes which are also relevant exposure routes for (most) other biota; through the respiratory tract (inhalation), through the digestive tract (ingestion), external irradiation, through the skin and direct into the body. These exposure routes are not explicitly defined in the assessment methodology of this safety assessment (the ERICA Tool, Beresford et al. 2007), but dose rates are calculated using empirically-derived concentration ratios and may therefore take into account any and all routes of exposure. Of these five exposure routes, dermal absorption and direct transfer into the body are considered negligible compared with the others, and are not discussed in further detail.

Internal exposures via ingestion and inhalation are not modelled separately, as the organism's body is modelled as one unit and has not been divided into different parts. Radionuclide uptake in organisms is modelled using concentration ratios (CR) between the radionuclide concentration in an organism and a corresponding environmental medium (water in aquatic ecosystems and peat in terrestrial). Depending on how these CR values are estimated, inhalation of radionuclides may or may not be taken into account. For a restricted number of radionuclides, which may be in gaseous form, the organism's uptake from air is more relevant, and these have been modelled somewhat differently in order to consider this (in this safety assessment these radionuclides are C-14 and H-3, see Saetre et al. 2013b).

External exposure may, in terrestrial ecosystems, occur from radionuclides in peat, in the atmosphere and in other primary producers and consumers. Since the concentrations of all the radionuclides considered are expected to be much lower in other biota and the atmosphere compared with concentrations in peat, exposure from these sources has not been considered. In aquatic ecosystems, external exposure may occur from radionuclides in sediment or water. Both exposure routes have been considered in this safety assessment.

3.5.1 Identification of organisms for the assessment

Concerning exposure estimates to biota, it is practically impossible to consider and ensure protection of every distinct species 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 a number of representative species for the Forsmark area were identified, based on three criteria related to the regulations (SSM 2008):

- Organisms 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, freely available at http://erica-tool.com/), which is widely used and becoming an internationally standard tool for assessment of dose rates to non-human biota. The reference organisms are a set of organism types that have been selected as assessment targets that are likely to get the highest exposure in the ecosystems of relevance. The objective in Jaeschke et al. (2013) was to investigate how well the reference organisms could represent important aspects (for estimation of dose rate) of the identified representative (site-specific) species. The parameters manipulated in this dose assessment were organism size, habitat preferences and radionuclide uptake (expressed as a Concentration Ratio, CR). The comparison showed that CR in some cases had a large influence on the estimated dose rates, and the influence of concentration ratios, as the main source of uncertainty in assessments of dose to non-human biota, has been discussed and quantified within the inter-comparisons carried out within the context of the IAEA EMRAS programme (Beresford et al. 2008a, b). The recommendation in Jaeschke et al. (2013) as well as others (e.g. US EPA 1999, IAEA 2010) is to use CR values based on site information whenever such are available. This has been implemented in SR-PSU (Tröjbom et al. 2013).

Habitat preferences also influenced the results, in that organisms living within sediments or soil received higher dose rates than those living on these media. It was therefore recommended in Jaeschke et al. (2013) that habitat occupancies should be weighted toward sediment and soil occupancy, where relevant for the organism type at the specific site, if reference organisms were to be used to represent site-specific species in dose assessments. Jaeschke et al. (2013) identified that underestimation of dose due to occupancy assumptions may occur for marine benthic molluscs and limnic bivalve molluscs and crustaceans, so in SR-PSU the occupancy of these reference organisms has been set to be 100% within sediments in order to be conservative. Dose rates to limnic microphytobenthos, very small primary producers living in thick carpets on sediments in many of the lakes in the Forsmark area today (Andersson 2010), may also be underestimated since these are mapped to phytoplankton (100% occupancy in water). Limnic microphytobenthos has therefore been added as an organism, using the size and CRs of reference phytoplankton but a residence of 100% on sediment. A potential for underestimation of dose rates was also identified for large terrestrial mammals for which the reference organism is assumed to live on soil whereas one of the identified representative species (red fox) lives partly within soil. The occupancy of the reference organism, Small mammal, is 100% in soil and, since the same CR values are used for small and large mammals for all included radionuclides (except for Pu for which a higher CR value is used for small mammals, see Tröjbom et al. 2013) and organism size (in the range of interest) had negligible impact on the estimated dose rate (further discussed below), it has not been considered necessary to change the occupancy of the reference Large mammal since the exposure of soil-dwelling species is considered to be covered by that of Small mammal in the assessment.

Another type of concern was for organisms living in several ecosystems (e.g. amphibians utilising both aquatic and terrestrial ecosystems and birds feeding in aquatic ecosystems and nesting in terrestrial environments). For these organisms there is a risk of underestimation of dose rate if only residence in the main habitat is considered. In Jaeschke et al. (2013) large differences in dose rates for these representative species compared with their corresponding reference organisms were seen in the marine environment (which had the lowest radionuclide concentrations). Since the same pattern of radionuclide concentrations is seen also in SR-PSU (highest exposure seen in terrestrial and limnic ecosystems) considering the same site and the same type of source (radionuclides fed to the environment through groundwater discharge), it has been considered relevant to add a few marine organisms with more realistic habitat preferences. This is of relevance for marine mammals and birds, since the marine reference bird and mammal are assumed to spend all their time within the water. The estimated habitat occurrences for representative species of marine birds and mammals are shown in Table 3-6. The occupancy chosen for the extra marine bird was that estimated for Ruddy turnstone

(*Arenaria interpres*), since it is estimated to spend most time on soil and received the highest dose rate of the representative marine bird species in Jaeschke et al. (2013). For the same reasons, European otter (*Lutra lutra*) was selected as representative marine mammal. For simplicity its occupancy was adjusted to 40% within water instead of 10% in water and 30% on water (a conservative assumption since external exposure is larger for organisms within water). Since both these species feed in the marine environment (CR values for marine reference bird and mammal are used for estimating internal exposure) the difference compared with the reference organisms is only for external exposure. The combination of exposure from the two most contaminated environments, freshwater and terrestrial ecosystems, was also examined by adding one representative bird species which spends approximately the same amount of time in each ecosystem. The selected species was Black tern (*Chlidonias niger*), a freshwater bird that is assumed to spend 60% of its time in air and 20% each of its time in or on water (Table 3-6). A conservative adjustment of the occupancy estimation (in Table 3-6) has been made as the time spent in air is classified as on soil (terrestrial environment) and all time spent within or on water is assumed to be within water. As for the representative marine species, its internal exposure is assumed to be entirely from aquatic food (CR values for freshwater reference bird were used).

The amphibian representative species, identified as resident in two ecosystems (freshwater and terrestrial) in Jaeschke et al. (2013), were not explicitly included in the present assessment, as their internal and external exposures corresponded to whichever ecosystem they inhabit. Thus, by assessing the reference amphibians separately, in terrestrial and freshwater environments, a maximum exposure in one or the other ecosystem is identified.

Table 3-6. Marine reference organism habitats and comparison to the habitat uses of relevant site-specific species. From Jaeschke et al. (2013).

Reference organism	Habitat	Representative species habitat
Marine bird	In water 100%	In water 20%, on water 60%, on soil (terrestrial) 20% (Sea birds, multiple species) On soil (terrestrial) 100% (*Arenaria interpres*) In water 20%, on soil (terrestrial) 30%, in air (terrestrial) 50% (*Haliaeetus albicilla*)
Marine mammal	In water 100%	In water 10%, on water 30%, on soil (terrestrial) 60% (*Lutra lutra*) In water 50%, on water 10%, on soil (terrestrial) 40% (*Pusa hispida*)
Freshwater bird	In water 100%	In water 30%, in soil (terrestrial) 40%, on soil (terrestrial) 30% (*Triturus cristatus*) On water 80%, in water 20% (Swimming birds, multiple species) In water 20%, in soil (terrestrial) 10%, in air (terrestrial) 70% (*Alcedo atthis*) In water 20%, on water 20%, in air (terrestrial) 60% (*Chlidonias niger*)

The difference of organism size between reference organisms and representative species was of less importance for the estimated dose rate in Jaeschke et al. (2013). It was shown that the impact of size on dose rate was minimal compared to the impact of habitat or CR and was not proportional, with size differences of several orders of magnitude varying dose rates by only a small fraction. As the largest differences due to size were c 30% (marine primary producer), and with estimated dose rates several orders of magnitude below the screening value, this has not been considered a relevant issue and therefore the default organism sizes of the ERICA tool have been used in SR-PSU.

In total, 41 organism types have been included in the safety assessment (13 limnic, 11 marine, 14 terrestrial, 2 marine and terrestrial, and 1 freshwater and terrestrial), see Table 3-7.

The ecosystem types included in the safety assessment are sea (brackish), lake/stream and wetlands. Agricultural ecosystems have not been considered relevant in the analysis, since future contaminated agricultural land in Forsmark is likely to originate from drained wetland, and these agricultural soils are only expected to be productive (providing a stable environment) for 100 years or less (Lindborg 2010). Thus, the species associated with this land would either be introduced by humans (crops or livestock), or immigrate into the area from adjacent land and consequently they would be part of larger and more stable biological populations. The populations are also 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).

Table 3-7. Organisms included in the SR-PSU dose assessment for non-human biota, habitat occupancies (TE=terrestrial habitat) and organism sizes. RO=Reference organism, RS=Representative species.

Organisms	RO/RS	Habitat	Occupancy factor	Mass (kg)	Length (cm)	Width (cm)	Height (cm)
Terrestrial Ecosystem							
Soil Invertebrate	RO	In soil	1	5.24E–03	1.00E+01	1.00E+00	1.00E+00
Detritivorous invertebrate	RO	In soil	1	1.70E–04	1.74E+00	6.13E–01	3.05E–01
Gastropod	RO	On soil	1	1.40E–03	1.88E+00	1.54E+00	9.27E–01
Amphibian	RO	On soil	1	3.14E–02	7.99E+00	3.00E+00	2.50E+00
Reptile	RO	On soil	1	7.44E–01	1.16E+02	3.49E+00	3.49E+00
Flying insects	RO	On soil	1	5.89E–04	2.00E+00	7.50E–01	7.50E–01
Lichen and bryophytes	RO	On soil	1	1.10E–04	4.01E+00	2.29E–01	2.29E–01
Grasses and Herbs	RO	On soil	1	2.62E–03	5.00E+00	1.00E+00	1.00E+00
Shrub	RO	On Soil	1	2.62E–03	5.00E+00	1.00E+00	1.00E+00
Tree	RO	On soil	1	4.71E+02	1.00E+03	3.00E+01	3.00E+01
Mammal (small)	RO	In soil	1	3.14E–01	2.00E+01	6.00E+00	5.00E+00
Mammal (large)	RO	On soil	1	2.45E+02	1.30E+02	6.00E+01	6.00E+01
Bird	RO	On soil	1	1.26E+00	3.00E+01	1.00E+01	8.02E+00
Bird egg	RO	On soil	1	5.03E–02	6.00E+00	4.00E+00	4.00E+00
Marine Ecosystem							
Phytoplankton	RO	In water	1	6.54E–11	5.00E–03	5.00E–03	5.00E–03
Macroalgae	RO	On sediment	1	6.54E–03	5.00E+01	5.00E–01	5.00E–01
Vascular plant	RO	On sediment	1	2.62E–02	9.29E+00	2.32E+00	2.32E+00
Zooplankton	RO	In water	1	6.14E–05	6.20E–01	6.10E–01	3.10E–01
Polychaete worm	RO	In sediment	1	1.73E–02	2.30E+01	1.20E+00	1.20E+00
Benthic mollusc	RO	In sediment*	1	1.64E–02	5.00E+00	2.50E+00	2.50E+00
Crustacean	RO	On sediment	1	7.54E–01	2.00E+01	1.20E+01	6.00E+00
Benthic fish	RO	On sediment	1	1.31E+00	3.99E+01	2.49E+01	2.51E+00
Pelagic fish	RO	In water	1	5.65E–01	3.00E+01	6.00E+00	6.00E+00
(Wading) bird	RO	In water	1	1.26E+00	3.00E+01	1.00E+01	8.02E+00
Mammal	RO	In water	1	1.82E+02	1.80E+02	4.39E+01	4.39E+01
European otter	RS	On soil (TE)/in water	0.6/0.4	6.60E+00	7.50E+01	1.30E+01	1.30E+01
Ruddy Turnstone	RS	On soil (TE)	1	6.00E–01	2.30E+01	5.00E+00	1.00E+01
Freshwater Ecosystem							
Phytoplankton	RO	In water	1	2.05E–12	7.97E–03	7.01E–04	7.01E–04
Vascular plant	RO	On sediment	1	1.05E–03	1.00E+02	1.00E–01	2.00E–01
Zooplankton	RO	In water	1	2.35E–06	2.00E–01	1.40E–01	1.60E–01
Insect larvae	RO	In sediment	1	1.77E–05	1.50E+00	1.50E–01	1.50E–01
Bivalve mollusc	RO	In sediment*	1	7.07E–02	1.00E+01	4.50E+00	3.00E+00
Gastropod	RO	On sediment	1	3.53E–03	3.00E+00	1.50E+00	1.50E+00
Crustacean	RO	In sediment*	1	1.57E–05	1.00E+00	3.00E–01	1.00E–01
Benthic fish	RO	On sediment	1	1.47E+00	5.00E+01	8.01E+00	7.01E+00
Pelagic fish	RO	In water	1	1.26E+00	5.00E+01	8.01E+00	6.01E+00
Amphibian	RO	In water	1	3.14E–02	7.99E+00	3.00E+00	2.50E+00
Bird	RO	In water	1	1.26E+00	3.00E+01	1.00E+01	8.02E+00
Mammal	RO	In water	1	3.90E+00	3.30E+01	1.50E+01	1.50E+01
Black tern	RS	On soil (TE)/in water	0.6/0.4	1.26E+00	3.00E+01	1.00E+01	8.02E+00
Microphytobenthos	RS	On sediment	1	2.05E–12	7.97E–03	7.01E–04	7.01E–04

*The occupancy of this organism has been changed from on sediment/soil to in sediment/soil according to the discussion in the text.

3.6 Summary

This chapter has identified the potential exposure pathways relevant for the long-term safety of humans and non-human biota from a geological disposal facility at the Forsmark site. These exposure pathways have been analysed with the aim of eliminating those not considered significant for long-term safety.

The ATSDR exposure pathway evaluation (ATSDR 2005) has been the base for the analysis. The goals were to identify relevant potential site-specific exposure situations and the resulting environmental contamination, and to evaluate whether people may be exposed and under what conditions these exposures may occur. Finally, a set of potential most exposed groups were discussed.

In the analysis, 44 exposure route cases were identified related to terrestrial environments (Table 3-3) and aquatic environments (Table 3-4). A screening evaluation was performed on each case to decide if it should be propagated further in the long-term safety assessment for a deep geological repository at the Forsmark site or if it could be excluded. The justifications for screening out certain cases are documented (Section 3.3.2).

For the exposure route cases considered potentially safety relevant, i.e. recommended to be included in a safety assessment, a set of potential, most exposed groups was identified. The strategy to do this was to first identify population(s) related to three types of societies suitable to use as basis when identifying most exposed groups: Hunter-gatherers, Inland-outland farmers and Drained mire farmers (Section 3.4.1). Most exposed groups based on these three societies cover many but not all potentially safety relevant exposure route cases, thus, an additional land-use variant, the Garden plot household, was identified, that would cover all remaining exposure route cases (Section 3.4.2).

The exposure route cases that are recommended to be included in a safety assessment and the potential most exposed groups that may be suitable when analysing the cases are summarised in Table 3-5 and illustrated in Figure 3-4.

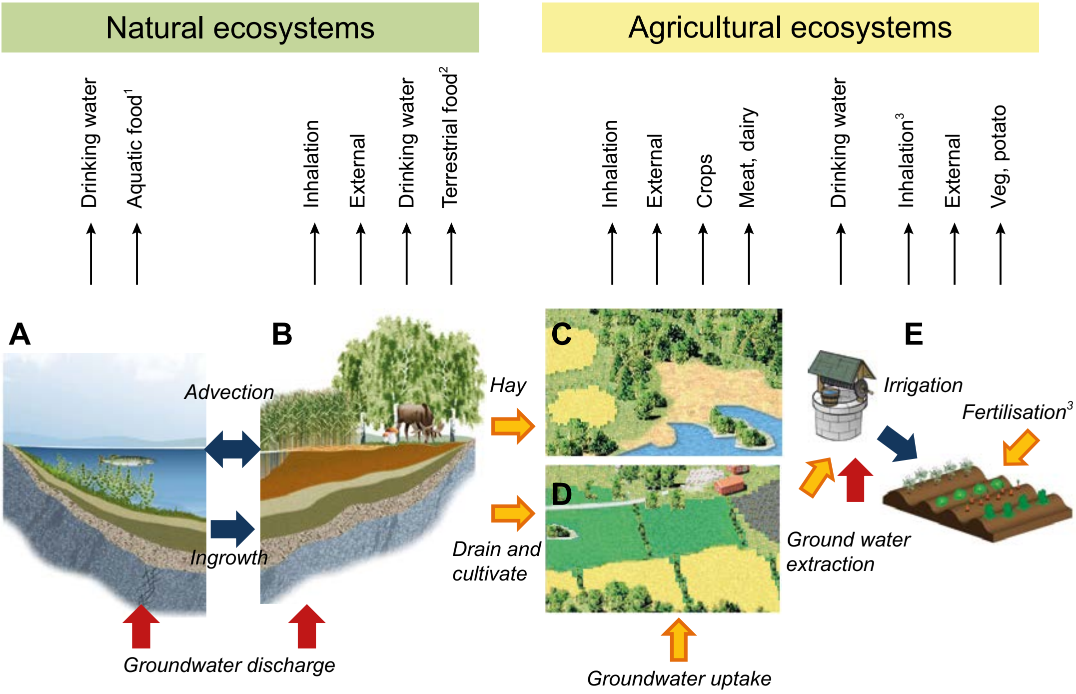

Figure 3-4. *Exposure pathways included in the dose calculations for exposed populations using natural resources and/or living in biosphere objects. Hunter-gatherers use natural aquatic (A) and mire (B) ecosystems. The other three exposed populations represented different uses of arable land, namely 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 mushrooms, 3 = the exposure pathway inhalation and fertilisation includes radionuclides from combustion of biofuel.*

The exposure routes included for non-human biota in this safety assessment are summarised Table 3-9. Terrestrial organisms are exposed to external and/or internal exposure from radionuclides present in the mire peat. For aquatic organisms, external exposure occurs from radionuclides in sediment and/or water depending on the habitat preferences of each organism type (pelagic or benthic), whereas internal exposures are related to radionuclides in the water irrespective of habitat.

Table 3-9. Non-human biota exposure pathways for groundwater contamination. The contaminated area is the biosphere objects that go through a succession from a coastal sea basin to a lake/mire ecosystem in response to land uplift and shoreline displacement. The table represents effects on biota in the primary biosphere object, the same exposure routes are also relevant for biota present in a downstream object, with the difference that the radionuclide source is then contaminated surface water.

	Source			Exposure route		
Ecosystem	Type	From	Environmental media and transport	Internal	External	Exposed population
Sea	Groundwater discharge	Geosphere	Seawater	X	X	Pelagic and benthic marine organisms
	Groundwater discharge	Geosphere	Sediment		X	Benthic marine organisms.
Lake/stream	Groundwater discharge	Geosphere	Lake/stream water	X	X	Pelagic and benthic limnic organisms
	Groundwater discharge	Geosphere	Sediment		X	Benthic limnic organisms.
Mire	Groundwater discharge	Geosphere	Peat	X	X	All terrestrial organisms.

4 Irrigation of agricultural land

Irrigation of agricultural land is sometimes necessary in order to sustain a high crop yield of good quality (Malm and Berglund 2007). Generally, in the boreal region there is no deficit considering the annual water budget, but there may be water deficit during the vegetation period (Mäkelä et al. 2012). This deficit is a result of losses mainly from evaporation and transpiration that exceed the input from precipitation. If the groundwater table is deep, capillary rise will not be able to compensate this deficit and irrigation would consequently enhance the yield.

In Sweden today, the portion of the arable land that is irrigated is small, 3–4% (Bergström and Barkefors 2004). The irrigated land is primarily located in the county of Skåne (southern Sweden) and the use of irrigation is less common in northern regions. In Uppsala County, the total irrigated area was estimated to be below 100 ha in 2006 and irrigated areas thus make up less than 0.1 percent of the total arable land in the county (Brundell et al. 2008, see also Löfgren 2010 for a discussion).

4.1 Crops

Mainly areas cultivated with potatoes and horticultural products are irrigated (see Table 4-1 for a national overview). Typically, potatoes are grown on sand and silt soil, which have a small soil water reservoir. For Uppsala County, between 14% and 28% (upper limit) of the land used to produce potatoes (both for processing and for the table) and horticultural products is irrigated, which is less than expected from the national survey (Table 4-1).

Table 4-1. Percentage of irrigated area relative to total area for each crop. Statistics based on a survey of 700 agricultural holdings in Sweden during 2006 (modified after Brundell et al. 2008).

Crop	Percent (%)
Horticultural products	66
Table potatoes	59
Sugarbeet	16
Temporary grasses and grazing	1
Spring cereals	1
Winter cereals	1
Other crops	1
Oil seed	1

4.2 Amount of water used for irrigation

Water use for irrigation has been investigated in Sweden by Johansson and Klingspor (1977), where the daily balance between precipitation and evapotranspiration was considered in combination with soil type during the vegetation period for a number of different regional areas (Table 4-2). A need for additional water was defined as when the water content in the root zone comes close to the wilting point. At this point, additional water is needed to support plant maintenance and growth. With this approach, the authors identified periods with water deficit during the vegetation period. The modelled need for additional water input could be provided either by irrigation or by capillary rise from deeper soil layers and the groundwater table, i.e. “groundwater uptake”. Capillary rise may not reach values higher than 10 mm day^{-1} under boreal conditions, but more typical values would be around 1 mm day^{-1} during longer periods with water deficit (Johansson 1973). Johansson and Klingspor (1977) concluded that 100 mm was the mean amount of water used for irrigation in southern and central Sweden during a dry year. The difference in the overall mean between for example Uppsala County (73 mm) and Kristanstad County (128 mm) is largely due the presence of sandy soils in the latter region and differences in crops grown. In Uppsala County, there were more cereals, hay and oil-containing plants. Their results suggest that potatoes and fodder generally need more water than barley. The need for irrigation varies between years and using 1976 irrigation data, Johansson and Klingspor (1977) also made a calculation of the water need during a dry year, representing number 25 of 30 years ordered from the wettest to the driest year (Table 4-2).

Table 4-2. Estimated water deficit in mm compensated for by irrigation for different crops in different regions of Sweden during 1976, and calculated irrigation during 1976 if that year would be a dry year. After Johansson and Klingspor (1977), with a detailed description of methods in Johansson (1973).

Region i Sweden	Spring barley		Potatoes		Hay (Slåttervall)	
	Irrigation 1976	Dry year	Irrigation 1976	Dry year	Irrigation 1976	Dry year
North	15	35	65	90	55	90
Central	15	40	80	100	70	100
South-central coastal area	20	65	90	115	80	110
Southern coastal area	20	65	105	125	80	120

The studies mentioned above represent arable land dominated by low organic contents and fine-grained soils, such as clay, whereas the agricultural soils considered in the biosphere objects all are dominated by peat soils with a relatively shallow groundwater table. Generally, the evapotranspiration during the vegetation period is dominated by evapotranspiration from the unsaturated zone, but Mueller et al. (2005) found that this fraction decreased as the water table depth decreased and groundwater uptake (see defintion above) became dominant for e.g. grasslands with a shallow groundwater depth and also for wetlands (see also Johansson 1973). Mueller et al. (2005) also found that a broad selection of different crops showed a tendency to suffer from wetness at groundwater tables shallower than 0.8 m below ground, including crops grown on peaty soils. Moreover, there was a tendency of higher water-use efficiency at deeper groundwater tables, i.e. less water is needed to produce a certain amount of carbon. They estimated the groundwater uptake during the vegetation period to be 10–60 mm for spring barley, 20–250 mm for winter wheat and 80–300 mm for pasture grasses for various soils and groundwater depth levels. The higher end represents conditions with shallower groundwater depths, which would be similar to conditions in a drained peatland. However, these values are higher than what would be expected in central Sweden, because of the higher annual mean temperature (but similar annual precipitation) and higher production on the fields investigated by Mueller et al. (2005) (compare with Table 4-2).

These studies provide estimates of similar magnitudes, although they are dependent on factors such as crop type, soil properties, groundwater-table depth and climate. Based on these studies, it is feasible to suggest that uptake of groundwater from a drained mire with a shallow groundwater table (cf. Section 4.4) is within the range of 20 to 60 mm as a long-term annual average for barley, while the uptake for potatoes and hay would be between 80 and 300 mm. Winter wheat is regarded less suitable on peat soils, but may be grown on postglacial clay (Berglund 2010). These figures include a fairly large span in environmental factors and more precise estimates would need a model approach where these factors can be changed in accordance with assumed conditions. Water fluxes in agricultural land in general and more specifically for agricultural land in groundwater discharge areas is conceptually described in Werner et al. (2013) (Section 6.1.2 and 6.1.3).

4.3 Water sources for irrigation

According to national surveys, arable land is primarily irrigated with water from lakes and streams or from temporary surface-water storages. Groundwater drainage can also be used for irrigation and groundwater may be used for irrigation in areas with sufficient groundwater supplies. Statistics Sweden, SCB (the Swedish national agency supplying statistics) has estimated that groundwater contributes between 20 and 30% to the nationwide water use for irrigation and livestock raising (SCB 2007, Brundell et al. 2008).

4.4 Irrigation of peat soils

To what extent arable land with peaty soil is irrigated is not known from public statistics. Generally, the need for irrigation of arable land increases when the depth to the groundwater table increases. Factors affecting this pattern are the water-retention capacity of the soil and the topographic location of the arable land. Peat has a high water-retention capacity and peaty soils suitable for agricultural purposes are most often found in low-lying areas in the landscape, i.e. former sea bays or lake basins (Sohlenius and Hedenström 2008). These areas often have a shallow groundwater table and require drainage channels to optimize the growing conditions. In general, it would be expected that such areas, especially those being part of a former lake basin, would not be in need of sprinkler irrigation. However, manipulation during wet and dry periods using upstream surface water has historically been a method to increase the hay production in such areas. In low-lying areas, it was earlier common (the method is still in use) to use upstream water by embanking during the spring flood followed by draining 3 to 4 weeks before hay harvest (in Swedish "dämmängar"). It could also be done by a system of shallow channels located across the slope where water slowly was distributed through the peaty soil between the channels (in swedish "silängar") (e.g. Juhlin Dannfelt 1923). These types of water management ensured continuous water availability during critical parts of the vegetation period, and they also facillated transport of oxygen to stimulate decomposition and nutrient availability in areas having periods with low water turnover. The production of hay from such manipulated fens is much higher than from natural wetlands. As a comparison, 500 to 600 gDW m^{-2} $year^{-1}$ can be harvested compared with 50 gDW m^{-2} $year^{-1}$ from unmanipulated poor fens (Pajusi 1998) (240 gDW m^{-2} $year^{-1}$ is assumed to be typical for the Forsmark area). If a biosphere object has a direct release it is always cautious to use the surface-water concentration of radionuclides in the biosphere object (lake and/ or stream), compared to irrigating with upstream water, to evaluate radionuclide concentrations in agricultural products if there is a water shortage (and resourcing by wells disregarded).

4.5 Potential cases with irrigation

As described above, irrigation on arable land as defined in the safety assessment is considered to be unlikely. However, in a modern industrial society, similar to the situation of today, irrigation could be plausible under other conditions. The exposure would be maximized under conditions in which a large part of the food eaten is grown locally i.e. a high degree of self-sufficiency. Accordingly, vegetables can be grown in a garden plot for family use, where the soil properties can be optimized for the crops being grown, i.e. the soil is not a recently drained organic soil. In the Forsmark area today, clayey till dominates the soil that is used for agricultural purposes. In the future Forsmark landscape, large areas with glacial clay, sandy soils and other marine sediments will be uncovered as the shoreline displacement proceeds (Lindborg 2010). These areas would be suitable for agriculture on the basis of how land uses are distributed today among different regolith types in Sweden. These regolith types suggest that irrigation would be possible using different water supplies such as surface water or groundwater from wells. Accordingly, it is possible to use data from Johansson and Klingspor (1977) (Table 4-2) to describe the amount of water used for irrigation under these circumstances.

4.6 Conclusion

Generally, the groundwater-table depth in drained mires used for agricultural purposes suggests that irrigation would be less likely compared to agricultural areas developed on mineral soils. If necessary, the water availability could be increased by manipulating the water input from upstream surface water and embanking. Furthermore, the availability of water in peaty soils, directly connected to a lake (i.e. within the lake basin), that have been made available for agriculture by manipulation of the lake outlet would be controlled by the lake level. Under such circumstances, it would be easier to annually manipulate the lake level at the lake outlet or to embank water upstream than to use irrigation. Therefore, it is assumed that no irrigation using a sprinkler system is necessary in low-lying biosphere objects. Accordingly, it is argued that irrigation will neither be an issue under a climatic conditions similar to the present climate, and probably nor for a global warming case due to the possibility to embank water. However, it seems plausible that irrigation could occur under other circumstances, such as for a small household garden plot, supplying the household with crops such as vegetables and potatoes. Such garden plots would not be found on regolith types similar to the discharge areas for deep groundwater, and they would therefore be expected to be similar in terms of soil properties to typical agricultural land in central Sweden.

5 Exposure to contaminated air following the combustion of peat or wood in power plants and households

The combustion of contaminated peat or wood may result in doses to humans by exposure to contaminated air (Stenberg and Rensfeldt 2014). In SR-Site, the doses per kg burnt fuel were higher (by a factor of 270) for combustion of peat or wood in a household than for corresponding combustion in a power plant. This was primarily due to a higher elevation of the release from a power plant (Stenberg and Rensfeldt 2014). Even though the doses per kg burnt fuel is less in a power plant, it may still lead to a higher exposure since a power plant can burn more contaminated peat or wood than a household. Therefore, it was of interest to re-evaluate whether the combustion of biofuel in a household or in a power plant gives rise to the higher dose, in order to include the worst exposure pathway in the dose calculations for the most exposed group in SR-PSU.

Concentrations of radionuclides in peat and wood for a unit release rate (1 Bq year^{-1}) were calculated for the areas in the landscape where radionuclides originating from the repository may reach the surface ecosystems (so called biosphere objects). For unit release situations, the highest peat activity concentration in the biosphere objects occurred in the primary discharge area (biosphere object 157_2) followed by concentrations in the downstream biosphere object (157_1) (for details see SKB 2014a). The radionuclide concentrations in the peat layer in the downstream and larger biosphere object (116) were typically an order of magnitude lower than in the upstream objects 157_2 and 157_1. (The areas and volumes of the biosphere objects in SR-PSU are presented in Grolander 2013). Exposure from inhalation of air was then calculated following the methods used in the previous SKB safety assessment SR-Site (Stenberg and Rensfeldt 2014). Below follows a brief description.

To compare the doses resulting from combustion of biofuel in a household or in a power plant, doses were calculated by multiplying the dose conversion factors per unit fuel usage rate (kg_{DW} s^{-1}) (Stenberg and Rensfeldt 2014) with the fuel usage rate, and the activity concentrations in peat or wood in each of the biosphere objects 157_1, 157_2 and 116. The fuel usage rate for a household corresponded to an annual heat output of 20,000 kWh year^{-1}, whereas for a power plant it represents the production capacity of a 100 MW electricity and heat. Such a capacity represents a large (90th percentile) contemporary biofuel power plant in Sweden. Using an effective heating energy content of 5 (wood) and 5.8 kWh kg_{DW}^{-1} (peat), the fuel usage rates for a household and a power plant were estimated to be 3,450 kg_{DW} and $151 \cdot 10^6$ kg_{DW} peat per year, respectively. The corresponding fuel consumption rates for burning wood as biofuel were 4,000 kg_{DW} y^{-1} and $176 \cdot 10^6$ kg_{DW} y^{-1}.

The amount of peat available for energy production was calculated from the deep peat inventory that had accumulated until the point in time for the evaluation. For large objects like 116 this reflected many thousands years of peat accumulation at the end of the simulation period. The amount of available wood for biofuel burning was estimated from the annual sustainable rate of wood production from the areas considered (i.e. forested wetlands). The amount of peat and the production of wood were sufficient to cover the fuel usage rate associated with the heating of several household for fifty years, even for the smallest of the three biosphere objects (Table 5-1). However, the accumulated peat was not sufficient to provide the power plant with fuel, and the annual production of wood only amounted to a fraction of the biomass fuel used in a large power plant (Table 5-1). Consequently it was assumed that peat or wood from other areas were used to cover the remaining fuel demand.

For a household it is reasonable to assume that peat or wood from only one biosphere object is combusted (i.e. the object with the highest concentrations). However, for large scale energy production in a power plant it was considered sensible to utilize resources from all radionuclide containing biosphere objects. Thus annual doses per unit release rate were calculated for each year up to year 20,000 AD, for each of the biosphere objects 157_2, 157_1 and 116, and doses were summed when assessing the release from a power plant.

Table 5-1. Number of households that can be supported and fraction of power plant fuel demand that can be coverd by potential biofuel production in an object. The peat deposits are assumed to be utilized during a fifty year period, where as wood fuel consumption corresponds to the sustainable yearly harvest from a forested wetland.

Biosphere Object	Number of households supported		Fraction of power plant fuel demand	
	Peat	Wood	Peat	Wood
116	849	53	1.94%	0.12%
157_1	83	4	0.19%	0.01%
157_2	9	8	0.02%	0.02%

Although all radionuclides in the peat (or in the wood produced) were released in the power plant calculations, the maximum annual effective doses (summed over all three biosphere objects) were at most 25% of the doses resulting from household combustion (Table 5-2). As wood production was sufficient for household heating but covered an even smaller fraction of the power plant fuel demand (Table 5-1), the doses from the wood-fuelled power plant were even smaller compared to those from household heating (data not shown). Therefore, combustion of peat and wood on a household scale is included as exposure pathways in the SR-PSU safety assessment, whereas the exposure from power plant scale combustion were screened out by these calculations.

Table 5-2. Maximum annual effective doses per unit release rate (Sv year^{-1} per Bq year^{-1}) obtained in each of the biosphere objects. The annual effective doses for the peat-fuelled power plant were, at most, 25% of the doses for the peat-fuelled household even if all the peat from all three biosphere objects were to be used as fuel, as indicated by the ratios in the sum column. $PP_{sum}/Max_{household}$ is the ratio of the sum of the doses from the three biosphere objects (equal to the dose from one power plant burning peat from all biosphere objects) and the largest of the household doses from the three biosphere objects.

	Annual effective dose per unit release rate (Sv year^{-1} per Bq year^{-1})							$PP_{sum}/Max_{household}$
	Household combustion			Power plant combustion				
Radionuclide	116	157_1	157_2	116	157_1	157_2	Sum	
Ac-227	$7.3\cdot10^{-23}$	$3.0\cdot10^{-22}$	$1.1\cdot10^{-19}$	$2.7\cdot10^{-25}$	$7.5\cdot10^{-24}$	$6.3\cdot10^{-21}$	$6.3\cdot10^{-21}$	6%
Ag-108m	$7.4\cdot10^{-21}$	$3.7\cdot10^{-18}$	$2.3\cdot10^{-17}$	$9.9\cdot10^{-21}$	$1.1\cdot10^{-18}$	$1.4\cdot10^{-18}$	$2.5\cdot10^{-18}$	11%
Am-241	$7.4\cdot10^{-20}$	$1.8\cdot10^{-17}$	$3.7\cdot10^{-16}$	$4.3\cdot10^{-20}$	$5.2\cdot10^{-18}$	$2.2\cdot10^{-17}$	$2.7\cdot10^{-17}$	7%
Am-242m	$4.1\cdot10^{-21}$	$1.9\cdot10^{-19}$	$1.2\cdot10^{-17}$	$9.9\cdot10^{-23}$	$3.9\cdot10^{-20}$	$7.4\cdot10^{-19}$	$7.8\cdot10^{-19}$	6%
Am-243	$2.3\cdot10^{-17}$	$4.0\cdot10^{-14}$	$1.2\cdot10^{-13}$	$7.0\cdot10^{-17}$	$1.2\cdot10^{-14}$	$7.4\cdot10^{-15}$	$1.9\cdot10^{-14}$	16%
Ba-133	$1.1\cdot10^{-26}$	$1.5\cdot10^{-24}$	$1.3\cdot10^{-22}$	$9.6\cdot10^{-29}$	$1.8\cdot10^{-25}$	$7.7\cdot10^{-24}$	$7.9\cdot10^{-24}$	6%
C-14	$2.2\cdot10^{-24}$	$3.3\cdot10^{-23}$	$2.6\cdot10^{-21}$	$4.2\cdot10^{-26}$	$1.0\cdot10^{-23}$	$1.4\cdot10^{-22}$	$1.5\cdot10^{-22}$	6%
Ca-41	$5.3\cdot10^{-22}$	$5.6\cdot10^{-19}$	$1.8\cdot10^{-18}$	$1.4\cdot10^{-21}$	$1.7\cdot10^{-19}$	$1.1\cdot10^{-19}$	$2.8\cdot10^{-19}$	16%
Cd-113m	$3.5\cdot10^{-25}$	$9.7\cdot10^{-25}$	$2.4\cdot10^{-21}$	$1.3\cdot10^{-27}$	$2.7\cdot10^{-26}$	$1.4\cdot10^{-22}$	$1.4\cdot10^{-22}$	6%
Cl-36	$1.4\cdot10^{-20}$	$2.1\cdot10^{-17}$	$4.3\cdot10^{-17}$	$2.8\cdot10^{-20}$	$6.5\cdot10^{-18}$	$2.6\cdot10^{-18}$	$9.1\cdot10^{-18}$	21%
Cm-242	$1.9\cdot10^{-37}$	$5.3\cdot10^{-35}$	$3.0\cdot10^{-24}$	$1.1\cdot10^{-37}$	$3.8\cdot10^{-37}$	$1.1\cdot10^{-26}$	$1.1\cdot10^{-26}$	<0.1%
Cm-243	$2.3\cdot10^{-22}$	$5.2\cdot10^{-23}$	$3.9\cdot10^{-20}$	$1.2\cdot10^{-24}$	$5.5\cdot10^{-24}$	$2.3\cdot10^{-21}$	$2.3\cdot10^{-21}$	6%
Cm-244	$3.4\cdot10^{-24}$	$1.8\cdot10^{-23}$	$5.5\cdot10^{-21}$	$1.3\cdot10^{-26}$	$2.4\cdot10^{-25}$	$3.3\cdot10^{-22}$	$3.3\cdot10^{-22}$	6%
Cm-245	$2.6\cdot10^{-17}$	$4.7\cdot10^{-14}$	$1.4\cdot10^{-13}$	$8.2\cdot10^{-17}$	$1.4\cdot10^{-14}$	$8.7\cdot10^{-15}$	$2.3\cdot10^{-14}$	16%
Cm-246	$1.5\cdot10^{-17}$	$2.2\cdot10^{-14}$	$7.5\cdot10^{-14}$	$4.5\cdot10^{-17}$	$6.7\cdot10^{-15}$	$4.5\cdot10^{-15}$	$1.1\cdot10^{-14}$	15%
Co-60	$8.6\cdot10^{-27}$	$2.0\cdot10^{-28}$	$3.5\cdot10^{-25}$	$1.2\cdot10^{-28}$	$1.5\cdot10^{-29}$	$2.1\cdot10^{-26}$	$2.1\cdot10^{-26}$	6%
Cs-135	$2.2\cdot10^{-23}$	$6.3\cdot10^{-20}$	$2.5\cdot10^{-19}$	$7.0\cdot10^{-23}$	$1.9\cdot10^{-20}$	$1.5\cdot10^{-20}$	$3.4\cdot10^{-20}$	14%
Cs-137	$8.2\cdot10^{-28}$	$1.0\cdot10^{-26}$	$2.0\cdot10^{-25}$	$1.5\cdot10^{-29}$	$1.9\cdot10^{-27}$	$1.2\cdot10^{-26}$	$1.4\cdot10^{-26}$	7%
Eu-152	$2.3\cdot10^{-26}$	$7.5\cdot10^{-28}$	$1.7\cdot10^{-24}$	$8.4\cdot10^{-29}$	$6.8\cdot10^{-29}$	$1.0\cdot10^{-25}$	$1.0\cdot10^{-25}$	6%
H-3	$7.1\cdot10^{-24}$	$7.4\cdot10^{-21}$	$5.3\cdot10^{-20}$	$3.6\cdot10^{-24}$	$2.0\cdot10^{-21}$	$2.5\cdot10^{-21}$	$4.5\cdot10^{-21}$	9%
Ho-166m	$2.9\cdot10^{-21}$	$2.0\cdot10^{-18}$	$1.8\cdot10^{-17}$	$8.0\cdot10^{-21}$	$5.9\cdot10^{-19}$	$1.1\cdot10^{-18}$	$1.7\cdot10^{-18}$	9%
I-129	$2.2\cdot10^{-18}$	$1.5\cdot10^{-16}$	$9.2\cdot10^{-16}$	$5.7\cdot10^{-18}$	$4.4\cdot10^{-17}$	$5.3\cdot10^{-17}$	$1.0\cdot10^{-16}$	11%
Mo-93	$4.7\cdot10^{-19}$	$8.3\cdot10^{-17}$	$2.6\cdot10^{-16}$	$1.3\cdot10^{-18}$	$2.5\cdot10^{-17}$	$1.6\cdot10^{-17}$	$4.2\cdot10^{-17}$	16%

	Annual effective dose per unit release rate (Sv year^{-1} per Bq year^{-1})							
	Household combustion			Power plant combustion				PP_{sum}/ $Max_{household}$
Radionuclide	116	157_1	157_2	116	157_1	157_2	Sum	
Nb-93m	$1.9\cdot10^{-29}$	$1.5\cdot10^{-30}$	$2.1\cdot10^{-26}$	$1.1\cdot10^{-31}$	$1.4\cdot10^{-31}$	$1.9\cdot10^{-28}$	$1.9\cdot10^{-28}$	1%
Nb-94	$1.2\cdot10^{-21}$	$5.5\cdot10^{-18}$	$2.1\cdot10^{-17}$	$3.9\cdot10^{-21}$	$1.7\cdot10^{-18}$	$1.3\cdot10^{-18}$	$2.9\cdot10^{-18}$	14%
Ni-59	$6.8\cdot10^{-21}$	$3.4\cdot10^{-18}$	$1.0\cdot10^{-17}$	$2.0\cdot10^{-20}$	$1.0\cdot10^{-18}$	$6.2\cdot10^{-19}$	$1.7\cdot10^{-18}$	16%
Ni-63	$1.2\cdot10^{-24}$	$1.4\cdot10^{-22}$	$3.8\cdot10^{-21}$	$1.8\cdot10^{-25}$	$2.7\cdot10^{-23}$	$2.3\cdot10^{-22}$	$2.6\cdot10^{-22}$	7%
Np-237	$5.6\cdot10^{-18}$	$1.5\cdot10^{-14}$	$2.7\cdot10^{-14}$	$1.7\cdot10^{-17}$	$4.6\cdot10^{-15}$	$1.6\cdot10^{-15}$	$6.2\cdot10^{-15}$	23%
Pa-231	$7.5\cdot10^{-17}$	$1.4\cdot10^{-13}$	$4.0\cdot10^{-13}$	$2.3\cdot10^{-16}$	$4.3\cdot10^{-14}$	$2.4\cdot10^{-14}$	$6.8\cdot10^{-14}$	17%
Pb-210	$3.7\cdot10^{-24}$	$4.6\cdot10^{-25}$	$1.9\cdot10^{-22}$	$5.2\cdot10^{-26}$	$6.8\cdot10^{-27}$	$1.1\cdot10^{-23}$	$1.1\cdot10^{-23}$	6%
Pd-107	$1.3\cdot10^{-20}$	$7.5\cdot10^{-18}$	$2.4\cdot10^{-17}$	$3.9\cdot10^{-20}$	$2.3\cdot10^{-18}$	$1.5\cdot10^{-18}$	$3.8\cdot10^{-18}$	16%
Po-210	$1.1\cdot10^{-36}$	$1.9\cdot10^{-37}$	$7.0\cdot10^{-28}$	$7.3\cdot10^{-38}$	$1.2\cdot10^{-38}$	$2.6\cdot10^{-30}$	$2.6\cdot10^{-30}$	<0.1%
Pu-238	$1.2\cdot10^{-21}$	$2.6\cdot10^{-20}$	$3.1\cdot10^{-18}$	$7.2\cdot10^{-24}$	$4.6\cdot10^{-21}$	$1.9\cdot10^{-19}$	$1.9\cdot10^{-19}$	6%
Pu-239	$1.2\cdot10^{-16}$	$1.0\cdot10^{-13}$	$3.0\cdot10^{-13}$	$3.8\cdot10^{-16}$	$3.1\cdot10^{-14}$	$1.8\cdot10^{-14}$	$4.9\cdot10^{-14}$	16%
Pu-240	$5.6\cdot10^{-17}$	$4.0\cdot10^{-14}$	$1.3\cdot10^{-13}$	$1.7\cdot10^{-16}$	$1.2\cdot10^{-14}$	$7.8\cdot10^{-15}$	$2.0\cdot10^{-14}$	15%
Pu-241	$1.5\cdot10^{-24}$	$6.6\cdot10^{-26}$	$9.1\cdot10^{-23}$	$1.8\cdot10^{-26}$	$2.6\cdot10^{-27}$	$5.4\cdot10^{-24}$	$5.4\cdot10^{-24}$	6%
Pu-242	$1.6\cdot10^{-16}$	$1.3\cdot10^{-13}$	$3.8\cdot10^{-13}$	$5.0\cdot10^{-16}$	$4.0\cdot10^{-14}$	$2.3\cdot10^{-14}$	$6.4\cdot10^{-14}$	17%
Ra-226	$1.0\cdot10^{-17}$	$2.1\cdot10^{-15}$	$8.8\cdot10^{-15}$	$2.7\cdot10^{-17}$	$6.3\cdot10^{-16}$	$5.3\cdot10^{-16}$	$1.2\cdot10^{-15}$	13%
Ra-228	$2.5\cdot10^{-24}$	$1.4\cdot10^{-24}$	$1.5\cdot10^{-21}$	$3.5\cdot10^{-26}$	$8.1\cdot10^{-26}$	$8.9\cdot10^{-23}$	$8.9\cdot10^{-23}$	6%
Se-79	$2.9\cdot10^{-19}$	$2.2\cdot10^{-17}$	$7.3\cdot10^{-17}$	$8.0\cdot10^{-19}$	$6.8\cdot10^{-18}$	$4.4\cdot10^{-18}$	$1.2\cdot10^{-17}$	16%
Sm-151	$3.9\cdot10^{-26}$	$1.0\cdot10^{-24}$	$1.2\cdot10^{-22}$	$2.7\cdot10^{-28}$	$1.8\cdot10^{-25}$	$7.4\cdot10^{-24}$	$7.5\cdot10^{-24}$	6%
Sn-126	$2.5\cdot10^{-20}$	$7.2\cdot10^{-17}$	$2.5\cdot10^{-16}$	$7.8\cdot10^{-20}$	$2.2\cdot10^{-17}$	$1.5\cdot10^{-17}$	$3.7\cdot10^{-17}$	15%
Sr-90	$3.0\cdot10^{-22}$	$8.0\cdot10^{-20}$	$1.7\cdot10^{-18}$	$6.3\cdot10^{-23}$	$1.5\cdot10^{-20}$	$9.9\cdot10^{-20}$	$1.1\cdot10^{-19}$	7%
Tc-99	$1.5\cdot10^{-20}$	$8.0\cdot10^{-18}$	$3.9\cdot10^{-17}$	$4.7\cdot10^{-20}$	$2.4\cdot10^{-18}$	$2.3\cdot10^{-18}$	$4.8\cdot10^{-18}$	12%
Th-228	$7.2\cdot10^{-30}$	$7.9\cdot10^{-30}$	$5.5\cdot10^{-26}$	$2.7\cdot10^{-32}$	$6.6\cdot10^{-32}$	$3.3\cdot10^{-27}$	$3.3\cdot10^{-27}$	6%
Th-229	$5.9\cdot10^{-18}$	$9.1\cdot10^{-15}$	$3.0\cdot10^{-14}$	$1.8\cdot10^{-17}$	$2.8\cdot10^{-15}$	$1.8\cdot10^{-15}$	$4.6\cdot10^{-15}$	15%
Th-230	$6.8\cdot10^{-18}$	$1.1\cdot10^{-14}$	$3.3\cdot10^{-14}$	$2.1\cdot10^{-17}$	$3.2\cdot10^{-15}$	$2.0\cdot10^{-15}$	$5.2\cdot10^{-15}$	16%
Th-232	$8.7\cdot10^{-18}$	$1.3\cdot10^{-14}$	$4.1\cdot10^{-14}$	$2.7\cdot10^{-17}$	$4.0\cdot10^{-15}$	$2.4\cdot10^{-15}$	$6.5\cdot10^{-15}$	16%
U-232	$2.8\cdot10^{-19}$	$1.3\cdot10^{-16}$	$2.6\cdot10^{-14}$	$2.0\cdot10^{-20}$	$2.0\cdot10^{-17}$	$1.6\cdot10^{-15}$	$1.6\cdot10^{-15}$	6%
U-233	$8.1\cdot10^{-15}$	$2.6\cdot10^{-12}$	$4.6\cdot10^{-12}$	$2.5\cdot10^{-14}$	$8.0\cdot10^{-13}$	$2.8\cdot10^{-13}$	$1.1\cdot10^{-12}$	24%
U-234	$8.1\cdot10^{-15}$	$2.6\cdot10^{-12}$	$4.6\cdot10^{-12}$	$2.5\cdot10^{-14}$	$8.0\cdot10^{-13}$	$2.7\cdot10^{-13}$	$1.1\cdot10^{-12}$	24%
U-235	$7.6\cdot10^{-15}$	$2.4\cdot10^{-12}$	$4.2\cdot10^{-12}$	$2.4\cdot10^{-14}$	$7.4\cdot10^{-13}$	$2.5\cdot10^{-13}$	$1.0\cdot10^{-12}$	24%
U-236	$7.8\cdot10^{-15}$	$2.5\cdot10^{-12}$	$4.2\cdot10^{-12}$	$2.4\cdot10^{-14}$	$7.5\cdot10^{-13}$	$2.5\cdot10^{-13}$	$1.0\cdot10^{-12}$	24%
U-238	$7.2\cdot10^{-15}$	$2.3\cdot10^{-12}$	$3.9\cdot10^{-12}$	$2.2\cdot10^{-14}$	$6.9\cdot10^{-13}$	$2.3\cdot10^{-13}$	$9.5\cdot10^{-13}$	24%
Zr-93	$4.2\cdot10^{-20}$	$2.8\cdot10^{-17}$	$8.6\cdot10^{-17}$	$1.3\cdot10^{-19}$	$8.5\cdot10^{-18}$	$5.1\cdot10^{-18}$	$1.4\cdot10^{-17}$	16%

5.1 Exposure to contaminated ash used as fertiliser

Exposure originating from peat or wood ash used as fertilizer was examined for the garden plot household (SKB 2014a). Based on the calculations described above and assuming that an effective combustion leaves 1% of the original dry weight as ash (stem wood dominating, Hakkila and Kalaja 1983), and that 75% of the ash leaves the chimney as fly ash (Möre and Hubbard 2003), the amount of the remaining ash to potentially be used as a fertilizer was calculated. A household with the yearly demand of 20,000 kWh for heating would thus be left with 9 and 10 kg_{DW} ash per year from peat and wood burning, respectively. The size of the garden plot was assumed o be 140 m^2, supporting a household of five individuals with their yearly demand of vegetables and root crop (Grolander 2013). Thus combustion of peat and wood yielded 0.06 and 0.07 kg_{DW} ash per square meter and year for fertilization, respectively. These amounts are similar to the suggested input of peat and wood ash (0.1 and 0.2 kg_{DW} m^{-2} y^{-1}) needed to give a sustainable input of nutrients (Cardfelt 1989, Gruvaeus and Marmolin 2007). Thus the amount of ash produced balances the demand for fertilizers for a small cultivation unit. However, the ash produced by two households does not by any mean cover the fertilization demand of the larger areas cultivated by self sufficient farmers associated with infield-outland, or drain mire agriculture.

6 Transformation of wetland to agricultural land

6.1 Introduction

Agricultural land is the main contributor of food to humans and livestock. Historically, different types of soils and crop types have been used to sustain food production depending on the technical and economical prerequisites. Areas suitable for food production may have quite different properties, e.g. soil organic content, and different ontogeny during landscape development (Sohlenius et al. 2014). In SR-Site, low-lying areas in catchment areas that were subjected to discharge of deep groundwater, i.e. wetlands, were used for cultivation if underlain by suitable deposits (Lindborg 2010). Such areas were generally described by the developmental sequence; sea bay – lake – wetland. However, wetlands may also develop directly without a preceding lake stage (Löfgren 2010). Mire areas are the most important ecosystem for long-term accumulation of organic carbon. In such environments, radionuclides may accumulate due to plant uptake and production of organic material, and later due to adsorption on the organic material (i.e. the peat).

In Sweden before the end of the 19th century mires were mostly used as mowing fields. During the first half of the 20th century, numerous wetlands were converted to arable land due to a high demand for food in combination with increasing technical possibilities for draining mires (Runefelt 2008). However, in densely populated parts of Europe, such as the Netherlands, cultivation of wetlands began during medieval times. Consequently, the use of mires for food production after draining is considered to be a relevant source for exposure to humans in the case of a potential release of radionuclides from an underground storage facility. Below is a review of factors that are important for describing the spatial patterns of mires in the landscape, for mire develop over time, and for their suitability for agricultural use. A description of the draining process is also provided. This information is intended to be used to underpin assumptions in the radionuclide modelling of the safety assessment SR-PSU, which is further described in Saetre et al. (2013b).

Figure 6-1. *A cultivated peat area situated in the County of Västmanland, which has a similar geological setting as Forsmark. The peat soils are recognised by a characteristic dark colour (Photo: Henrik Mikko SGU).*

6.2 Development of mires

Peat formation can be initiated in different types of wetland environments: 1) in wetlands directly formed in uplifted areas, 2) in wetlands formed long after an area has been uplifted, 3) in wetlands formed after infilling of lakes. Peat initiation in these environments is referred to as primary peat initiation, paludification and terrestrialization, respectively (Kellner 2003).

Forsmark is situated in a flat coastal area where the land area is currently increasing due to isostatic land upheaval. Wetlands and lakes are continuously formed and are thereafter successively covered by different types of peat reflecting the environments occurring during infilling of lakes and development of wetlands. Since the present Forsmark area is recently uplifted only a small proportion of the area is covered by peat and these peat layers are generally not thick enough for cultivation (Fredriksson 2004, Hedenström and Sohlenius 2008). The peat-covered area will, however, increase in the future.

Mires are often subdivided into fens and bogs which are characterized by different hydrological properties. The fen is a discharge area for groundwater and the peat accumulating in fens can be enriched in radionuclides and other elements from surrounding bedrock and soils. At a certain point, the peat accumulation may make the surface of the mire hydrologically independent of the landscape. The mire has then reached an ombrotrophic bog stage in which the production by vegetation is all rain-feed. This means that the potential accumulation of radionuclides, entering from below, within accumulating peat and vegetation will level off as the bog rises. The succession of a bog from a fen is, however, not instantaneous and parts of a wetland may have developed into a bog when other parts still remain as a fen. Formation of bog peat is dependent of climate and bogs frequently occur in the central parts of southern Sweden (Granlund 1932, von Post and Granlund 1926). The bogs situated in the surroundings of Forsmark are generally small and covered by pine forest (Schoning 2014). Especially in young fens, the succession of different types of vegetation causes changes in peat properties. Also, climatic variations may cause changes in accumulation rates and peat properties.

Sohlenius et al. (2014) studied the development of a large numbers of mires in northern Uppland, i.e. the surroundings of Forsmark. The data was mainly derived by compiling data from an investigation that was carried out c. 90 years ago (von Post and Granlund 1926). Inspite of its age, the original data has been shown to be of high quality (Lundgren and Modig 2013). The results from that study showed that about an equal amount of the peatlands were formed through primary peat initiation and paludification as through terrestrialization. Peat which is underlain by gyttja was interpreted as having formed in wetlands proceeded by a lake stage, i.e. these wetlands have formed by terrestrialization. The wetlands formed through primary peat initiation were mainly underlain by clay gyttja indicating initiation of peat formation directly when shallow bays of the Baltic Sea appeared above the sea-level. Primary peat formation is a common process also in other parts of Sweden (Kellner 2003, Rundgren 2008, Rydin and Jeglum 2006). In the study by Sohlenius et al. (2014) only a few sites were clearly assigned to paludification.

Sohlenius et al. (2014) studied the succession, peat properties and rate of peat accumulation in mires situated in northern Uppland. The mires in the data set are of highly variable types, but a general pattern is that relatively young mires, formed in areas that have been uplifted for 1,500 years or less, reflect different types of fen environments, whereas older peatlands are of both bog and fen types. The two far most common succession paths of wetlands in the data-set are: 1) an initial *Carex* phase followed by an ombrotrophication with a dominance of *Sphagnum* mosses, 2) a birch/alder fen environment followed by *Bryales* or *Carex* stage, and finally ombrotrophication with *Sphagnum* mosses. The wetlands in this region with accumulation of *Sphagnum* peat are characterized by pine forest, and are still in an early stage of bog formation.

For the safety assessment, the distribution and thickness of peat and gyttja sediments during the present interglacial has been modelled by Brydsten and Strömgren (2013). Clay gyttja and gyttja in that model are accumulated at the floor of the Baltic Sea and in lakes, respectively. During the sea stage sediments can only accumulate when the water depth is large enough to avoid resuspension by waves. In the model of Brydsten and Strömgren (2013), peat is assumed to form in shallow water-covered areas that are colonized by vegetation such as reed. Specifically, lakes with water depths of less than two metres and shallow parts of bays with 1.3 metres water depth or less are successively colonized with vegetation that forms peat. The final peat depth corresponds to the water depth when the area was colonized by vegetation initiating peat accumulation. In deeper lakes, peat can only start to form when accumulating gyttja has decreased the water depth to less than two metres. The colonisation of mire vegetation in sea bays and lakes are based on estimates from present Forsmark (Brydsten and Strömgren 2013). Moreover, the primary mire formation is described by the use of a Topographical Wetness Index (TWI) in order to include areas with mire formation not preceded by a lake stage. These areas will however not achieve peat layers since there is no water depth. General information regarding land use in the present Uppland has been combined with the model by Brydsten and Strömgren (2013) to produce a Landscape Development Model (LDM), which illustrate the development of the landscape and land use between 1500 BC and 40,000 AD (Chapter 5 in SKB 2014a).

6.3 Properties of mires suitable for cultivation

Since peat is accumulating in wetlands, arable land preceded by a mire stage is covered by peat (Figure 6-1). During the forthcoming thousands of years, peat thicknesses will increase in the Forsmark area and cultivation of peat-covered areas will consequently be possible (Lindborg 2010, Lindborg et al. 2013). However, many wetlands are underlain by clay gyttja or other sediments suitable for cultivation and young mires can consequently often be converted to arable land before thick layers of peat have formed. Many young cultivated mires in the surroundings of Forsmark are therefore situated in areas with clay gyttja, which lacks or almost lack a peat layer (cf. Sohlenius et al. 2014).

Bog peat is characterized by low pH, low contents of nutrients, and high C/N-ratio, and is consequently not suitable for cultivation without amelioration (Berglund 1996, Osvald 1937). The bog peat is also characterised by a high water content and low stability, making cultivation problematic. Furthermore, bog peat is often built up by *Sphagnum* remnants with a low degree of decomposition, which makes it difficult for roots to penetrate the soil and get access to water. Fen peat is generally more suitable for cultivation, since the pH and contents of nutrients are relatively high. Fen peat also has physical properties suitable for cultivation. After the groundwater table has been lowered, nitrogen and phosphorus bound in the fen peat can become successively available for plants during the first few years of peat mineralization. Osvald (1937) made one of the most thorough discussions regarding cultivation of Swedish peat covered wetlands and concluded that, even though bog peat is less suitable for cultivation, all types of peat can be cultivated, and it is possible to cultivate bog peat after adding sand and clay.

Sohlenius et al. (2014) identified 45 sites in northern Uppland which were cultivated peatlands in the early 1900s. Most of these cultivated peatlands are situated at relatively low elevations and were isolated from the Baltic Sea during the last 4,000 years. When investigated in the early 1900s, the mean peat depth was 90 cm and peat depths larger than 150 cm were rare in the cultivated areas. As in the case of the non-cultivated peatlands, there is an even distribution between peatlands formed through primary peat initiation and paludification, and peatlands with a preceding lake stage. Cultivated peatlands formed through terrestrialization generally have relatively large peat depths and have been preceded by more development stages. The absolute majority of the cultivated peatlands (96%) had not reached a bog stage, when claimed for agricultural purposes. The cultivated sites were instead preceded by different types of fen stages. These results are in accordance with results presented by (Hjertstedt 1946), who showed that most of the cultivated peatlands in Uppland are situated on fen peat, mostly Carex and Bryales peat. In some parts of Sweden, cultivation of *Sphagnum* peat is more common. This is especially so in south western Sweden, which has a high abundance of *Sphagnum* peat, which may accumulate both in bogs and nutrient poor fens.

Peat and gyttja sediment are characterised by high water content and the thicknesses of these deposits therefore decreases significantly when wetlands are drained for cultivation (Berglund 2008, Berglund et al. 1989). Furthermore, peat will oxidize when the ground water is lowered and thereby diminish with time. Cultivation on drained wetlands can therefore be difficult to maintain for long periods. The cultivated peatlands studied by Sohlenius et al. (2014) are, however, all underlain by gyttja sediments or clay, which may be cultivated when the peat has completely oxidised. If underlain by gyttja (lake sediments) it may, however, be difficult to maintain the drainage of these areas for a long time, since these deposits are extremely sensitive to compaction (Berglund et al. 1989). Furthermore, gyttja is accumulating in lakes and it will take a lot of effort to keep the groundwater level low enough in an area formerly covered by a lake (Mc Afee 1985). It is consequently difficult to use peatlands underlain by lake sediments for long periods (> 100 years). Future locations with relatively thin peat layers that will form in low-lying clay and sand-dominated areas can, however, be suitable for cultivation for a long period of time. This is because these areas are underlain by deposits that are not sensitive to compaction (Berglund et al. 1989) and are also suitable for cultivation when the peat has disappeared.

The onset of bog peat accumulation can be delayed due to e.g. unfavourable climatic conditions and bog peat can start to form after a fen stage of more than thousand years (cf. Lundqvist 1963). Consequently, it seems that the window of opportunity for agriculture on mires may be variable. A wetland can constitute both parts with thick layers of bog peat and areas with fen peat. This means that certain parts of a wetland may be suitable for agriculture when other parts are not. Based on regional observations it seems less likely that drainage and cultivation will occur on bogs that have been accumulating carbon (and radionuclides) for a long time. Furthermore, if they were to be used for that purpose, the accumulation of peat that had occurred under ombrotrophic conditions would not include radionuclides discharged with deep groundwater.

6.4 Drainage of peatland

Many peat areas can potentially be cultivated, but only c 6% of the Swedish cultivated land is presently situated in areas with peat and it is clear that large peat areas formerly used for cultivation have been abandoned (Berglund et al. 2009). However, further south in Europe much larger proportions of the peatlands are currently used for agriculture, the great majority being used as meadows and pastures (cf. Strack et al. 2008), which indicates that a larger proportion of the Swedish peatland could potentially be used for cultivation. According to Osvald (1937), it is technically possible to convert all types of wetlands with a thick enough peat layer to arable land, but it is not always economically favourable to do so. 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. An increasing demand for food would probably also increase the use of peatland as arable land. In the LDM, all peatlands that are regarded as possible to cultivate are therefore treated as arable land (SKB 2014b).

To meet the requirements of crop cultivation, the groundwater level in peat-covered wetlands must be lowered (Berglund 2008). Draining a peatland is labour-intensive, due to the need for rather closely spaced ditches (Juhlin Dannfelt 1923). According to studies in Finland by Valmari (1977), depths of 50–60 cm below the surface are suitable water table depths for many crops and plants can tolerate a water table depth of 20–40 cm for a period. However, farming is problematic when the water table is less than 30–40 cm below the ground surface, since the wet conditions cause unstable ground. Berglund (1996) reports drained depths between 50 and 100 cm in six cultivated organic soils from Sweden. Due to oxidation and compaction the original peat layer must, however, be considerably thicker than that to make cultivation possible. Groundwater has been shown to be a significant water resource for crops in agricultural fields with a shallow water table (Mueller et al. 2005; see also FAO 1973).

After draining a wetland, the accumulation of peat stops and the peat layers start to subside due to oxidation, shrinkage and compaction (Figure 6-1). Several studies have shown that this subsidence is a fast process (Berglund 1989, Kluge et al. 2008, Oleszczuk et al. 2008, Maljanen et al. 2010, Sohlenius et al. 2013). A peat land can consequently only be used for cultivation for a limited period of time. Cultivation can, however, be continued when the peat layers are completely oxidized, if the underlying soils are suitable and if it is possible to maintain the ground water table low enough. The subsidence of peat after draining can be divided into different phases (Figure 6-1). During the first years after draining, compaction is the main contributor to subsidence, which is extremely fast. For several years, compaction continues to be the main process causing subsidence, but rates slow down with time. At 10–15 years after drainage subsidence is still high, but has decreased and is mainly caused by oxidation. In a longer time perspective, decreasing subsidence rates can be expected as the content of minerals and slowly oxidizing organic material increases in the top soil. Depth of the ground water level, peat properties and climate are probably the most important conditions affecting the rate of oxidation.

Data compiled by Kasimir-Klemedtsson et al. (1997) show that the total subsidence in cultivated peat areas in Sweden can vary between 5 and 30 mm year^{-1} depending on the intensity of the management. A large part of that subsidence was attributed to oxidation. Accordingly, high management intensity may cause a subsidence as large as 1.5 m during a 50-year period. One study from an area close to Uppsala ("Bälinge mosse") showed that the ground surface had subsided 1.5 metres or more on large parts of the former mire during approximately 80 years of cultivation (Mc Afee 1985).

The cultivated peatlands in eastern Uppland studied by Sohlenius et al. (2013) are generally larger in size than the studied pristine mires from the same area, which rarely exceed 25 ha. This indicates that it has been regarded as too labour intensive to drain the smallest mires in order to obtain arable land. As mentioned above, the smallest areas used for cultivation in the LDM are 0.25 ha. It is, however, not likely that single mires of that small size will be cultivated if not surrounded by other deposits suitable for cultivation.

6.5 Cultivation of mires in the landscape development model and the safety assessment.

Peat-covered mires illustrated in the Landscape Development Model (LDM) are formed in areas which are covered by water after uplift (Brydsten and Strömgren 2013). Large water-covered areas are modelled as lakes which may persist for thousands of years. Thus organic sediments (i.e. gyttja) may accumulate over long periods of time, and these sediments are then covered by a thick layer of peat. When the succession from lake to mire is completed the mire can be drained and converted to arable land at any time. However, the study by Sohlenius et al. (2013) suggests, that many cultivated areas are situated in areas where peat accumulation started through primary peat initiation. In the LDM, such areas are also identified. One example of a mire that is formed without a lake stage is the biosphere object 157_2 (SKB 2014a, Chapter 6).

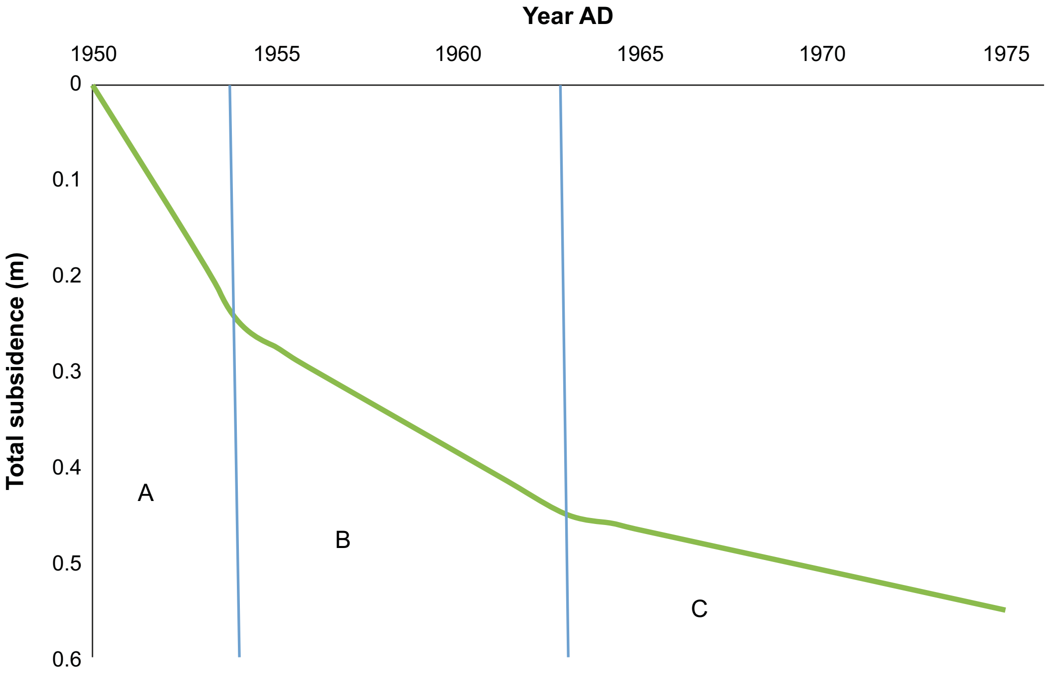

Figure 6-2. The subsidence of peat after the draining of a wetland in southern Sweden (Lidhult) for cultivation (modified from Berglund 1989). The initial period (A) after the peatland was drained is characterised by fast subsidence primarily reflecting compaction. The compaction continues after the initial period but at a much lower rate (B). After 10–15 years oxidation is the main contributor to subsidence (C). Oxidation occurred at constant rate throughout the observed period.

The smallest areas identified for cultivation in the LDM are 0.25 ha. Smaller areas are difficult to classify and model based on the present information on the scale of the landscape. This size limit is also supported by the low frequency of areas presently used as arable land of a smaller size in data from the Swedish Board of Agriculture. Moreover, historically, small size areas surrounded by non-suitable potential agricultural land have not been characterized by the same persistence of cultivation as larger units of arable land in the Forsmark and Laxemar areas (Berg et al. 2006).

In the LDM it is assumed that cultivation is only possible when an area is elevated at least 1 metre above sea level, and periodic saltwater intrusion due to high water levels can be avoided. This threshold is supported by observations of the recent location of arable land in coastal areas. The current land uplift (6 mm year^{-1}) will continuously increase the areas with potential arable land. At present, mires with suitable deposits can be cultivated in areas that emerged from the sea about 200 years ago. In the future, the rate of land upheaval is expected to decrease with time.

In southernmost Sweden there are a few areas where land situated below sea levels has been cultivated. In such areas, the water level is controlled by pumping, and walls preventing the fields from being flooded of salt water. Since areas with such low-lying arable land are uncommon, the 1 metre level used in the LDM is also regarded as appropriate for evaluating radiological safety in the Forsmark area.

Many lakes in Uppland have been artificially lowered to make cultivation of the wetlands surrounding the lakes possible. In the LDM, cultivation of a wetland occurs when the succession from a lake to mire has been completed. This means that conversion to arable land is somewhat delayed in the LDM relative to what may occur in practice.

In the SR-PSU safety assessment, it is assumed that all lakes may be artificially lowered, in order to include the outcome of cultivation at an early successional stage. Cultivation of peat and lake sediments is assumed to be possible as soon as lake-mire complex is at least 1 m above sea level, preventing flooding by the sea and salt water intrusion. The peat in wetlands is often underlain by gyttja sediments which have accumulated in the Baltic or during the lake stage. Gyttja sediments are also sensitive to compaction. A factor/function for both peat and gyttja sediments is therefore used to describe the subsidence (Grolander 2013). As the water table is lowered, crops and grass can be cultivated, and radionuclides that have accumulated through adsorption or incorporation into organic matter is exposed to plant uptake.

Moreover, there is no assumption on the specific point in time when the mire or lake-mire complex is claimed for cultivation. Instead radiological effects of drainage and cultivation are evaluated at each time step of the simulation, assuming that the mire has been undisturbed until this point in time. This approach ensures inclusion of the time point that yields the highest dose to the most exposed group.

7 Sensitivity of water flow to regolith discretisation and area delineation

7.1 Introduction

In the Radionuclide Transport Model for the biosphere (Saetre et al. 2013), advective water flows are important input data. The models for the hydrology and near-surface hydogeology in the projects SR-Site and SR-PSU were implemented using the software MIKE SHE (Bosson et al. 2010, Werner et al. 2013), why they are also referred to as the MIKE SHE models. A mapping of water flows calculated with MIKE SHE onto input data representing flow in the compartmental radionuclide transport model, was developed in the SR-Site project (Bosson et al. 2010). This mapping is based on the delineation of biosphere objects and water balances analysed over sub-volumes of these objects which are represented as compartments in the radionuclide transport model. The mapping has to address different time scales (sub-annual vs. annual) and spatial resolutions of the models. Necessary simplifactions by mapping a three dimensional flow field onto a relatively coarse compartmental structure must not deteriorate the function of the radionuclide transport model within the assessment context with the final aim to demonstrate transport and dose of radionuclides originating from SFR. For the SR-PSU assessment the approach had to be adopted to the specific conditions of SFR and was also methodologically refined.

The present chapter discusses the impact of the vertical spatial discretisation in MIKE SHE and of alternative biosphere object delineations on the mapping of water flow from the hydrological model onto input parameters of the radionuclide transport model comparing results in two series of calculation cases.

The domain of the MIKE SHE model includes bedrock and the overlying layers of regolith (e.g. till, glacial clay, postglacial clay, peat), which are represented in MIKE SHE as so called "geological layers"[2]. The geological layers are parametrised as porous media according to the local properties of the represented formation. MIKE SHE calculation layers define the spatial discretisation of the domain, which can be appointed independently from the geological layers. However, input data of a calculation layer, as e.g. hydrologic conductivity, is derived by interpolation of input data of those geological layers which the calculation layer overlaps. This might lead to biased calculation results as could occur for adjacent geological layers with highly different conductivities covered by the same calculation layer.

Precipitation, evaporation and transpiration affects the flow of water across the upper surface of the model domain which contributes to the water balance of the uppermost calculation layer. Therefore, this calculation layer cannot be arbitrarily refined if evapotranspiration is not to be underestimated, e.g. during dry subannual periods. Calculation cases were defined to compare simulation results for various choices of number and appointment of calculation layers. Also the impact of changing thickness and conductivity of a single layer was addressed in this study.

In a second study, the effect of alternative delineations of a biosphere object on the mapping of water flows was investigated, an issue which was also discussed in a broader context in the Biosphere Synthesis Report (SKB 2014a). The same alternative delineations of biosphere object 157_2 as in SKB (2014) are studied.

In the following Section 7.2, the hydrological model is shortly characterised, the two model areas for which the investigations were performed are described and calculation cases are defined. In Section 7.3 results from the comparison of the calculation cases are presented and discussed.

7.2 Model and methods

This section gives a short characterisation of the hydrogeological model, describes the two different model areas on which the two studies are based and defines the two series of calculation cases.

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[2] The radionuclide transport model represents (only) the layers of regolith by dedicated compartments.

7.2.1 The hydrological model

In the hydrological model (MIKE SHE, Werner et al. 2013), bedrock and regolith layers are treated as porous media. Bedrock properties are derived from hydrogeological modelling (Odén et al. 2014). The boundary condition at the surface of the MIKE SHE model is precipitation and potential evapotranspiration. In the model calculations of actual evapotranspiration occur only at the surface and in the upper calculation layer. Meteorological and vegetational data are used to derive the actual evapotranspiration and subsequently, net rainfall taking the following processes into account:

- interception of rainfall by the canopy,
- drainage from the canopy to the soil surface,
- evaporation from the canopy surface,
- evaporation from the soil surface, and
- uptake of water by plant roots and its transpiration, based on soil moisture in the unsaturated root zone.

7.2.2 Modeled areas

Two areas in Forsmark were modeled for the two sensitivity studies. The first area, for which calculations cases with varying vertical discretisation and varying layer properties were set up, is Lake Stocksjön (Figure 7-1). Based on the MIKE SHE model for SR-Site with present climate conditions (Bosson et al. 2010), a local model was created for Lake Stocksjön and its local catchment. The lake is surrounded by a mire and a creek is running through the catchment, coming from the upstream lake Eckarfjärden and crossing through the lake and mire area. The spatial resolution for the description of bedrock and regolith is 20 m by 20 m and for the topography and vegetation 10 m by 10 m. The initial conditions and the time-varying boundary conditions were taken from the regional SR-Site model (Bosson et al. 2010).

Alternative biosphere object delineations were studied for biosphere object 157_2 of the SR-PSU biosphere assessment (SKB 2014a, Werner et al. 2013; Figure 7-1). Hydrological simulations were run with a local model representing conditions for the year 5000 AD. The spatial resolution for the description of the regolith is 20 m by 20 m and 40 m by 40 m for the bedrock.

For the case of Lake Stocksjön, Figure 7-2 shows the regolith layers that are present within the catchment area, and the thicknesses of each layer. Further description of the regolith layer properties are provided in Table 7-1. The regolith model is described in more detail in Bosson et al. (2010).

Biosphere object 157_2 is an object identified for the SR-PSU assessment. Particle-tracking simulations identified object 157_2 as a main location for possible releases of radionuclides from SFR. The area is at present submerged but will within some thousand years emerge from the sea and form a wetland. In 5000 AD, the year for which the object was studied, the land has risen by 16.60 m due to the post-glacial rebound.

The thickness of the regolith in biosphere object 157_2 is generally small, mostly less than 4 m. Only on ca 14% of the biosphere object, the regolith depth is greater than 4 m and on ca 27% of the object area the total thickness of regolith is less than 2.5 m. The regolith is thinner on more elevated and thickest in the low, downstream (northern) parts of the object. The delineation of the biosphere object together with the thickness of all regolith layers and the topography (surface elevation) for present conditions are shown in Figure 7-3.

The sub-catchments for the two studied objects, and the delineation for the mire and lake areas used for the extraction of water balances are shown in Figure 7-4. Lake Stocksjön constitutes both a lake and a mire part. The size of the Lake Stocksjön catchment area in the MIKE SHE model is 212,800 m^2, the lake area is 5,300 m^2, and the mire area 32,400 m^2. The biosphere object 157_2 consists only of a mire. The size of the catchment area is 1,029,600 m^2, the one of the biosphere object 167,600 m^2.

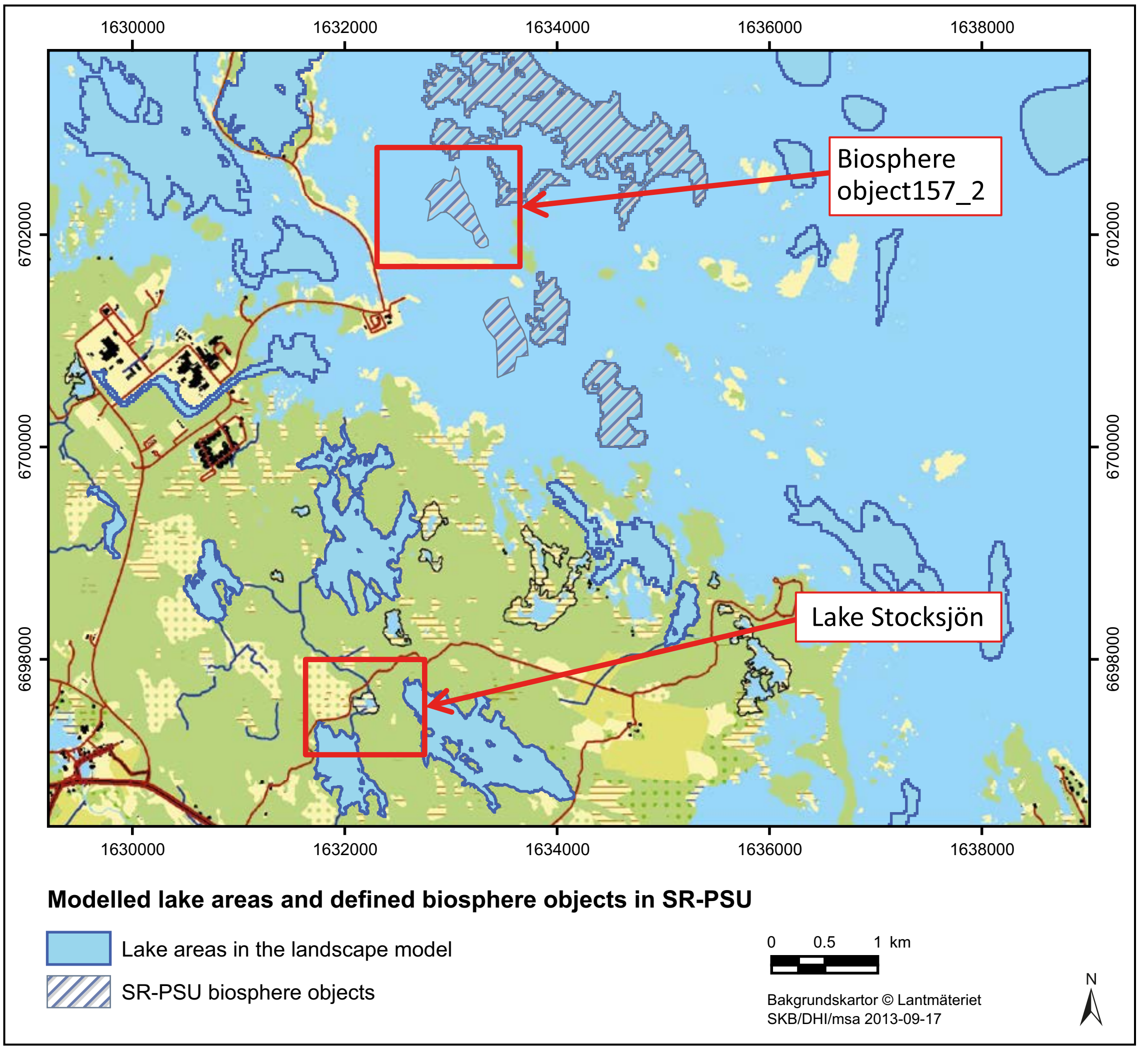

Figure 7-1. *Location of the two modelled areas, Lake Stocksjön (southern marked area) and biosphere object 157_2 (northern marked area).*

Table 7-1. Description of regolith layer types present in the model of Lake Stocksjön.

Code	Description	Comment
L1	Gyttja (algal gyttja, calcareous gyttja, clay gyttja – gyttja clay).	Peat in the vicinity of a lake is included in this layer.
Z1	Surface layer.	Everywhere present except under the lakes, i.e. L1.
Z2	Peat.	Present only where peat is mapped on the map of Quaternary deposits from the Geological Survey of Sweden.
Z3	Postglacial sand/gravel or glaciofluvial sediments.	Present only when surface layer (Z1) consists of postglacial sand/gravel or glaciofluvial sediment.
Z4b	Glacial clay.	
Z5	Till.	
Z6	Fractured bedrock.	Represents a highly conductive zone in upper bedrock.

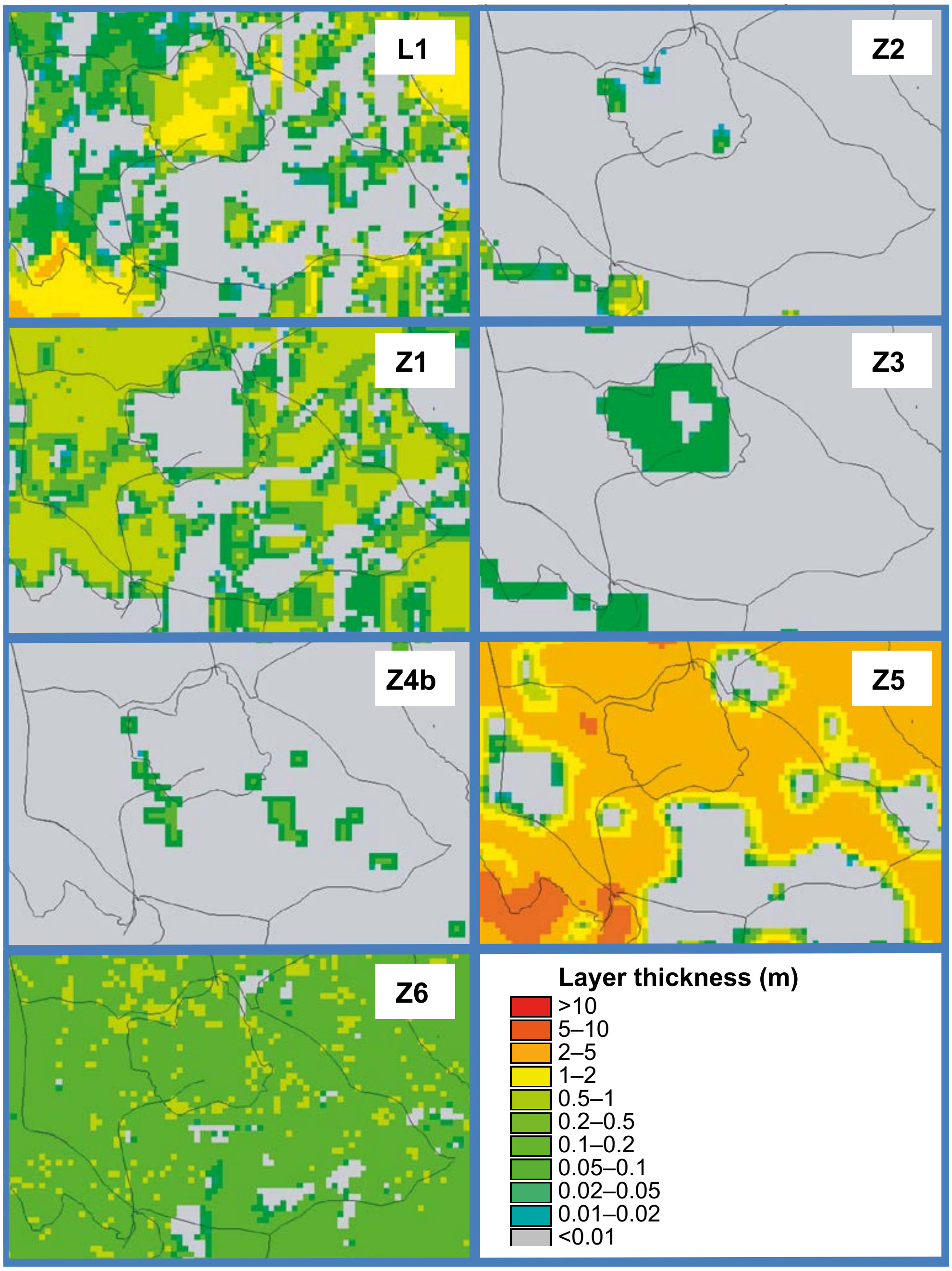

Figure 7-2. *Distribution of regolith layers and layer thickness in the Lake Stocksjön catchment where L1=gyttja, Z1=surface layer (except in lakes), Z2=peat, Z3=postglacial sand/gravel or glaciofluvial sediments, Z4b=glacial clay, Z5=till, and Z6=fractured bedrock. The regolith layer types are further described in Table 7-1.*

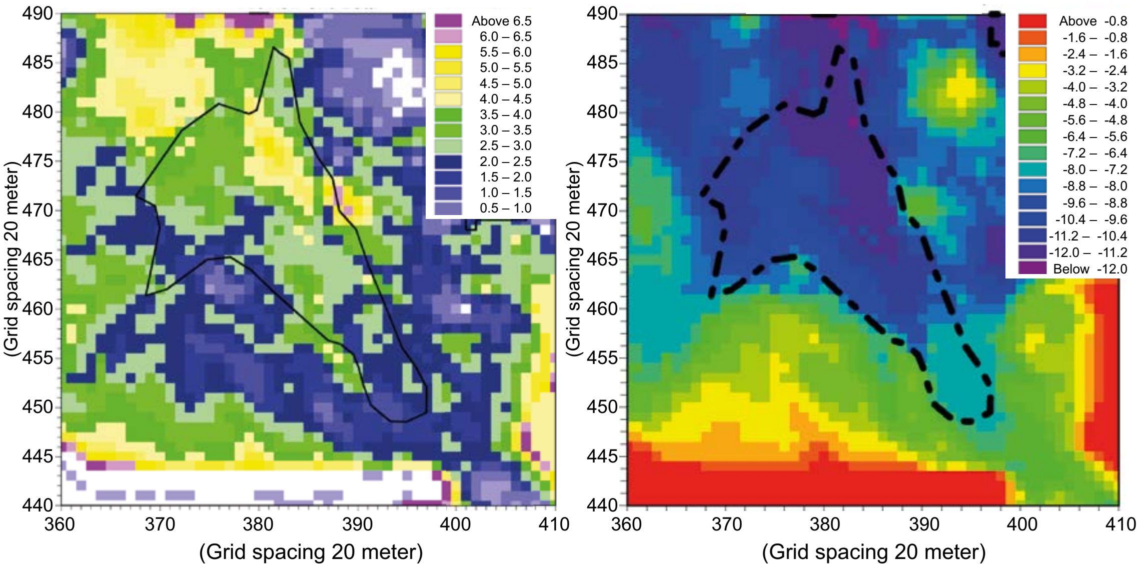

Figure 7-3. *Total thickness of regolith (m, left figure) and topography (m, right figure) for the delineated biosphere object 157_2. The topography levels are given with regard to present conditions with an average sea level of 0 m, i.e with the submerged conditions at the location of 157_2 today many values are negative.*

The two models for Lake Stocksjön and biosphere object 157_2 were run with slightly different climatic data. The mean annual precipitation for Lake Stocksjön was 604 mm, while 583 mm was used for biosphere object 157_2. For more details see Bosson et al. (2010) and Werner et al. (2013).

7.2.3 Calculation cases

Sensitivity of water flow to vertical discretisation (Lake Stocksjön)

In the MIKE SHE model, the regolith layers are given properties separately and called geological layers (e.g. Table 7-1). Each regolith layer from the regolith model is given an extent, a thickness, hydraulic conductivities in both horizontal and vertical directions, as well as a specific yield and specific storage. However, in the MIKE SHE model, surface processes such as evaporation and transpiration only take place at the surface and in the uppermost layer and if the layer is too thin some parameters will be underestimated. Therefore, the MIKE SHE model distinguishes the geological layers from the computational layers. The calculation layers can have any thickness, independently of the thicknesses of the geological layers. In this sensitivity analysis, the effect of number of, and properties of, calculation layers were studied.

The calculation cases defined for **Lake Stocksjön** are listed in Table 7-2 and are categorised by the number of calculation layers used for the discretisation of the regolith. In the basecase 2CalcL_basecase, the regolith has two calculation layers, an upper regolith layer (minimum thickness 2.5 m and a lower regolith layer (minimum thickness 1 m) as for the basecase in Bosson et al. (2008, 2010), see table 7-2 for more details. In the alternative cases with two calculation layers 2CalcL_Z1 and 2CalcL_Z4b, the upper calculation layer represents {L1, Z1, Z2} and {L1, Z1, Z2, Z3, Z4b} respectively. For calculation cases with three calculation layers (3CalcL_1, 3CalcL_2 and 3CalcL_3), the the two calculation layers covering the regolith always represent the same sets of layers, which are {L1, Z1, Z2}, {Z3, Z4b} and {Z5, Z6}; the alternative cases change thickness and conductivity of Z3 as described in Table 7-2. In the last calculation case 7CalcL_1 each geological layer is represented by a dedicated calculation layer.

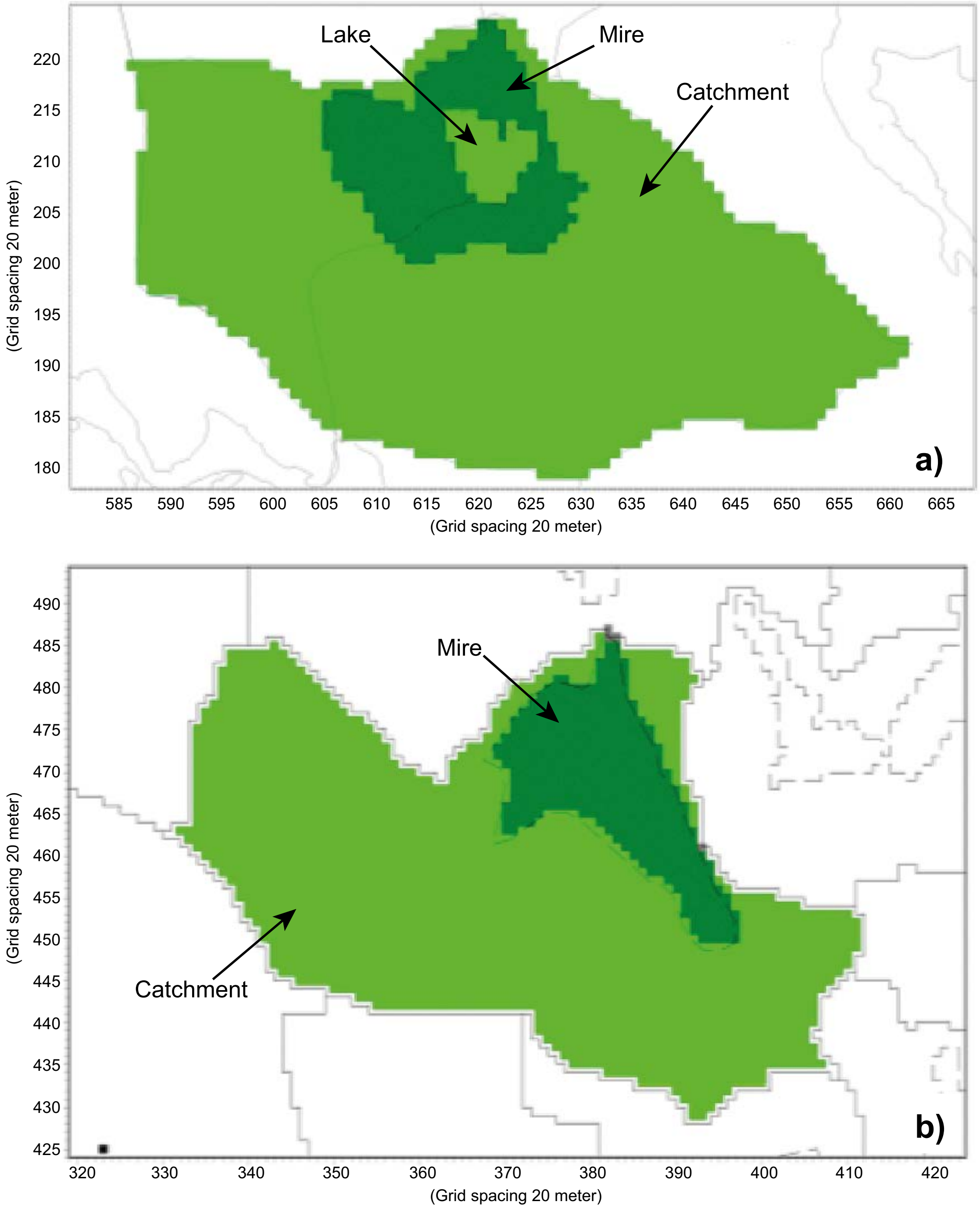

Figure 7-4. *Catchment areas for the two studied objects, Lake Stocksjön (top) and biosphere object 157_2 (bottom). Note that Lake Stoksjön is made up by both lake and mire whereas biosphere object 157_2 is entirely made up by mire.*

Table 7-2. Calculation cases for Lake Stocksjön.

Calculation case	Description
2CalcL_basecase	The sets of geological layers (regolith) L1, Z1, Z2, Z3, Z4b, Z5 and Z6 are represented by two calculation layers where the upper layer is minimum 2.5 meter and the lower layer is minimum 1 m (when the regolith is to thin for this, the calculation layer 2 enters the uppermost geological bedrock layer). The stratigraphy in the upper calculation layer is either determined by only lake sediment (L1, L2, L3) or {Z1, Z2, Z3, Z4b, Z5}.
2CalcL_Z1	The sets of geological layers {L1, Z1, Z2} and {Z3, Z4b, Z5, Z6} are represented by one calculation layer each. Depending on stratigraphy, the thickness of the upper calculation layer is defined by {L1, Z1, Z2} with a minum of 1 m.
2CalcL_Z4b	The sets of geological layers {L1, Z1, Z2, Z3, Z4b} and {Z5, Z6} are represented by one calculation layer each. Depending on stratigraphy, the thickness of the upper calculation layer is defined by {L1, Z1, Z2, Z3, Z4b} with a minum of 1 m.
3CalcL_1	The sets of geological layers {L1, Z1, Z2}, {Z3, Z4b} and {Z5, Z6} are represented by one calculation layer each. The thickness of the upper calculation layer is defined as in 2CalcL_Z1, but without the condition of a minimum thickness of 1 m.
3CalcL_2	Variation of 3CalcL_1 with the thickness of Z3 increased from 0.2 m to 0.5 m.
3CalcL_3	Variation of 3CalcL_2 with properties of Z3 changed from gravel to clay.
7CalcL_1	Each of the seven geological layers, i.e. each layer of regolith and fractured bedrock, is represented by a dedicated calculation layer.

Senstitivity of advective water flows to horizontal discretisation (biosphere object 157_2)

As stated before, biosphere object 157_2 is identified in particle tracking simulations as the main discharge area from the SFR repository. In this sensitivity analysis the sensitivity to alternative discretisation of the horizontal delineation fo this object is investigated. The model for the **biosphere object 157_2** is described in Werner et al. (2013) and the alternative delineations analysed are listed in Table 7-3 and shown in Figure 7-5. The vertical discretisation, i.e. the stratigraphy of calculation layers, is the same in all calculation cases for biosphere object 157_2 and identical with the SR-PSU main case (Werner et al. 2013).

The base case for biosphere object 157_2 consists of the delineation as defined in the SR-PSU main case. The first alternative delineation "Discharge area" is defined by the area (within the main delineation) with an upward gradient of the hydraulic head (at 5000 AD) in the regolith, in the bedrock below the regolith and in the bedrock at a depth of ca 60 m simultanuously. The upward gradients are calculated by subtracting the hydraulic heads in two adjacent layers, based on annual average hydraulic heads. Thus, the case defined as "Discharge area" is the area with an upward gradient at all three depths.

The delineation "Shallow gw" is defined as the areas (within the main delineation) where the depth to the annual average groundwater level is less than 0.25 m at year 5000 AD (Werner et al. 2013). The delineation "Exit points" is represented by an area defined as the area with a high density of exit points derived from partickle tracking for the year 5000 AD (see Werner et al. 2013). Finally, the delineation "Arable land" is based on an area representing possible future arable land, determined by a minimum thickness of at least 0.5 m of compacted and cultivable soil (Saetre et al. 2013b).

Table 7-3. Alternative delineations (defining calculation cases) for biosphere object 157_2.

Name	Description
Base case	Entire biosphere object 157_2, i.e. the main delineation as defined in SR-PSU.
Discharge area	Area with upward gradients of hydraulic head at each of three various depths (year 5000 AD).
Shallow groundwater	Area with shallow groundwater table (depth less than 0.25 m below ground at 5000 AD).
Exit points	Area with high density of exit points from SFR at year 5000 AD.
Arable land	Area of possible future arable land, i.e. minimum thickness of 0.5 m of compacted and cultivable soil.

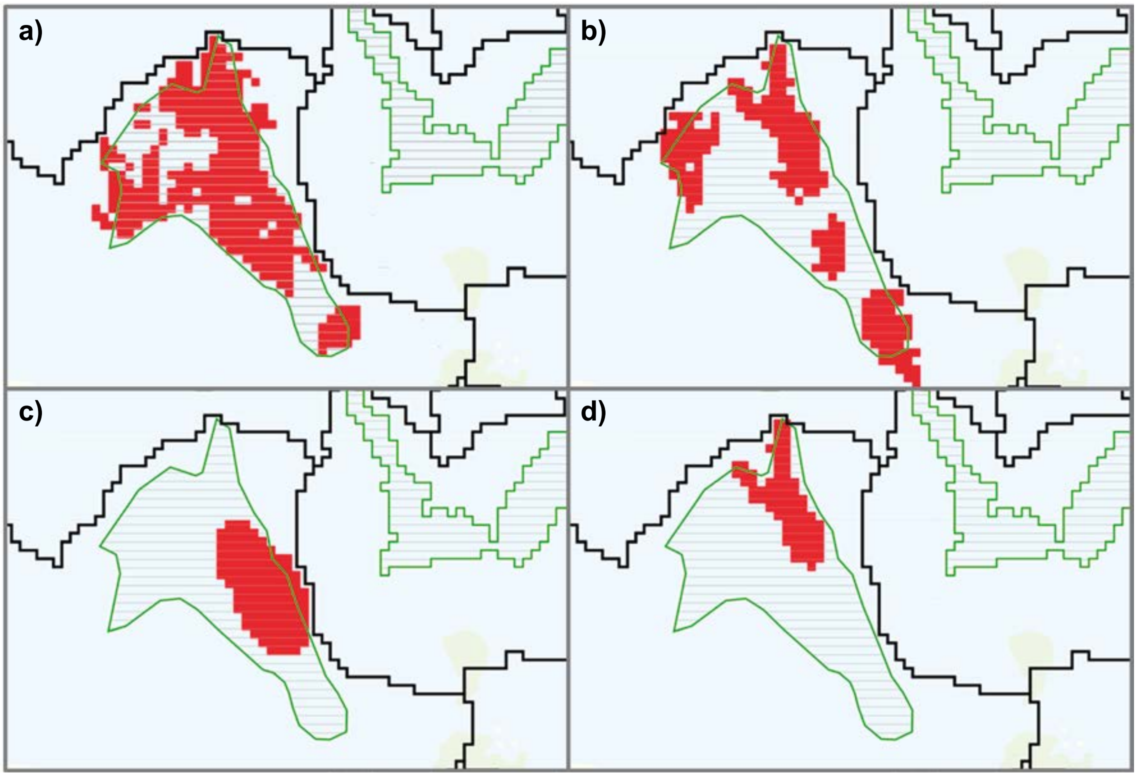

Figure 7-5. Cases of delineation of biosphere object 157_2 as represented in the MIKE SHE model. The green striped area shows the main case delination, whereas the red denotes, a) the upward hydraulic gradients in the regolith, in the upper part of the rock and at c –60 m elevation in the rock, b) the annual average depth to the groundwater table less than 0.25 m, c) the high exit-location density of tracked particles at the interface between rock and regolith, d) the potential arable land.

Table 7-4 shows mean, minimum and maximum thickness of the regolith for each delineation. Although the regolith model and layer sequence is the same for all calculation cases, the regolith depths differ since the studied areas differ from case to case.

The uppermost calculation layer of the hydrological model is 2.5 m thick. However at some locations, the total depth of regolith is less than 2.5 m so that bedrock parameters take their influence on input parameters of the upper calculation layer. The four uppermost calculation layers, which are supposed to represent the regolith, are 6.5 m thick. This means that the lower calculation layers have partly to be considered as bedrock layers. This makes the interpretation of results more difficult.

Table 7-4. Thickness of regolith layers as MIKE SHE geological layers for alternative delineations of biosphere object 157_2, [m].

	Entire object			Discharge area			Shallow gw.			Exit points			Arable land		
Layer name	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Organic material	0.17	0.00	1.76	0.17	0.00	1.76	0.40	0.00	1.76	0.23	0.00	1.76	0.58	0.00	1.76
Postglacial marine sediments	0.31	0.20	0.44	0.33	0.20	0.50	0.36	0.20	0.44	0.31	0.12	0.44	0.41	0.37	0.44
Glacial clay	0.17	0.00	2.68	0.23	0.00	2.68	0.35	0.00	2.68	0.11	0.00	1.74	1.04	0.00	2.68
Till	2.40	0.36	6.17	2.23	0.34	4.30	1.89	0.65	3.28	2.66	1.59	5.85	1.82	0.34	2.55
Sum	3.06			2.96			3.00			3.31			3.85		

7.3 Results

The hydrological model simulates the flow of water over a period of several years under constant climatic conditions taking seasonal changes into account. Most relevant for the mapping from the MIKE SHE model to the radionuclide transport model are annual averages over defined bounding surfaces. These quantities are reported as flows with the unit of an anual velocity ((Length^3/Time)/Length^2 = Length/Time). The surfaces over which the water flow is balanced is defined by bounding surfaces between MIKE SHE calculation layers. Of particular interest is the surface defining the boundary between bedrock and regolith and the surfaces between the upper regolith calculation layers.

The flow across the boundary of adjacent calculation layers represent (on average) a vertical flow (upwards or downwards). Flows across the boundary occur simulatenously in both directions. Both directions have to be evaluated separately to capture simultanuous transport in both directions in the radionuclide transport model. "Vertical flows" are particularly important for the parametrisation of the flow of water between compartments of a single biosphere object.

7.3.1 Sensitivity of water flow to vertical discretisation (Lake Stocksjön)

Figure 7-6 shows the location of a profile (cross section) across the Lake Stocksjön lake-mire complex on which data from two calculation cases are illustrated in Figure 7-7. In Figure 7-7 the vertical hydraulic conductivity in the calculation layers of calculation case 2CalcL_basecase and 7CalcL_1 are compared.

The annual mean net vertical flow for the calculation areas in Stocksjön always points upwards. Vertical flow derived at the boundary between bedrock and regolith for all calculation cases studied for Lake Stocksjön (listed in Table 7-2) are reported in Table 7-5. The flows are reported for both the mire area and the lake area and are given in terms of upward (vertical) flow and net upward flow, i.e upward flow minus downward flow. Furthermore, the net precipitation is also reported, which is the precipitation minus all evaporation and transpiration.

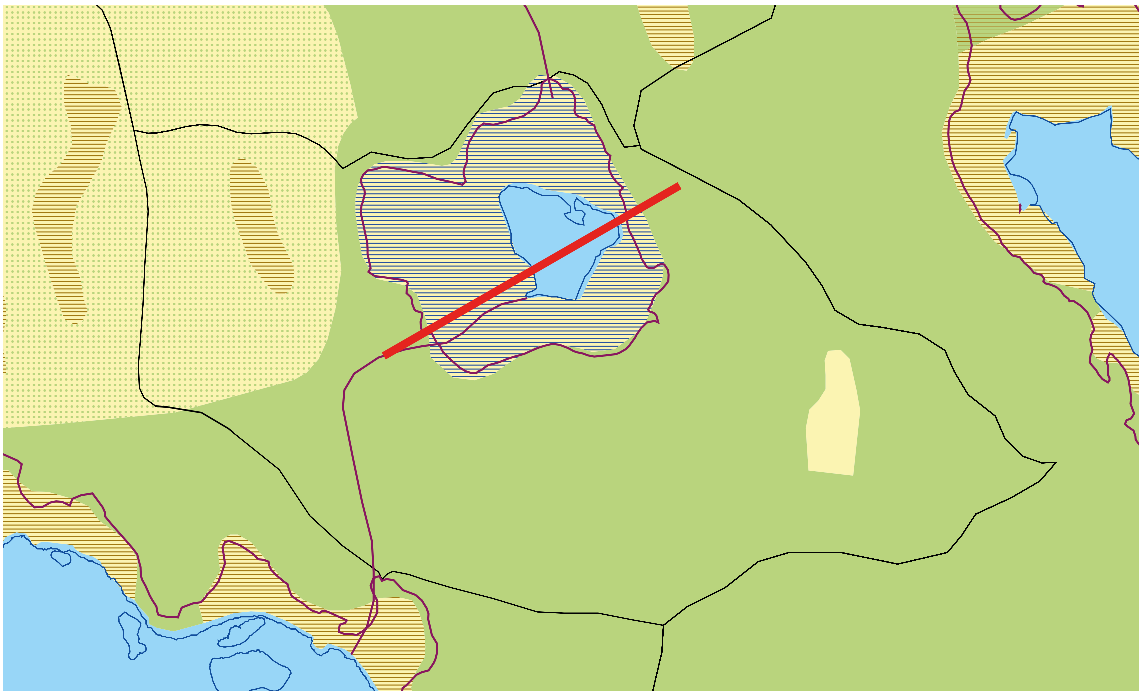

Figure 7-6. *Location of the profile in the Lake Stocksjön area on which vertical conductivities are reported for two calculation cases in Figure 7-7.*

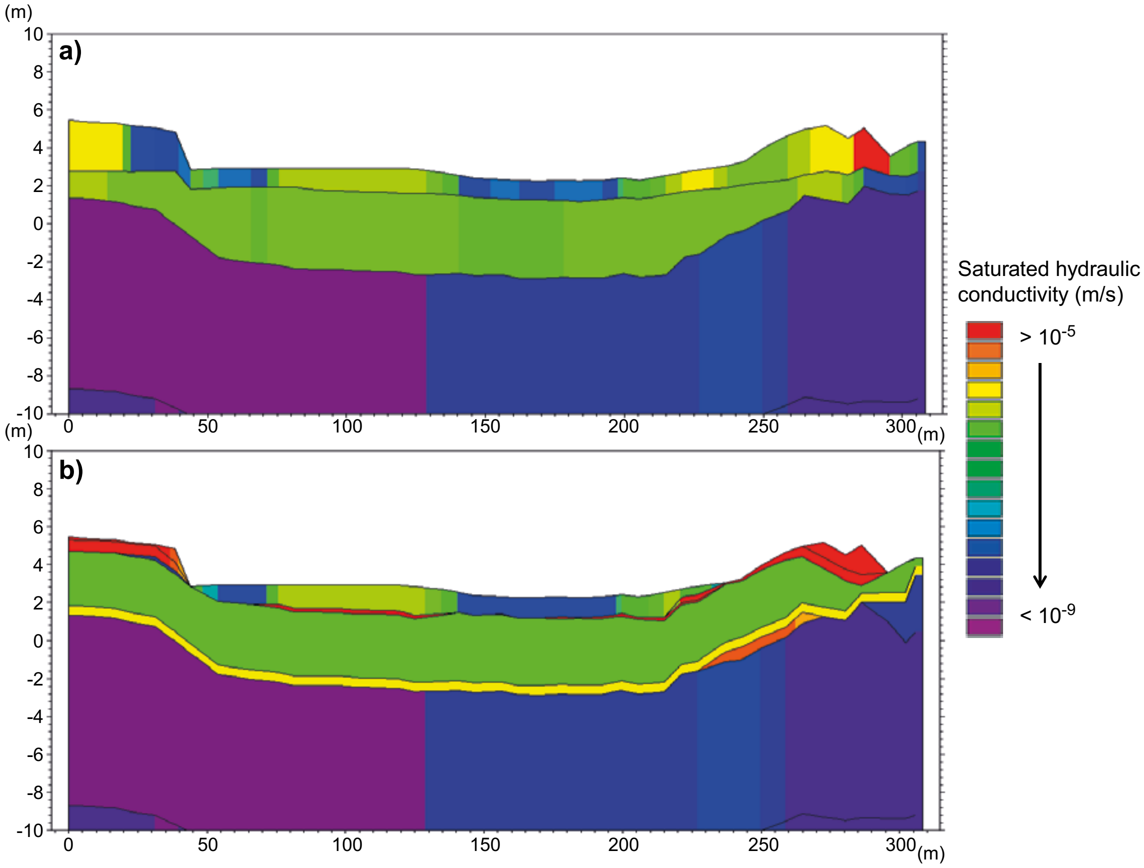

Figure 7-7. *Vertical hydraulic conductivity along the profile defined in Figure 7-6 for the two simulation cases a) 2CalcL_basecase and b) 7CalcL_1. The lower layer represents the bedrock and is identical between the two calculation cases.. Conductivity is ranging from approximately 10^{-9} m/s (violet/blue) to 10^{-4} m/s (red).*

For the lake the flow between bedrock and regolith is robust with respect to all variants of the calculation cases (Table 7-5). The results vary more for the mire. For the cases with an increased number of calculation layers in the regolith, the upward flow is higher than for the cases with only two calculation layers. However, also the net precipitation is higher, implying that the uppermost layer in the mire is too thin to allow for full evaporation and transpiration. This is particularly notable for the case 7CalcL_1. For all calculation cases, the net vertical flow equals almost the total upward flow. This implies that the downward flow is very small in all cases.

Table 7-5. Net precipitation (NetP) and upward and net vertical flows at the bedrock-regolith boundary, [mm/year], for calculation cases for Lake Stocksjön.

	Mire			Lake		
		Vertical flow			Vertical flow	
	NetP	Upward	Net	NetP	Upward	Net
2CalcL_basecase	194	28	27	26	6	6
2CalcL_Z1	194	23	22	26	6	6
2CalcL_Z4b	195	23	22	26	6	6
3CalcL_1	204	33	33	26	8	8
3CalcL_2	204	33	33	26	8	8
3CalcL_3	202	31	31	26	7	7
7CalcL_1	305	37	37	26	8	8

Figure 7-8 shows the vertical flow in the mire (upward flow and net upward flow) for calculation cases with two regolith calculation layers (2CalcL_basecase, 2CalcL_Z1, and 2CalcL_Z4b) as a function of depth. As seen in the figure, the difference in the average thickness of the uppermost layer is small, just a few cm difference between the three simulations. However, over the surface there may be larger differences in thickness. In the case 2rego_Z4b, the lower layer is purely consisting of till; for the case 2rego_Z1, the lower layer consist of till and postglacial sediments, mainly post-glacial sand.. The upward flow shows a similar profile over depth in the three cases (Figure 7-8a). However, the net vertical flow shows a larger discrepancy between the calculation cases. The net vertical flow increases in all cases from bedrock up to the boundary between the regolith calculation layers; but, while it keeps increasing up to the surface for the cases 2CalcL_basecase and 2CalcL_Z1 it decreases to a minimum value in the case of 2CalcL_Z4b. This implies that in 2CalcL_Z4b water leaves the uppermost layer horizontally, i.e. without reaching the surface.

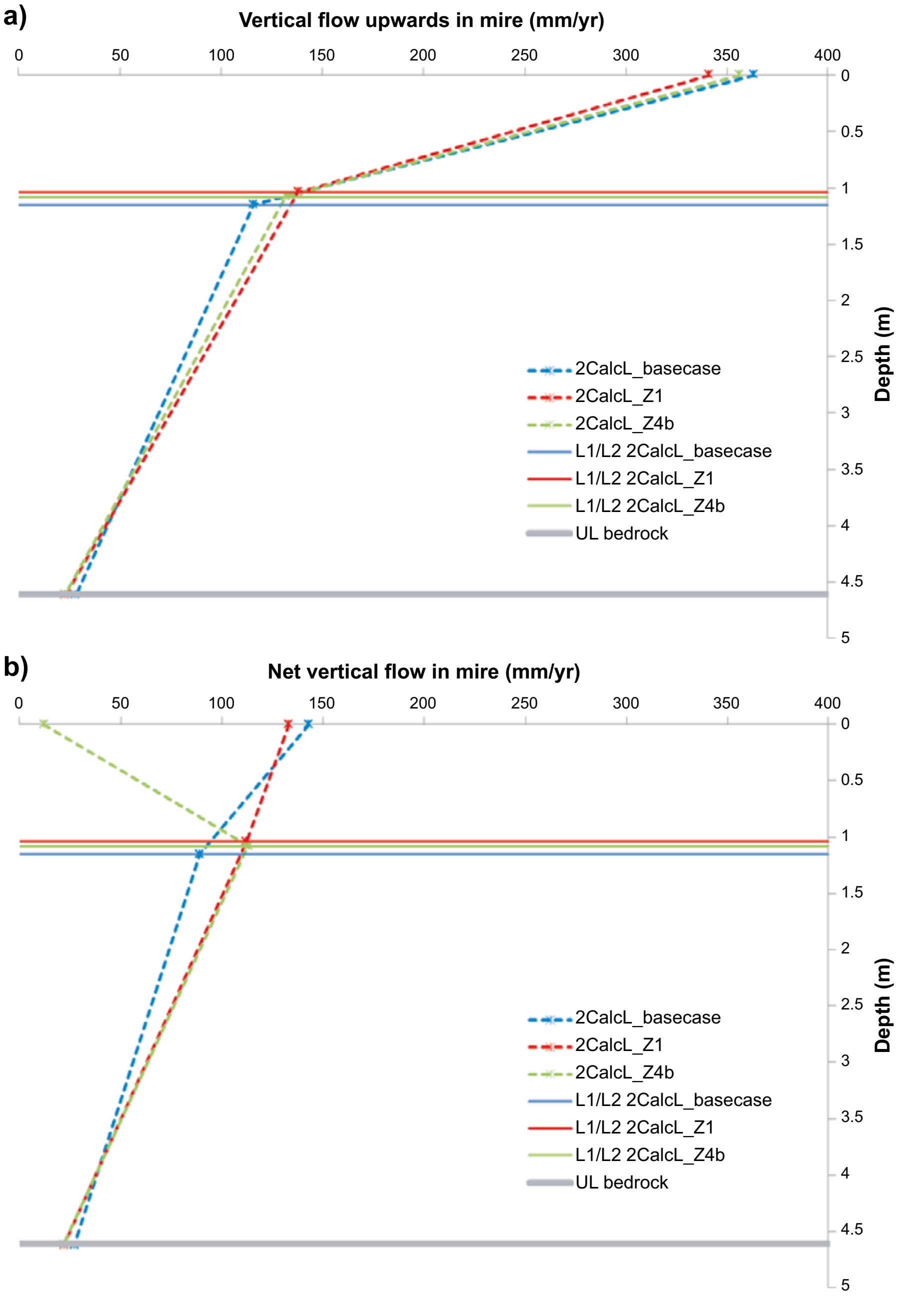

Figure 7-8. *Vertical flows in the mire part of Lake Stocksjön for calculation cases with two regolith calculation layers. The upper figure shows upward flow, and the lower figure net vertical flow. The horizontal lines represent the average levels of the bedrock surface (UL bedrock) and of the average level of boundary between the upper and lower calculation layers in the respective calculation cases (L1/L2).*

As can be seen in Figure 7-7b, there is a thin layer of higher conductivity consisting of sand/gravel (red in the figure) in the mire area of the Lake Stocksjön. For the case 2CalcL_Z1, this layer is not part of the uppermost calculation layer, while this is the case for 2CalcL_4Zb. Although the sand layer is not very thick, this increases the average hydraulic conductivity of the upper calculation layer significantly in 2CalcL_4Zb. Therefore water in the upper calculation layer will leave it horizontally, while it in 2CalcL_Z1 will move vertically up to the surface.

A comparison between the hydraulic conductivity in the uppermost calculation layers of calculation case 2CalcL_Z1 with 2CalcL_Z4b are visualised in Figure 7-9. Both the vertical and horizontal hydraulic conductivities are higher in the mire area for case 2CalcL_Z4b than in 2CalcL_Z1. The increased horizontal hydraulic conductivity in the upper regolith layer results in water being transported towards the surface streams. In fact, the total sum of water leaving the lake-mire-system in the same for the two cases; it is just a question of where the water leaves the studied area, depending on the soil types in the calculation layers.

Vertical flows through the regolith calculation layers for calculation cases with different numbers of regolith calculation layers, i.e. for 2CalcL_basecase, 3CalcL_1 and 7CalcL_1, are shown in Figure 7-10. There, average levels of the boundary between the upper two calculation layers and of the bedrock surface are plotted similar as in Figure 7-8. The figure indicates that the finer the vertical discretisation (i.e. the more calculation layers), the higher the net flow at shallow depths. However, for the case 7CalcL_1 with the highest number of calculation layers, the upward vertical flow close to the surface is lowest. As reported in Table 7-5, the net precipitation is higher for the calculation cases with more than two regolith layers leading to higher water flows in these calculation cases. When divided by net precipitation, the flows in the calculation case with a fine vertical discretization are no longer the highest and the ratio is particularly low for the case 7CalcL_1 (see the lower diagrams in Figure 7-10). The higher net precipitation indicates that the upper layers are too thin to allow for full evapotranspiration in the calculation cases with finer discretisation.

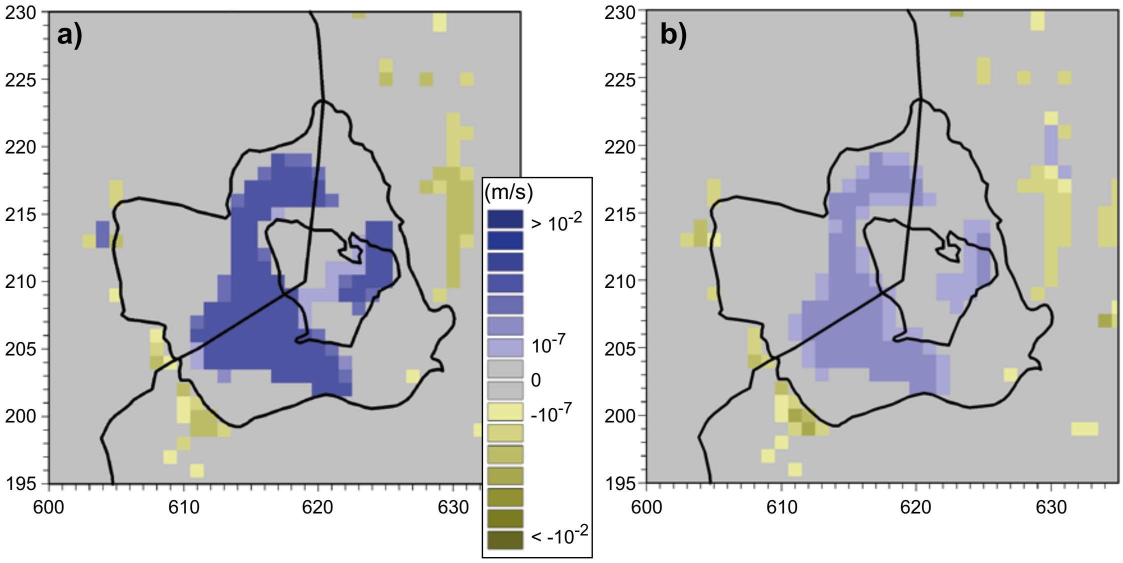

Figure 7-9. *Difference in hydraulic conductivities of the upper calculation layer between simulation cases 2CalcL_Z4b and 2CalcL_Z1 for Lake Stocksjön. a) horizontal conductivity i.e. horizontal conductivitiy in 2CalcL_Z4b minus horizontal conductivitiy in 2CalcL_Z1; and b) vertical conductivity i.e. vertical conductivitiy in 2CalcL_Z4b minus vertical conductivitiy in 2CalcL_Z1. Positive values indicate a higher conductivity in 2CalcL_Z4b.*

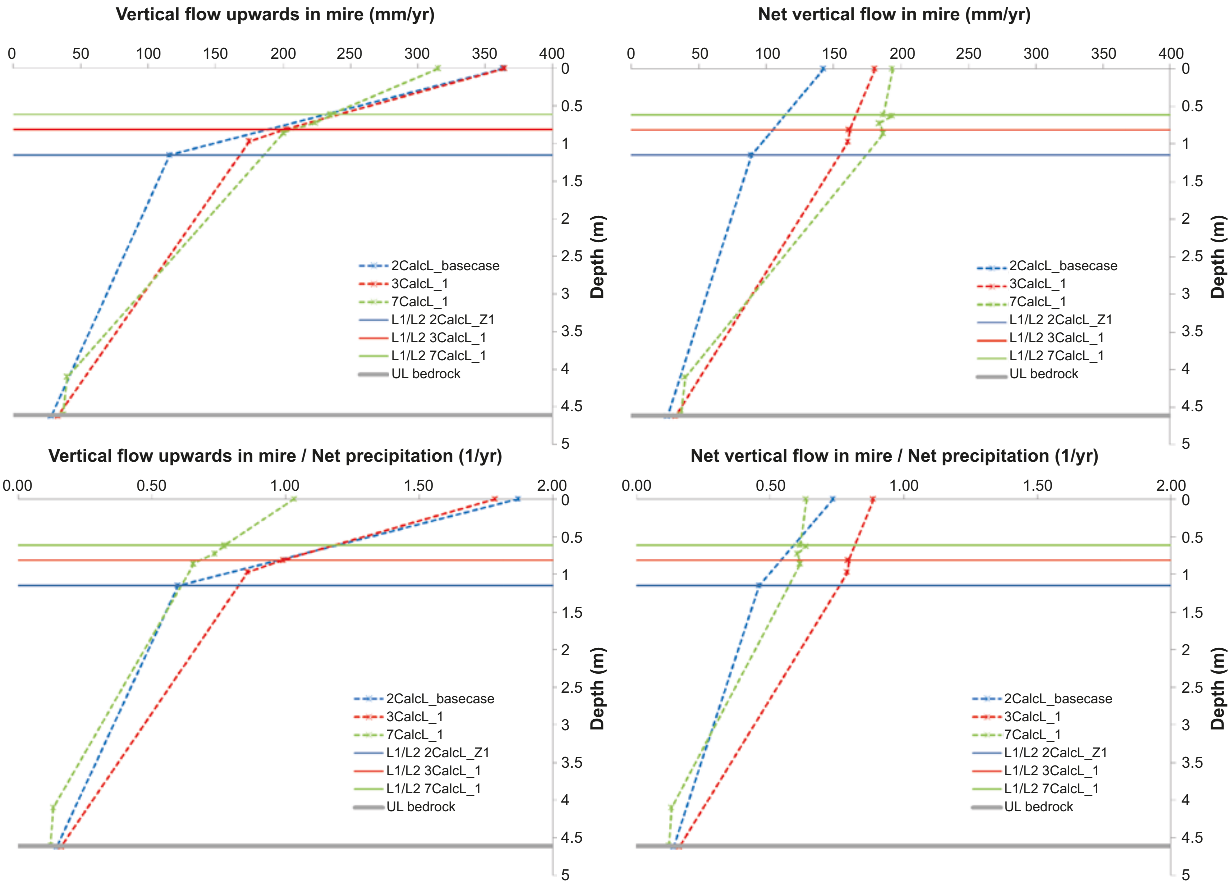

***Figure 7-10.** Vertical flow (top) and ratio of vertical flow over net precipitation (bottom) for upward (left) and net vertical flow (right) for the three calculation cases with increasing number of regolith layers, 2CalcL_basecase, 3CalcL_1, and 7CalcL_1. The horizontal lines (labelled with L1/L2 represent the average level of the boundary between the two upper calculation layers in the respective calculation cases. UL_bedrock is the average level of the surface bounding bedrock from regolith.*

The effect of changing the thickness of one of the layers and the effect of changing the soil type from sand/gravel to clay, i.e. decreasing the hydraulic conductivity of the layer are shown in Figure 7-11. The vertical flows in 3CalcL_1 (the same composition as the base case but with the regolith divided into three calculation layers) are compared with the flows in the cases 3CalcL_2 (thicker Z3 layer) and 3CalcL_3 (decreased conductivity in the layer Z3). Increasing the thickness of the postglacial sand/gravel layer Z3 does not change the vertical flow. Changing the hydraulic conductivity of the Z3 layer, from highly conductive sand/gravel to clay, reduces the vertical flow by almost 10% at the surface, both for upward flow and net vertical flow. The flow from the bedrock is the same in all cases.

7.3.2 The effect of horizontal extension on advective water flows

This section presents results for the calculation cases defined by alternative delineations of biosphere object 157_2, i.e the cases identified to analyse how horizontal discretization affects the flow results. The results are based on the local MIKE SHE model of the biosphere object for the year 5000 AD (Werner et al. 2013).

The upward flows and net vertical flows for the five calculation cases at the boundary-regolith boundary are reported in Table 7-6. Net precipitation and the size of the area for which the water balance was extracted are also reported in the table. As expected, the largest net vertical flows from bedrock to regolith are obtained for delineations with upward hydraulic gradients ("discharge area") and high exit-location density ("exit points"). For the delineation with a shallow depth to the groundwater table, net vertical groundwater flows are similar to those obtained for the entire biosphere object. The smallest net vertical flow is obtained for arable land, where the delineated area is characterised by thick layers of low-permeability regolith (soil). Also, the net precipitation is smaller for this case due to higher evaporation.

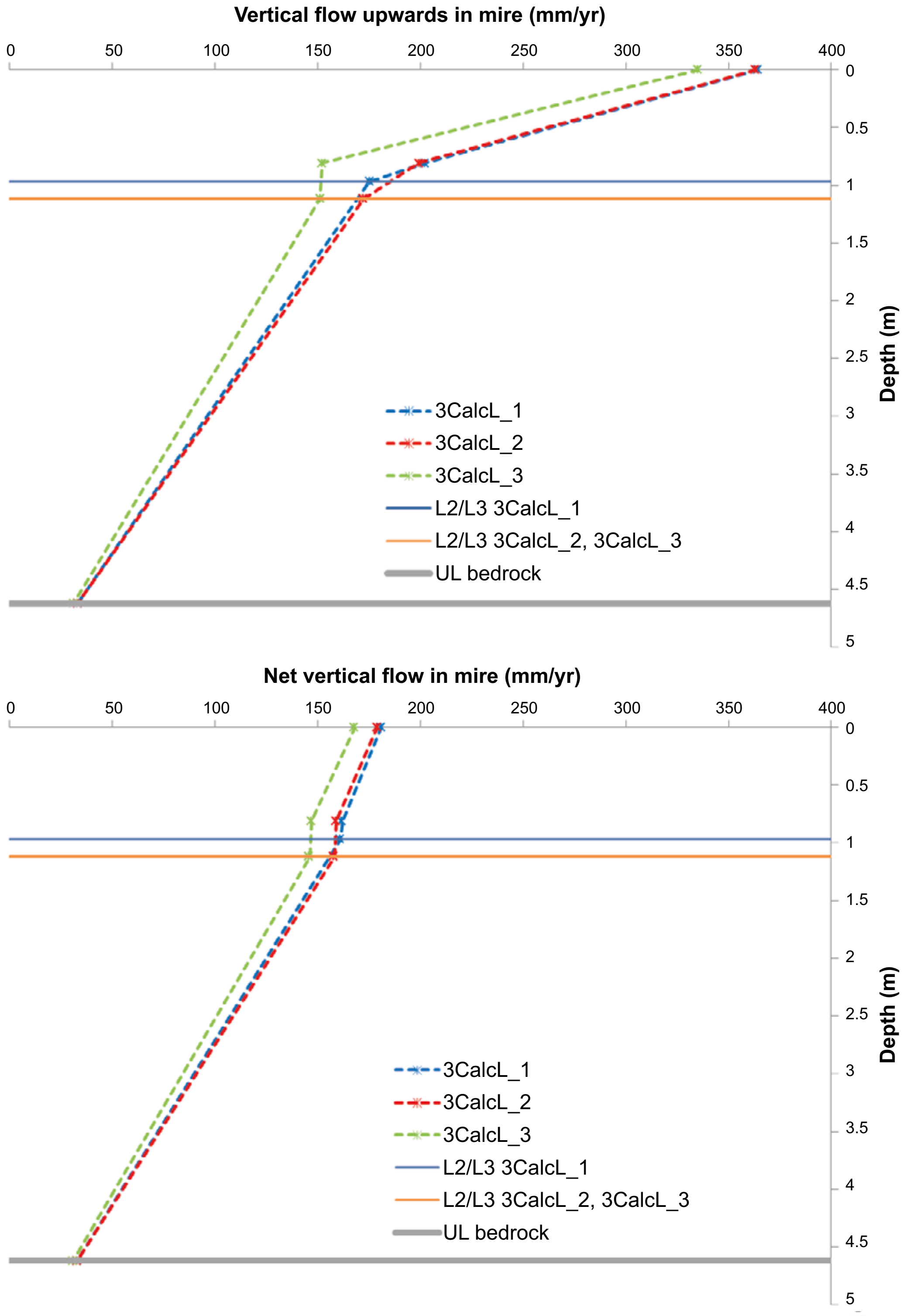

Figure 7-11. *Vertical flow compared for the calculation case 3CalcL_1 with its variations 3CalcL_2 and 3CalcL_3 (with a thicker layer Z3). The horizontal lines in the figure are showing the average level of the boundary between the second and third calculation layer (prefix "L2/L3"). UL_bedrock is the average level of the surface bounding bedrock from regolith. The upper figure shows upward flow, the lower figure net vertical flow.*

Table 7-6. Net precipitation (NetP) and upward and net vertical flows at the bedrock-regolith boundary, [mm/year], for alternative delineations of biosphere object 157_2. Reported is also the size of the area covered by the respective delineation.

	NetP (mm/yr)	Area (m^2)	Vertical flow Upward (mm/yr)	 Net (mm/yr)
Base case	175	167,600	114	101
Discharge area	179	132,400	143	141
Shallow groundwater	156	84,000	103	98
Exit points	174	47,200	149	134
Arable land	143	29,200	63	63

As flows are determined as annual average flows through boundary surfaces of different size, and because of different underlying base areas of the delineations, similar flows for different delineations can refer to different volumetric flows.

Figure 7-12 shows the annual average vertical flows (in mm/year and m^3/year) separate for upward only flows (left) and net flows (right) for the five investigated delineations. The averaged flow quantities are shown as functions over depth, and the horizontal lines indicate average levels of bounding surfaces of calculation layers.

For the delineations "discharge area" and "exit points" the inflow from the bedrock is particularly high. At the top surface the highest flows (upward and net vertical) are seen in the delineation "shallow groundwater"; this is possible with high superficial inflow from the surroundings into the top calculation layer of the delineation.

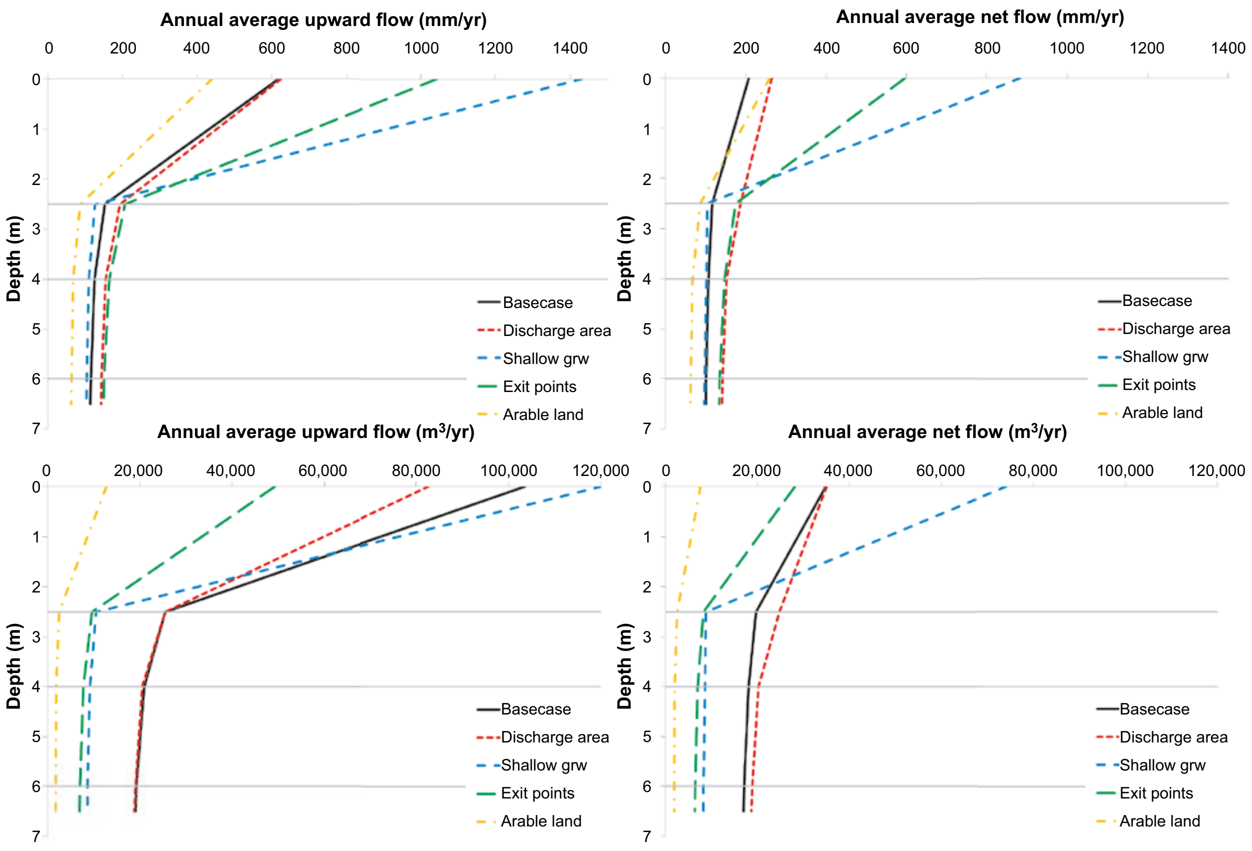

***Figure 7-12.** Annual average vertical flows (in mm/year and m^3/year) separate for upward only flows (left) and net flows (right) for the five investigated delineations of biosphere object 157_2.*

In all cases, both only upward flow and net flow increase significantly in the uppermost calculation layer. For the base case, the increase of net vertical flow in the upper calculation layer is lowest and so is the net vertical flow at the top surface itself. This might reflect that the approach to define the base case was the delineation of a hydrologically rather closed system. The delineation "arable land" generates the lowest flows almost everywhere (with exception of net flow at the top surface being lowest for the base case).

Mean annual recharge and discharge areas in the regolith of biosphere object 157_2, estimated as the annual average head difference between the two uppermost calculation layers, are shown in Figure 7-13. Most of the area of 157_2 function as a discharge area when calculated as mean over the year. However, wether an area function as discharge area or recharge area can change in the course of a year. This is illustrated for the cell in biosphere object 157_2 marked as "Example grid cell" in Figure 7-13.

Figure 7-14 shows examples of time series in the selected grid cell indicated in Figure 7-13. The figure illustrates discharge and recharge by showing the hydraulic head in different calculation layers (L1, L2, L5, L6, L11 and L12) over the course of one year, as well as the difference of hydraulic heads for the three pairs of adjacent layers. At the indicated cell, the conditions alternate between discharge and recharge in the course of a year at shallow depths. In the lower layers, the flow is always directed upwards (discharge condition).

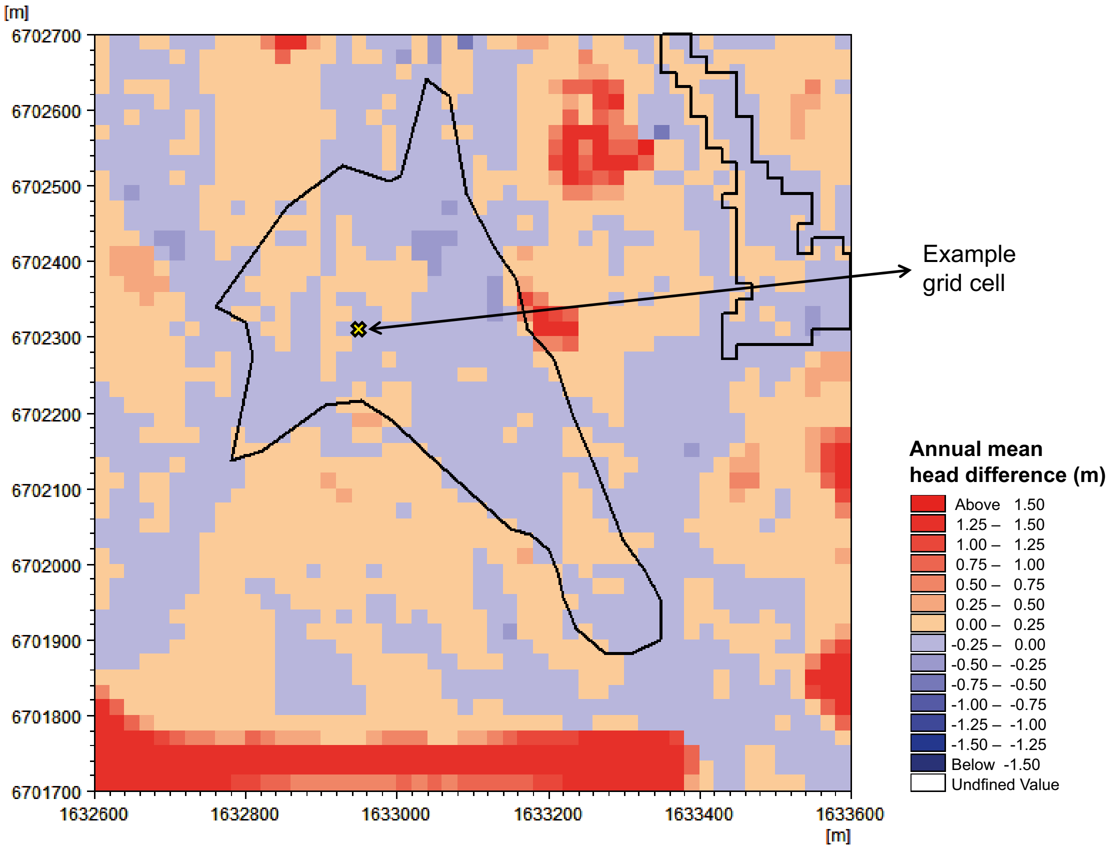

Figure 7-13. *Annual mean recharge and discharge areas in the regolith for biosphere object 157_2 (i.e. difference of the annual mean hydraulic heads in the uppermost two calculation layers) with the base case delineated in black. Positive values (red) indicate recharge areas and negative values (blue) indicate discharge. The example grid cell is further investigated in Figure 7-14.*

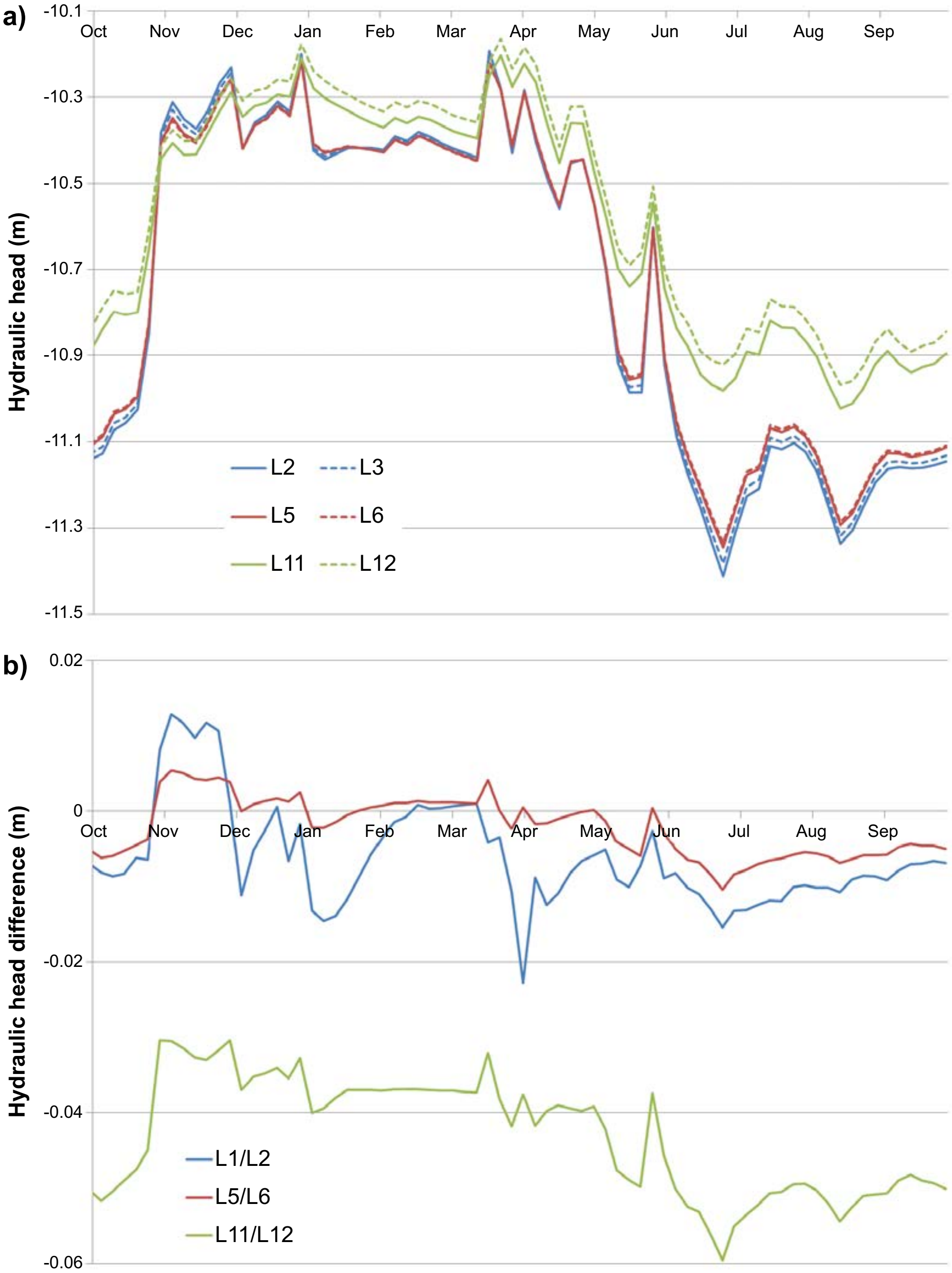

Figure 7-14. *(a) Times series over one year of hydraulic heads for three pairs of adjacent calculation layers (L1/L2, L5/L6, L11/L12) at the location indicated in Figure 7-13. Lines for time series of adjacent layers share the same colour with the dotted pattern representing the lower layer. When the dotted line is above the continuous line there is a discharge condition (upward flow). (b) Difference of hydraulic heads in adjacent layers where negative values indicate discharge and positive values recharge.*

Continuously discharging or recharging conditions in the biosphere object 157_2 at depth of the upper regolith (L1/L2), of the bedrock-regolith boundary (L5/L6) and of 60 m depth in the bedrock (L11/L12) are visualised in Figure 7-15. Almost the entire area of object 157_2 is discharging at the depth of 60 m, only a single small area in the southern part of the object is continuously recharging in the bedrock. In the regolith, the discharge area is significantly smaller and coincides with the topographically lower parts within the object. However, not only the area of continuously discharging locations is smaller in the regolith, but also the one of the continuously recharging. Recharge areas in the regolith are found in the northwest and southern parts of the object. There are also areas that are subject to changing directions of vertical flow.

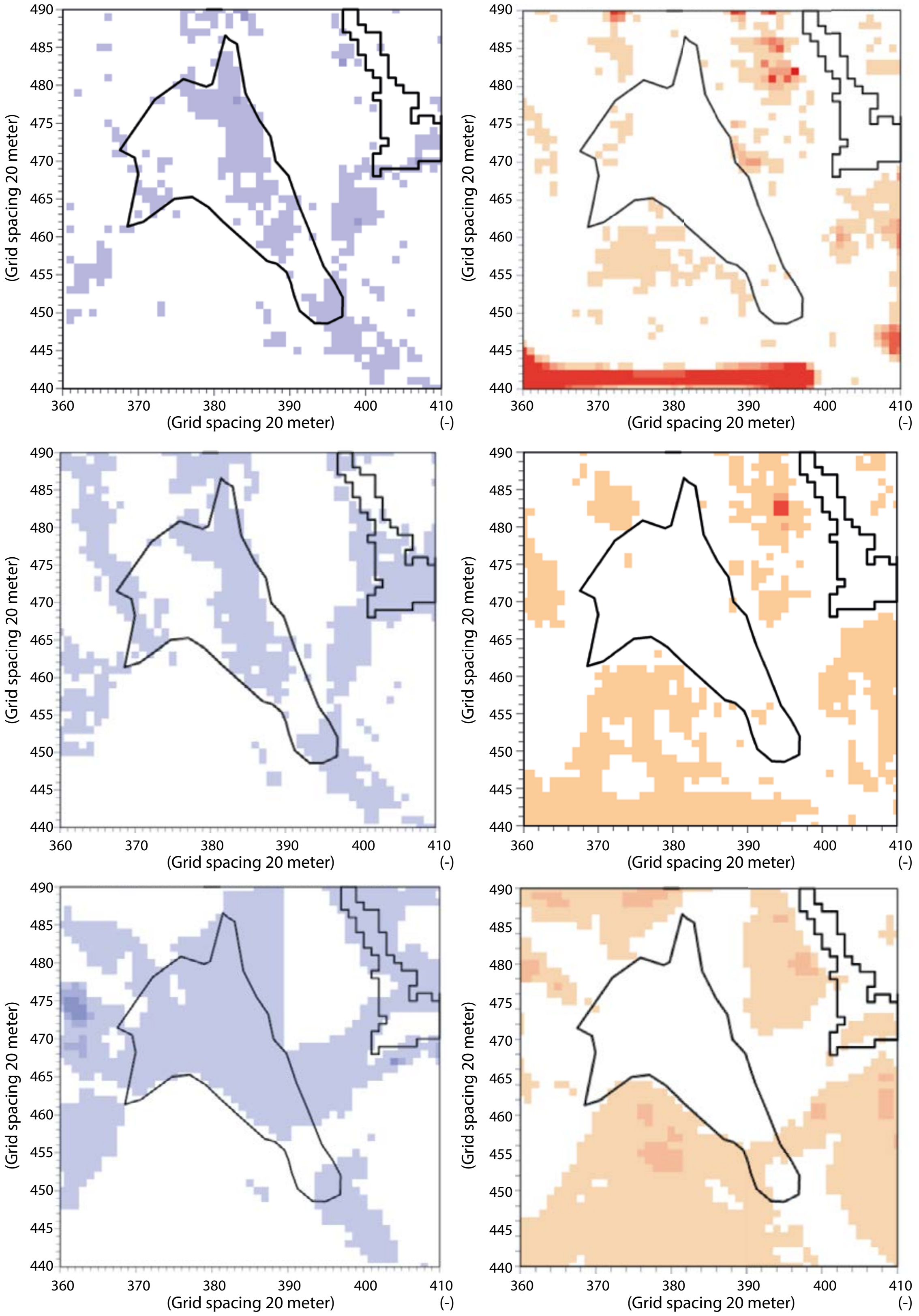

__Figure 7-15.__ Areas that are discharge areas (left side) or recharge areas (on the right side) throughout the entire year, i.e. the gradient between the two layers does not change direction over the year. Cells that are neither coloured in blue or red are subject to changing directions of vertical flow. The uppermost figures show the gradients in a regolith layer, the middle figures in a bedrock layer just below the regoith, and the lower figures in a bedrock layer at a depth of ca 60 m.

Figure 7-16 shows the annually averaged flow pointing upwards in two calculation layers L1 (uppermost) and L3. Layer 1 covers the uppermost 2.5 m of the profile, the third layer the depth from 4 m down to 6 m. In calculation layer 3 most of the object area is discharging (on annual average) and the spatial variation of flows is homogenous if compared with the distribution of flows in calculation layer 1. The area of arable land in the northern part of the object is on average discharging with a low annual net flow in its interior. According to Figure 7-15 the arable land is discharging only so that the low net flow is due to a constantly low discharge. However at the brim of the arable area the annual discharge is significantly higher.

7.4 Discussion and conclusions

A method for mapping sub-annually changing flows in a three dimensional hydrogeological model onto annual flow representing parameters of the compartmental radionuclide transport model was developed in project SR-Site and modified for the SR-PSU assessment. A number of calculation cases were run with the hydrological MIKE SHE model for two modelled areas to analyse in particular how changes in the vertical and horizontal discretisation affect the annually and spatially averaged vertical flows. These flows are of particular interest for the parametrisation of the radionuclide transport model.

7.4.1 Sensitivity of water flows to vertical discretisation

Based on the calculation cases with varying number of calculation layers, appointments of layers and varying layer properties for Lake Stocksjön it can be concluded that the vertical flow from the bedrock does not change significantly. The flow in upper layers may differ though, depending on case properties.

Changing the thickness of a geological layer had only limited impact. Though, changing its conductive properties from sand/gravel to less conducting clay had a significant impact on the flow field (with a barrier effect of the layer) and the resulting averaged flows. This barrier effect can be also observed in the alternative delineation of biosphere object 157_2 "arable land", see Figure 7-16.

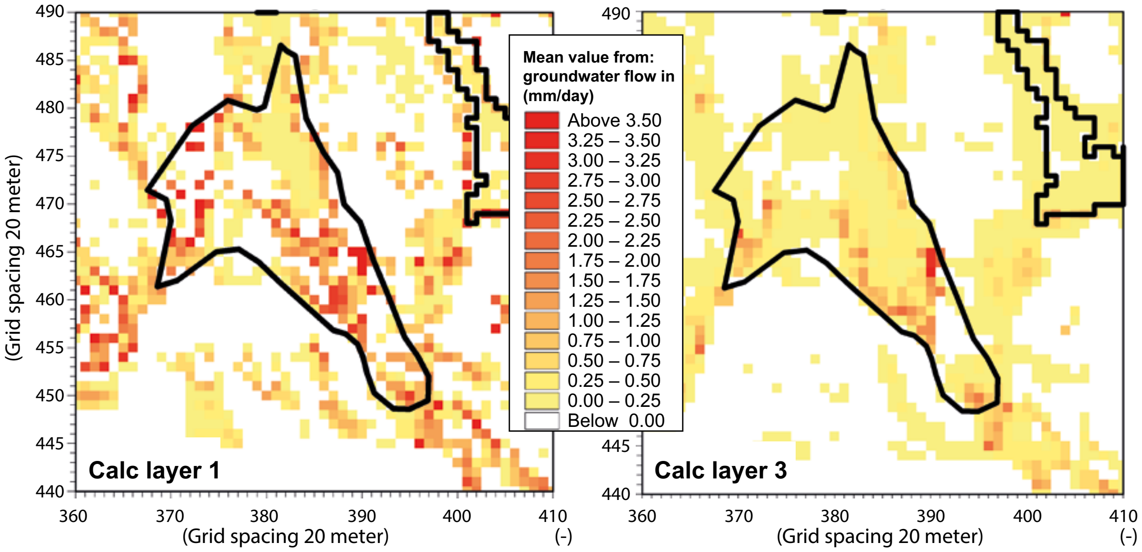

Figure 7-16. *Vertical annual average groundwater flow in calculation layers L1 (uppermost) and L3. Only positive values (i.e. discharge flows) are shown in the figure, and all recharge flow, independent on values are shown as white cells.*

Since, in the MIKE SHE model, evaporation and transpiration processes only take place at the surface and in the uppermost calculation layer, the layer has to be thick enough to allow for full evaporation and transpiration. Evapotranspiration can be only fully accounted for if the water can be supplied by this layer all over the year. Otherwise inflow of water into the system increases and flows tend to be overestimated. It appears that a thickness of only ca 0.8 m is sufficient for the uppermost layer in the case of Lake Stocksjön. However, it was previously found that the uppermost calculation layer has to be 2.5 m thick for more general conditions in Forsmark (Bosson et al. 2008), largely depending on the maximum depth of the groundwater table in the modelled area.

If, on the other hand, the calculation layers are thicker than the geological layers which are represented by compartments in the radionuclide transport model, flows need to derived at intermediate levels of the calculation layer. They have to interpolated from the values derived at the bounding surfaces of the layer. In the SR-PSU project, a method for mapping the values from the MIKE SHE model to the radionuclide transport model was developed (Werner et al. 2013).

7.4.2 Sensitivity of water flows to delineation of the modelled area

In order to study the effect of the delineation of a biosphere object on annually and spatially averaged flows from the bedrock and in the regolith, results from calculation cases derived from alternative delineations of biosphere object 157_2 of the SR-PSU assessment have been compared with each other.

The delineation “discharge area” (Figure 7-5a), defined by simultaneous average discharge conditions at three depths) results in 99% of the volumetric discharge from the bedrock as is the case for the entire object area. The delineation “shallow groundwater” (Figure 7-5b) and “high density of exit points” (Figure 7-5c), had a significantly smaller discharge from the bedrock, only about 40% of the base case. However, as seen in Figure 7-12, a lower flow into the regolith from the bedrock does not necessarily imply a lower discharge at the surface, as superficial water may enter the regolith from above from near-by areas.

An even smaller discharge from the bedrock is observed for the delineation “arable land” with only 10% of the base case discharge. However, since the arable land area is located at the downstream end of the object, water is reaching the area from other parts of the object, either on or close to the surface. Since the arable land is made up by a thick layer of sediment, the flow tends to diverge under this layer and reaches the surface at the outer rim of the arable land. This is consistent with observations from SR-Site (Bosson et al. 2010).

When studying the flow based on water balances, it should be remembered that all values are based on averages. The results are all based on areal and temporal averages with regard to, for example, layer thicknesses, hydraulic conductivities, and intra-annual flow variations. For example, for biosphere object 157_2 it was noted that in the bedrock, the object is a discharge object almost all over the area. However, in the shallow regolith, parts of the area alternate between recharge and discharge over the year. Therefore, the mapping of flows from the hydrological model onto the radionuclide transport model while averaging, also takes flow direction into account. Depending on what is relevant to the studied problem, it may not be sufficient just to look at annual mean flow values.

8 Comparison of the Radionuclide Transport Model for the Biosphere with empirical data for the natural carbon cycle

In SR-PSU, the radionuclide transport model for the biosphere is the tool to calculate the radionuclide concentrations in the environmental media in surface ecosystems, due to radionuclide inflow from the bedrock (Saetre et al. 2013b). These concentrations are further used to calculate doses to humans and dose rates to non-human biota. The performance of the radionuclide transport model for the biosphere can be studied by using naturally occurring elements, for which measurements are available. In SR-PSU, radiocarbon (C-14) is expected to be an important radionuclide in terms of potential dose to humans. At the same time empirical estimates describing pools and fluxes of stable carbon (C-12 making up 99% of natural pools) are available both from the region of Forsmark and from boreal conditions in general. Setting appropriate boundary conditions for incoming stable carbon, the accumulation and fluxes of carbon within a mire-lake complex can be modelled with the radionuclide transport model for the biosphere, and simulation results can be compared with empirical estimates. Through such a comparison the performance of the radionuclide transport model can be explored, and the model can be calibrated by tuning uncertain model parameters.

This approach was applied for two mire/lake biosphere objects:

1) The model was run for future conditions of a biosphere object that was identified as a potential recipient for radionuclide release in SR-PSU (Biosphere object 157_1, SKB 2014a).
2) The model was run for one existing biosphere object under present conditions in the Forsmark area for which field-estimated data were available (Lake Fiskarfjärden, Andersson 2010).

8.1 Modelling carbon cycling in the biosphere

Carbon enters a mire or lake by water flows, by litter fall into the mire (based on net primary production, NPP), or across the interface between the atmosphere and the water surface (Figure 8-1). In the safety assessment, it is cautiously assumed that the radiocarbon reaching surface ecosystems with deep groundwater will be in the form of dissolved inorganic carbon (DIC). In this form (CO_2 and HCO_3^-) carbon is available for uptake by primary producers. Dissolved organic radiocarbon (DOC) from the repository is expected to be in the form of low molecular weight carbon (LMWC), which will be mineralized when it reaches biologically active regolith layers. Under anaerobic conditions microbial mineralization may result in the formation of methane. However, it is assumed that this methane will be oxidized to carbon dioxide once it reaches aerobic environments (e.g. surface peat and lake water). However, for stable organic carbon that reaches lakes and wetland with discharge from the catchmernt area such assumptions are not realistic. Instead, only a small fraction of organic carbon that reach the ecosystems with runoff is in the form of LMWC, and most of the organic carbon is expected to be resistant to microbial degradation, i.e. recalcitrant DOC (e.g. Berggren et al. 2010). In this modelling excersise the recalcitrant DOC from the catchment is considered to be inert, and its fate is not handled explicitly in the model (i.e. it is assumed to pass through the ecosystem). On the other hand, easily decomposed organic carbon is assumed to be mineralised before it can leave the system, and is treated as inorganic carbon (DIC) in the simulations. The amount of incoming particulate organic carbon (POC) is usually small in comparison with DIC and DOC and constitutes less than 2% of the organic carbon in the stream flow in the Forsmark region (Tröjbom et al. 2007). It has therefore been disregarded in the simulations. Litter carbon (originating from NPP in the mire and in the lake) is divided into a fast carbon pool, which is assumed to mineralize into DIC, and a slow refractory pool, which accumulates in peat and lake sediments. This is illustrated by the production and accumulation of structural organic carbon in the mire and in the lake (POC in Figure 8-1). In the model, organic carbon in peat and sediments are continuously mineralised at a slow rate, which depends on the availability of oxygen. As with the fate of radiocarbon, the end product of stable carbon mineralisation is assumed to be CO_2, and escape of gasous methane (through ebbulation or plant aerencymes) are not included in the model.

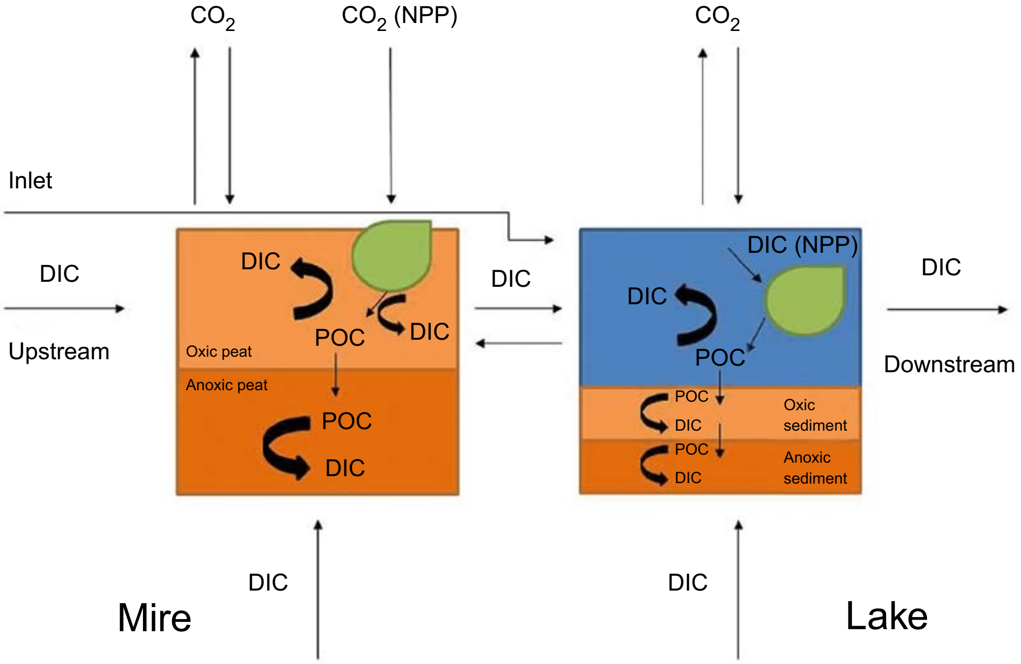

Figure 8-1. *Conceptual model of carbon cycling in the mire-lake complex. Dissolved Inorganic Carbon (DIC) and Particulate Organic Carbon (POC) are the modelled constituents. Brown colours represent peat and sediment, where lighter brown indicate oxic and the darker brown anoxic conditions. Blue colour shows the surface water of the lake and green denotes primary producers. The vertical transport of POC between the two compartments represents accumulation and burial of peat and organic sediments in the mire and lake ecosystems, respectively.*

8.2 Model endpoints for comparison

Based on the availability of measurements from the site, data in the literature and potential model outputs, a number of suitable model state variables were chosen for comparison in the lake and the mire of a mire-lake complex (Tables 8-1 and 8-2). These represent ecosystem performance as well as environmental conditions which affects calculations of doses to humans and dose rates to non-human biota.

The concentration of dissolved inorganic carbon (DIC) in the lake water is regarded as an important endpoint for the assessment of aquatic primary producers, fish and finally humans via ingestion of fish and drinking of water[3]. DIC in the surface peat pore water may be incorporated into the terrestrial food webs through root uptake, or through uptake from the plant canopy atmosphere after degassing. Thus DIC is of high relevance in the assessment of terrestrial primary producers and humans, via ingestion of food gathered on the mire or through the harvest of hay. Data on DIC concentration in lake water and near-surface peat is available from the Forsmark site.

In order to sense-check the total carbon balance for the lake and mire ecosystems, all fluxes of inorganic and organic carbon in to and out of the ecosystems were summed. This estimate is similar to the net ecosystem carbon balance (NECB) as suggested by Chapin et al. (2002). However, in this simulation study the balance also includes some fluxes that are not traditionally included in the NECB, such as import of DIC from the surrounding catchment, and diffuse inflow and transport of DIC from deeper groundwater (see Figure 8.1). A positive value suggests that the object is a net sink, whereas a negative value suggests that the ecosystem is a source of carbon. The NECB for the lake describes the net gain (or loss) for surface water, biomass and post-glacial sediments (gyttja/clay gyttja). Similarily, the NECB for the mire describes the net accumlation of carbon in peat (including pore water) and primary producer biomass.

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[3] DIC is here regarded as the dominant carbon form of carbon in water; however, DOC and POC are also relevant.

Lake sediments are a sink for long-term accumaltion of carbon, and the carbon concentration in the lake sediment is a source to both external and interal exposure for sediment living biota, and to exposure of humans if the lake is drained and cultivated Thus the carbon accumulation in postglacial deposits during the lake stage and the carbon concentration in surface sediments and post-glacial clay sediments, were chosen as three separate endpoint for the lake ecosystem. The amount of carbon transferred from the oxic surface sediments to the anoxic sediments (through burial) was used to approximate the yearly carbon accumulation.

Peat accumulation may be calculated in different ways. In literature the Long-term Apparent Rate of Carbon Accumulation (LORCA) is often used to describe average peat accumulation. It is usually estimated from combing peat depth with the age of peat at the base of the peat column. There are reliable estimates of the peat accumulation rate from the Forsmark area, and thus peat accumulation was chosen as an endpoint. It was only possible to investigate the long term peat accumulation for 157_1 for which time dependent parameters were available. However, peat accumulation is expected to vary over time (e.g. Turunen et al. 2002) and therefore a short term estimate was also investigated and this was possible to calculate for both mires. Peat is an important source for exposure for terrestrial biota and humans through severeal different pathways (see Chapter 3). However, in the model peat is treated as being entirely made up of organic matter and thus peat carbon concentration (gC gDW^{-1}) is a parameter rather than an endpoint for the simulations.

Table 8-1. Model states from the lake submodel that are compared with empirical estimates.

Expression	Description	Unit	Source of empirical estimate	Comment
Conc_DIC	Concentration of DIC in water	gC m^{-3}	Site	Short-term
NECB	Net Ecosystem Carbon Balance, where all fluxes in and out of the object is considered	gC m^{-2} $year^{-1}$	Site	Short-term
Sed Acc	Accumulation of carbon in the anoxic part of the sediment	gC m^{-2} $year^{-1}$	Site	Short-term
Carbon_regoUp	The concentration of carbon in the oxic upper part of the sediment	gC gDW^{-1}	Site	Short-term
Carbon_regoPG	The concentration of carbon in the anoxic part of the sediment	gC gDW^{-1}	Site	Short-term

Table 8-2. Model states from the mire submodel that are compared with empirical estimates.

Expression	Description	Unit	Source of empirical estimate	Comment
Conc_DIC_ox	Concentration of DIC in oxic porewater	gC m^{-3}	Site	Short-term
NECB	Net Ecosystem Carbon balance, where all fluxes in and out of the object are considered	gC m^{-2} $year^{-1}$	Generic	Short-term
PeatAcc	Peat accumulation	gC m^{-2} $year^{-1}$	Regional	Long-term/ short-term

8.3 Model and Simulation

8.3.1 Model system

In the safety assessment SR-PSU, the transport and accumulation of radionuclides in ecosystems are modelled using the the radionuclide transport model of the biosphere (Saetre et al. 2013b). This model (revision SVN:8517) was modified so that all incoming fluxes of C-12 to the biosphere object were based on parameter values estimated from the site or the region. The model simulations were made using the software ECOLEGO 5.0.356 (SKB 2014g) and the model was run with annual time steps.

8.3.2 The modelled lake/mire objects and the relevant time frame

The objects having lake-mire complexes that can be modelled with the purpose of comparing model states with empirical data are restricted by two conditions: 1) the availablity of data on relevant hydrological conditions from which parameters for the radionuclide transport model for the biosphere can be derived and 2) the amount and quality of appropriate empirical data. Thus the availability of a hydrological model describing the water fluxes within the biosphere object is a prerequisite for this study (Chapter 8). Accordingly, Lake Fiskarfjärden was chosen as the candidate representing a lake present today. The second candidate was the identified biosphere object 157_1 in SR-PSU (that has been identified as one out of two Biosphere objects that may give the potentially highest radionuclide concentrations in different environmental media, SKB 2014a). This object is today a part of the sea floor outside the SFR and will emerge as a lake approximately at 4500 AD. For this Biosphere object there is a complete parameter set available from SR-PSU (Grolander 2013). Tables 8-3 and 8-4 shows some important characteristics of the two modelled biosphere objects.

The starting point for the modelling was set to a time point shortly after the isolation of the lake from the sea i.e. there was a small or non-significant influence of sea water on the limnic ecosystem (Table 8-3). This time point also corresponded well to a situation where there was a similar amount of both mire and lake ecosystems in both objects (Table 8-4).

For the short-term modelling, all developmental parameters were held constant, e.g. the sizes of the lake and mire areas (Table 8-4). For object 157_1 a longer time period was also modelled using the lake/mire development characteristics (denoted long-term modelling).

Table 8-3. Lake characteristics. Date of isolation and transition are from Brydsten and Strömgren (2013). Water renewal time is calculated by using the lake volume and the discharge from the catchment area into the lake (Werner et al. 2013).

Biosphere object	Date of isolation from sea	Date of transition into mire	Short-term end point	Elevation a.s.l. (m)	Water renewal time (days)
157_1	4500 AD	5700 AD	4800 AD	1.5	55
Fiskarfjärden	1900 AD	6900 AD	2100 AD	0.5	155

Table 8-4. Mean lake depth and lake and mire areas of the two modeled biosphere objects at the start of the modeling (starting year within parentheses), which were constant in short-term modelling.

	Mean lake depth (m)	Lake area (m^2)	Mire area (m^2)
157_1 (4700 AD)	2	47,200	55,600
Fiskarfjärden (2000 AD)[1]	0.5	375,000	375,000

[1] Andersson 2010.

8.3.3 Parameterisation of the Radionuclide Transport Model of the Biosphere

Parameter values were taken from the SR-PSU assessment where appropriate (Grolander 2013), e.g. parameter values describing generic characteristics common to the area, such as mineralisation rates, NPP (per unit area and year) and atmospheric concentration of C-12 (Table C-1 in Appendix C). Parameters that describe characteristics specific to each biosphere object, such as geometries and water flows, were only available for biosphere object 157_1 (Grolander 2013). However, parameter values for biosphere object Fiskarfjärden had to be calculated with the same methodology, The parameter values describing water flows for Fiskarfjärden were based on a premodelling study for the SR-Site project (described in Chapter 8, Bosson et al. 2010). Parameters that describe the temporal development of the biosphere object, e.g. peat ingrowth and distribution of primary producers in the lake, were used only for object 157_1 in the long-term modelling and were held constant for the short-term modelling (of 100 years). All parameter values are listed in Appendix C (Table C-2 and C-3).

8.3.4 Parameterisation of boundary conditions

The boundary conditions describing the inflow of carbon into the objects were described in terms of the incoming inorganic carbon with water from the upstream drainage area (stream), with the diffuse discharge from the sub-catchment area, with the deep ground water discharge and with the transport across the atmosphere-water interface (lake and mire water). Compartmental concentrations of C-12 will mostly reach steady-state after a sufficient number of time steps, but to improve the numerical performance of the simulation initial conditions were calculated based on measurements at the site for many of the compartments (Table C-4).

The inflows of water to the biosphere objects were derived from the hydrological model (Werner et al. 2013) and measured concentrations of DIC were multiplied with these flows to calculate the inflow of DIC into the biosphere object. The DIC concentration of stream water was determined from meassurements in the Forsmark area (Table 8-5), and this concentration was also used for the diffuse discharge of groundwater into 157_1 and Lake Fiskarfjärden. The fraction of the easily decomposable part of the DOC was taken from Ågren et al. (2008), who calculated the relative contribution of low weight molecular carbon (LWMC) to the DOC during spring flood to be 0.38% and 1.1% in water from mires and forests, respectively. These values change during the season (with the highest values during early spring), but here they are assumed to be a reasonable approximation throughout the year. Mass balance modeling of three different catchments in the Forsmark area was used to estimate the area-specific diffusive discharge of DOC (Tröjbom et al. 2007). It was estimated to be 7.7 and 2.2 gC m^{-2} for wetland and forest, respectively. Lake Fiskarfjärden has no inlet stream, but it was assumed that a stream from the upstream object 157_2 drains into lake 157_1. Therefore all terrestrial carbon that was diffusivly discharged into Lake Fiskarfjärden was directed to the mire running around the border of the lake. The terrestrial carbon transported into 157_1 was, on the other hand, partitioned between the mire and the lake. That is, terrestrial carbon in stream water from the upstream catchment 157_2 entered the lake water directly, whereas carbon from the local catchment of 157_1 entered the mire surrounding the lake (Table 8-6).

DIC concentrations in deep groundwater were based on time series from a soil pipe (SFM0032) monitoring till below peat under Lake Bolundsfjärden, which is situated in the area. The DOC concentration in the water entering the lake from below is small and was assumed to be dominated by old and refractory carbon.

An atmospheric CO_2 concentration of 0.0002 kgC m^{-3} (385 ppm) was used to calculate the flux of carbon across the atmosphere/air interface.

The net primary production (NPP) is also a source of carbon to the mire ecosystems, and were based on site data representing a minerotrophic treeless mire in Forsmark (Grolander 2013). The NPP in lakes represents an internal carbon transformation (from inorganic to organic) and this rate was estimated from oligotrophic hardwater lakes in the area, accounting for lake depth (Grolander 2013).

Table 8-5. Initial carbon concentrations.

Pool/flux	Regional mean		157_1		Fiskarfjärden	
	DIC ($gC\ m^{-3}$)	DOC ($gC\ m^{-3}$)	DIC ($gC\ m^{-3}$)	DOC ($gC\ m^{-3}$)	DIC ($gC\ m^{-3}$)	DOC ($gC\ m^{-3}$)
Incoming drainage water (stream)	29[1)]	18	29[1)]	18	No inlet	
Groundwater	62	18	62	18	62	18
Subcatchment water drainage (diffuse)	No measurements		Same as stream discharge		Same as stream discharge	

[1)] Flow weighted average for two years from four stream locations (Tröjbom et al. 2007).

Table 8-6. Forest and wetland coverage of the catchment areas of Lake Fiskarfjärden and 157_1.

Object	Forest (m^2)	Wetland (m^2)
Fiskarfjärden	1,989,680	468,160
157_1 (4700 AD)	2,975,200	386,400
Of which corresponds to stream discharge	1,050,400	97,200

8.3.5 Tuning values of uncertain parameters

A piston model was used to calculate the exchange of carbon across the air/water interface of lakes and mires (Saetre et al. 2013b). The piston velocity was calculated using standard procedures for lakes and streams (Grolander 2013, Table A-1). The piston velocity used for these calculations assumed standing water, and was not deemed to be applicable to boreal peatlands, where large areas of surface peat are expected to be only partly saturated. Thus in the present simulations the piston velocity was coarsely adjusted, so that the calculated DIC concentrations in surface peat would agree with a typical value for the site in the future (14 gC m^{-3}) (Grolander 2013). Similarly, Wania et al. (2010) used this approach to model the exchange of gasous carbon of mires; and found a reasonable agreement with empirical measures of methane fluxes from seven different sites after calibration of the the methane/carbon dioxide ratio.

The estimated piston velocity for a mire was 50 m $year^{-1}$ (Table A-1), which is a third of the velocity expected given an area of open water which is sheltered from wind. The selected parameter value thus reflects a less effective exchange of gasous carbon, as compared to open water. This was deemed reasonable, given natural seasonal and spatial variation in boreal peatlands, with for example low ground water level in summer and at hummocks.

The mineralisation rate in the radionuclide transport model represents the rate of decomposition of refractory material, i.e. the long-term rate of mineralisation under oxic or anoxic conditions. This is a common conceptual representation of decomposition in models that describe long term carbon accumulation in peat (e.g. Clymo et al. 1998, Clymo and Bryant 2008), but it is not frequently used to describe carbon accumulation in aquatic environments. Instead, literature describing decomposition in the water column, or in surface sediments, tend to report rates derived from within-year measurements, where decomposition of labile carbon is expected to dominate the mineralisation rate. Thus in this study the mineralisation rate in aerobic aquatic environments was tuned to yield reasonable model predictions of carbon content in surface sediments. This tuning resulted in a rate of 0.03 $year^{-1}$, which was used for mineralisation in the in surface sediments. For lakes the organic carbon burial efficiency varies over a large range, from less than 1% to nearly 100% (Burdige 2007. Algesten et al. 2003, Sobek et al. 2009). The chosen value of 0.03 is much lower than the the mean burial efficiency reported by Sobek et al. (2009) for 27 lakes worldwide of 48%. However, much of the organic matter in the sediments in the Forsmark lakes are made up by autohctonous material and mineralisation rate of autocthonous biota is very high (e.g. Wetzel 2001, Belova 1993, Chimney and Pietro 2006). Moreover, it is an order of magnitude higher than the corresponding mineralisation rates in surface peat (Grolander 2013). Given that less structural carbon (which tend to decompose slowly) is needed to support macrophytes in aquatic environments, the rate used appears to be reasonable.

8.4 Simulation results

8.4.1 Concentration of dissolved inorganic carbon

The simulated DIC concentration in the lake water of object 157_1 matches the mean value from the Forsmark area, and the model result for Lake Fiskarfjärden agrees well with the measurements in this lake (Table 8-7). The calculated DIC concentration in lake 157_1 is approximately twice of that in lake Fiskarfjärden, reflecting the effect of differences in the balance between carbon load and the rate of degassing in the two lakes. That is, lake 157_1 has a similar catchement size (and carbon load) as lake Fiskarfjärden, but the surface area where degassing can occurs is much smaller.

The simulated level of the DIC concentrations in surface peat was primarily the result of coarsely tuning the parameter value of the piston velocity of wetlands (see Section 8.3.5), and resulted in concentratons of 14 and 13 gC m^{-3} in the mires. These values are in the lower end of the range reported from three mires in the Forsmark area (Table 8-8), but agrees well with the typical value for surface peat of boreal mires representing a later successional stage in the area (14 gC m^{-3}, Grolander 2013). The typical value was chosen to represent the DIC concentration in porewater of the root zone (0–30 cm) in mires of the most relevant successional stages (i.e. Bryales fen approximately 1,500 years of age). The empirical estimates are from the upper part of the anoxic zone (0.35 to 0.45 m, Table 8-8) and would be expected to be somewhat lower in the root zone as the DIC concentration tend to increase with depth (e.g. Clymo and Bryant 2008).

Table 8-7. Model results describing the lake system of biosphere object 157_1 and Lake Fiskarfjärden. Emperical estimates are from the boreal region if not stated otherwise. RegoUp refers to the compartment representing the upper layer of regolith and regoPG to the post-glacial clay regolith. Values in the two last columns describe means whereas values within paranthesis describe the range.

End points	157_1	Fiskarfjärden	Empirical estimate for Fiskarfjärden[1]	Empirical estimate
Conc_DIC (gC m^{-3})	22	13	14 (1–19)	21 (0–58)[1]
NECB (gC m^{-2} year^{-1})	1.6	0.5	–	9 (0.3–65)[1,2]
Sediment accumulation (gC m^{-2} year^{-1})[4]	1.9	1.6	–	5.6 (0.1–57.8)[3]
Carbon_regoUp (gC gDW^{-1})	0.23	0.26	0.17	(0.10–0.27)[1]

[1] Forsmark area, Andersson 2010. [2] Note that storage in sediments was treated as an output term in the original budgets. [3] Long-term sediment accumulation, estimate from European lakes including Swedish lakes (Kastowski et al. 2011) [4] Transport of organic material to post glacial deposits.

Table 8-8. Model results describing the mire system of biosphere object 157_1 and Fiskarfjärden. Emperical estimates are from the boreal region if not stated otherwise. Fiskarfjärden was only used to compare short-term results. Values in the last column describe means whereas values within paranthesis describe the range.

End pionts	157_1	Fiskarfjärden	Empirical estimate
Conc_DIC_ox (gC m^{-3})	13	14	(14–46)[1]
NECB (gC m^{-2} year^{-1})	37	31	38 (22–70)[2]
Carbon accumulation Long-term	17	–[3]	(7–17)[4]
(gC m^{-2} year^{-1}) Short-term	37	31	(18–58)[5]

[1] Forsmark area, Löfgren 2011. [2] Yu 2012. [3] No long-term result available. [4] Swedish, Finnish and Russian fens, Turunen et al. 2002. [5] Young fens in northern Uppland, Schoning 2014.

8.4.2 Net ecosystem carbon balance

The simulated values for the net ecosystem carbon balance (NECB) for both lakes were small and positive, suggesting that only a small fraction of the carbon that enters the lake are stored. In the simulation the carbon content in water and biota pool remained approximately constant between years, and thus the incoming carbon fluxes from atmosphere, ground and stream water are balanced by losses through degassing and ground and stream water fluxes from the lake. The small amounts of carbon that is captured by the lake is primarily stored in aquatic sediments (see next section). The modelled NECB values (1.9 and 1.6 gC m^{-2} year^{-1}) are in the lower range of empirical estimates from four lakes in the area (Table 8-7). Generally, NECB is sensitive to yearly variation in climate variables and empiricaly derived NECB's are therefore expected to include a fairly large variation. Moreover, the difference between large values describing the yearly fluxes suggest that empirical values of the NECB are sensitive to uncertainties and error propagation in the calculations. Due to the lack of influence of yearly climate variation the modelled NECB is expected to be a long-term estimate of the overall carbon balance, which would be reasonably close to the accumulation of carbon in the sediments for the Forsmark area (see discussion in 8.4.3). With this in mind, the simulated NECB agrees well with the empirical estimates and the positive sign of the balance is correct.

The NECB was also calculated for the two mires (Figure 8-1). As with the lakes, both mires had a positive NECB. Approximately 30 to 40 gC m^{-2} year^{-1} accumulated in the mire ecosystems, and this carbon was primarily stored in the peat layer (compare short-term accumulation in peat, Table 8-8). The modelled NECB was compared with empirical estimates from five northern peatlands (Yu 2012). The modelled NECB for the two mires fell within the range of reported values for northern peatlands ranging from minerogenic fens to bogs (Table 8-8), and thus the simulated carbon balance appears to be reasonable. However, we note that these balances reflects relatively young fen systems. As carbon accumulation proceeds and the peat store increase, the rate of accumulation will fall as more organic matter is available for mineralization. This aspect of long-term carbon accumulation is discussed in Section 8.4.4.

8.4.3 Carbon content and accumulation in aquatic sediments

The simulated carbon concentrations of lake surface sediments were primarily the result of coarsely tuning the parameter value of the mineralisation rate in aerobic aquatic environments (see Section 8.3.5), and resulted in a carbon content of 0.23 and 0.26 gC gDW^{-1} in surface sediments (RegoUp in Table 8-7). This value is somewhat higher than the value reported from the upper gyttja sediment in Lake Fiskarfjärden (0.17 gC gDW^{-1}) but still falls within range reported from three lakes in the Forsmark region (Table 3-10 in Andersson 2010).

Post glacial sediments start to accumulate in the sea stage directly after the latest deglaciation and are affected by both sedimentation and erosion during the marine stage. Once the lake has been isolated no erosion of aquatic sediments occur. In the simultaions the sedimentation rate was defined as the transfer of carbon from biologically active surface sediments down to the anoxic postglacial sediments underneath, which has a slower rate of mineralization.

The modelled whole lake sedimentation rates, 1.6 gC m^{-2} year^{-1} for Lake Fiskarfjärden and 1.9 gC m^{-2} year^{-1} for Lake 157_1, were one order of magnitude lower than empirically estimated long-term carbon accumulation based on sediment cores from Lake Eckarfjärden (Andersson 2010), which is also located in the area. The relatively large difference in estimates of carbon accumulation in local lakes can proabably be assigned to the fact that Anderson (2010) based her calculation on only one core representing the deepest part of the lake, which is expected to overestimate present whole-lake sedimentation rates.

In perspective, one can note that the variation in the reported rate of carbon sediment accumulation in boreal lakes is very large, and the rate may vary by more than three orders of magnitude between studies (e.g. Sobek et al. 2009, Algesten et al. 2011). The accumulation rate is dependent on, for example, the amount of carbon entering the lake from the catchment, mineralisation rates in the water, temperature, and oxygen conditions in the sediment. Therefore the sedimentation rate for a single lake is expected to vary over time (e.g. Rose et al. 2011). Algesten et al. (2003) calculated permanent carbon burial in boreal Swedish lakes to vary between 0.13 and 0.48 gC m^{-2} year^{-1} which is lower than reported from our simulations. However, there are also examples of Swedish lakes with considerable higher carbon burial rates (e.g. Sobek et al. 2009, 14–57 gC m^{-2} year^{-1} in three Swedish lakes). A European study of 228 lakes showed that carbon burial varies between 0.1 and 57.8 gC m^{-2} year^{-1} but noted that the majority of lakes (75%) have burial rates of less than 6.5 gC m^{-2} year^{-1} (Kastowski et al. 2011).

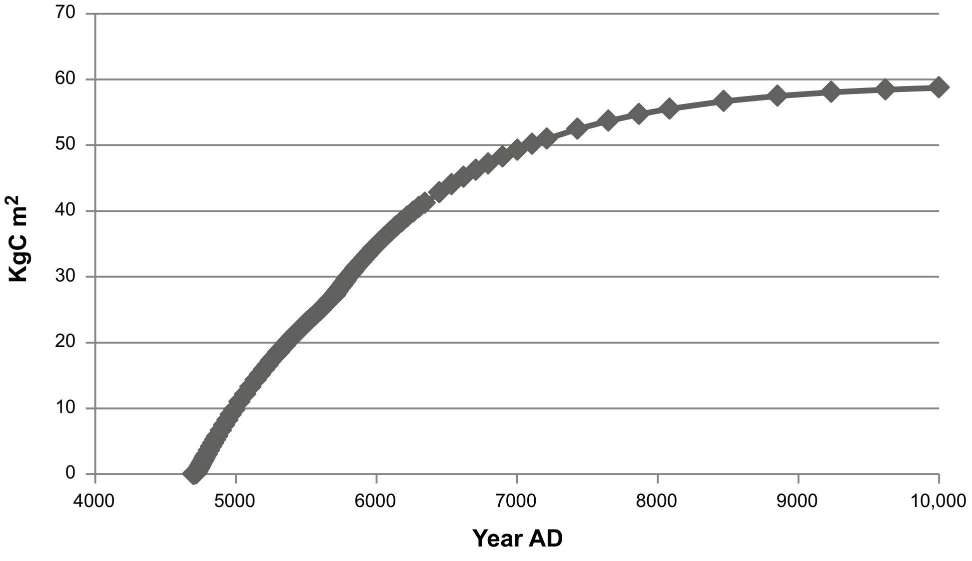

Figure 8-2. Cumulative peat accumulation in the mire of biosphere object 157_1 over time. The lake is formed at 4500 AD and is replaced by a mire in 5600 AD. The peat accumulation during the initial steep phase at 4800 AD approximates an accumulation of 37 gC m^{-2} year^{-1} (Table 8-8), while the overall accumulation between initiation and 8000 AD is 17 gC m^{-2} year^{-1}.

High carbon burial rates are typically associated with high inflow of allochthonous material (produced outside the lake) or eutrophic conditions, neither of which is expected in the Forsmark lakes. Allochthonous organic matter is more resitant to microbial degradation than autochthonous (in-lake produced) organic matter, and thus the relative contribution of allochthonous material to sediment carbon accumulation is large. Considering that primary production in the larger Forsmark lakes is high compared with inflow of allochtonous carbon (~65% to 90%, Andersson 2010) a relatively low empirical estimate of long-term whole-lake carbon accumulation in postglacial gyttja in lake Fiskarfjärden appears to be plausible. A low carbon burial rate primarily reflecting autochthonous production is also appropriate for a comparison with the output from the radionuclide transport model, which accounts for sedimentation from within lake primary production, but does not include the contribution of autochthonous refractory carbon.

8.4.4 Peat accumulation

Peat accumulation in boreal areas has been described and reviewed in several studies e.g. Turunen et al. (2002). Generally, differences in accumulation rate are related to the successional stage of the mire and variation in climate. Turunen et al. (2002) showed that the long-term apparent rate of carbon accumulation (LORCA) was larger in bogs than in fens in southern Finland (29 and 19 gC m^{-2} $year^{-1}$, respectively), but the difference was non-significant in the northern part of the country (17 gC m^{-2} $year^{-1}$). In another study of Swedish, Finnish and Russian fens LORCA ranged between 7 and 17 gC m^{-2} $year^{-1}$ (Turunen 2003). LORCA in young small fens in northern Uppland (i.e. less than 2,000 years old) has been estimated to be higher, ranging between 18 and 58 gC m^{-2} $year^{-1}$ with a mean carbon accumulation rate of 33 gC m^{-2} $year^{-1}$ for fen peat (Schoning 2014).

The mire in the radionuclide transport model represents the fen stage, as the hydrological exchange between the groundwater and vegetation (*Sphagnum*) is limited in a bog and *Sphagnum* peat has a low suitability for cultivation (cf. Chapter 6 in this report). Though the radionuclide transport modell has a coarse representation of peat accumulation (Chapter 6 in Saetre et al. 2013), the modelled long-term peat accumulation in the fen that develops in lake basin 157_1 (17 gC m^{-2} $year^{-1}$, ~3,300 years) shows a reasonable agreement with regional estimates of long term carbon accumulation over a similar time span (6–17 gC m^{-2} $year^{-1}$, ~5,000 years) (Table 8-8, Figure 8-2). The agreement between modelled accumulation and observed rate over a shorter time span is also good (Table 8-8), and the simulated rate of fen peat accumulation during the first steep phase is close to the empirical estimate of 33 gC m^{-2} $year^{-1}$ for young fens in the Forsmark region (Schoning 2014).

8.5 Implications for an assessment

The selected model end points were intended to give an indication of overall model performance (e.g. NECB, and sediment and peat accumulation rate), and to make sure that predicted concentrations of carbon was reasonable in environmental media with potential to directly expose future humans and non-human biota (e.g. DIC and sediment concentrations).

The agreement between modelled and field-estimated NECB suggest that the overall carbon fluxes are well-balanced over the investigated simulation times (and that models were approaching steady state conditions). All modelled NECB's were positive, which means that carbon is accumulating in the system. This is in agreement with mire ecosystems in general, and with present lake ecosystems in Forsmark. The modelled carbon accumulation in peat was in good agreement with empirical estimates from the Forsmark area. The modeled net transfer of carbon from aquatic surface sediments to the anaerobic sediment layer below was also within the range reported from the Forsmark area, but the valus was in the lower range. In the safety assessment humans are exposed to deep aquatic sediments when the lake-mire complex is drained and cultivated (Chapter 6). Given the multiple sources of radiocarbon in the drained/cultivated soil (e.g. organic carbon in peat, DIC in porewater and a continuous uptake from deep groundwater, Saetre et al. 2013) modest variation in the concentration of radiocarbon in aquatic sediments is not likely to have any significant effect on calculated dose.

Future humans (and non-human biota) may be directly exposed to radiocarbon in lake water, in aquatic surface sediments and in surface peat, and indirectly through consumption of plants and animlas that inhabit these environments (see Section 8.2). Stable carbon concentrations in all of these environmental medias agreed well with empirical estimates from the Forsmark area. In the case of DIC concentrations in surface peat and organic carbon concentrations in aquatic surface sediments the good agreement was primarily due to tuning of two model parameters. In the radionuclide transport model the uptake of radiocarbon follows that cycling of stable carbon. A specific activity approach is used for carbon fixation into plant biomass, which is the entry point for radiocarbon into the terrestrial and aquatic food webs. However, the cycling of stable carbon is not explicitly modelled in the safety assessment (peat accumulation being an exception). Instead DIC concentrations are entered as parameter values. Thus to avoid bias in the simulated specific activity, it is important that the parameter values used to represent stable DIC concentration in the safety assessment agrees with model predictions.

As the radionuclide transport model used in the safety assessment was designed to capture the fate of radionuclides discharged by deep groundwater processes with limited or insignificant effect on the fate of radiocarbon was not included. Thus sedimentation of allochtonous carbon and root respiration was not included in the model, as allochtonous carbon and plant carbon were expected to be relatively depleted in radiocarbon as compared to sources included in the model (i.e. allochtonous organic matter, and discharge of deep groundwater into the root zone). In an assessment perspective, the exclusion of these stable carbon sources means that tuning the model to agree with empirical data (i.e. organic carbon concentration in surface sediments and DIC concentrations in peat) is a cautious model simplification, as it will tend to overestimate the accumulation of radiocarbon in surface sediments and the specific activity of DIC in surface peat pore water.

In conclusion, this study suggests that the radionuclide transport model for the biosphere is able to simulate relevant aspects of stable carbon cycling in boreal lake-mire systems with a reasonably acccuracy. Comparison of model predictions and empirical estimates, sometimes after model calibration, ensured that simulations of the uptake and accumulation of radiocarbon will be consistent with the cycling of stable carbon. Moreover, exclusion of some carbon cycling processes with limited significance for the fate of radiocarbon, was expected to be cautious model simplifications in an assessment perspective. Thus, this model exercise builds confidence that the model is fit for purpose. That is, that it can provide robust estimtes of environmental C-14 activity concentrations, which can be used to calculate projected doses to evaluate the long-term safety of the extended SFR repository.

9 Summary

This report describes the handling of biosphere Features, Events and Processes (FEPs) in the assessment and an updated exposure pathway analysis. Moreover the report describes studies of specific topics related to the radionuclidetransport modelling of the biosphere underpinning assumptions in the modelling. The aim with respect to investigation of the assumptions in the radionuclide model for the biosphere has been to improve the assessment procedure and to understand the degree of caution that arises from applying the assumptions. The topics investigated have been identified during the work with previous safety assessments, work as well as from the work undertaken for the present safety assessment. The identified issues have been explored either by developing the conceptual understanding using information in the literature or by alternative modelling.

The systematic description of how the biosphere FEPs are handled in SR-PSU gives an overview on where they are handled in the different modelling steps of the safety assessment. In the biosphere interaction matrix (presented in SKB 2013), 10 physical components, 6 variables and 50 processes are identified as potentially being of importance for a safety assessment for a geological repository at Forsmark. In this report, a short description of the components, variables and processes is given, together with a description of how they have been included in the overall modelling approach in the calculation of doses to humans and non-human biota.

An exposure pathway analysis is a prerequisite for a safety assessment. The aim of the one presented in this report is to identify a set of potential exposure pathways, relevant for the long-term safety of a geological disposal facility at Forsmark. This is done by systematically identifying and excluding pathways that are not significant for long-term safety based on the characteristics and habits of future inhabitants, as well as the characteristics of the area potentially receiving radionuclides from the repository. The potential exposure pathways are then related to a set of possible most exposed groups which are identified based on potential land use variants and the habits of different societies. A set of relevant exposure pathways for both humans and non-human biota for the SR-PSU safety assessment is reported.

Irrigation is a potential source for exposure for humans, where food items are irrigated with water containing radionuclides originating from the repository. In general, in Sweden today, the irrigated area is small and is mostly found in the south of the country where irrigation is used for growing potatoes. It is concluded from the analysis that irrigation from a sprinkler system will not occur in combination with drained peatland, which is the potential biosphere object of relevance in the safety assessment. If a drained peatland needed to be sustained with additional water, it would be more convenient to use an embanking system based on upstream water supply. However, irrigation can be used under other circumstances and examples are given of calculations of potential amounts of water that could be needed to sustain and maximize plant growth in e.g. a garden plot irrigated with water.

The combustion of peat and/or wood containing radionuclides originating from the repository may be an additional source of human exposure. Combustion can occur in different contexts and here two different cases are investigated in detail; a power plant and a household. Maximum effective dose rates per unit release rate (Sv year^{-1} per Bq year^{-1}) obtained in each of the SR-PSU biosphere objects were calculated. The maximum dose rates for the peat-fuelled power plant summed over all three biosphere objects considered were at most 25% of the dose rates from household use. Therefore, it is recommended that peat and wood combustion by a household is included in the evaluation of human exposure in the safety assessment.

Wetlands are a sink for carbon and other elements because of the continuous accumulation of peat. The transformation of wetlands to agricultural land is considered to be one major source of exposure of humans. A close examination of the transformation of wetland to agricultural land by draining is presented, where topics such as spatial patterns of mires in the landscape, their suitability for agricultural use, successional pathways and the process of drainage are discussed and characterised. This is done in order to underpin assumptions in the radionuclide transport modelling performed for the assessment.

Hydrological modelling is an important feature in the radionuclide modelling because advective water fluxes are the main driver for radionuclide transport in the ecosystems considered. Concern has been raised as to how sensitive water fluxes would be to vertical and horizontal discretization. This issue is explored by alternative modelling using the modelling tool MIKE SHE, where a number of different cases are contrasted and discussed. A sensitivity case with manipulated regolith layers showed that a thicker regolith layer did not change the flow significantly. However, when changing the properties from a sandy soil to clay, the hydrological flow was reduced. Biosphere object 157_2 was delineated in different subareas to investigate the sensitivity of water fluxes to uncertainties in delineated area. Various differences were found in the upward transport, which were related to different properties of the delineations, e.g. the water flow in the area delineated based on the glacial clay distribution tended to diverge under the sediments and reach the surface at the edges of the sediment area.

In order to study the performance of the radionuclide transport model of the biosphere, and to be able to calibrate that model, it was parameterised with data appropriate for the simulation of transport of stable carbon (C-12). The model results were then compared with empirical estimates. This procedure was done for two different biosphere objects; one existing lake/mire object (Lake Fiskarfjärden) and one future lake/mire object of importance for the SR-PSU assessment (biosphere object 157_1). In general, the agreement between model results and empirical estimates derived from the existing object and data for analogue sites was good, i.e. the modeled values were close to the empirical values from lakes and mires existing today and can thus be seen as reasonable. One parameter that describes the exchange of carbon over the water/atmosphere interface in the mire (the piston velocity) could be adjusted to better fit the measured concentrations of dissolved carbon in the surficial peat layer.

Overall, this iterative work of exploring assumptions and their implications in the radionuclide modelling has, in some cases, resulted in changes in the radionuclide modelling. Nevertheless, even where changes have not been made, this study has increased understanding both in respect of evaluating the degree of caution in the assumptions underpinning the assessment and by clarifying and documenting the assessment procedure.

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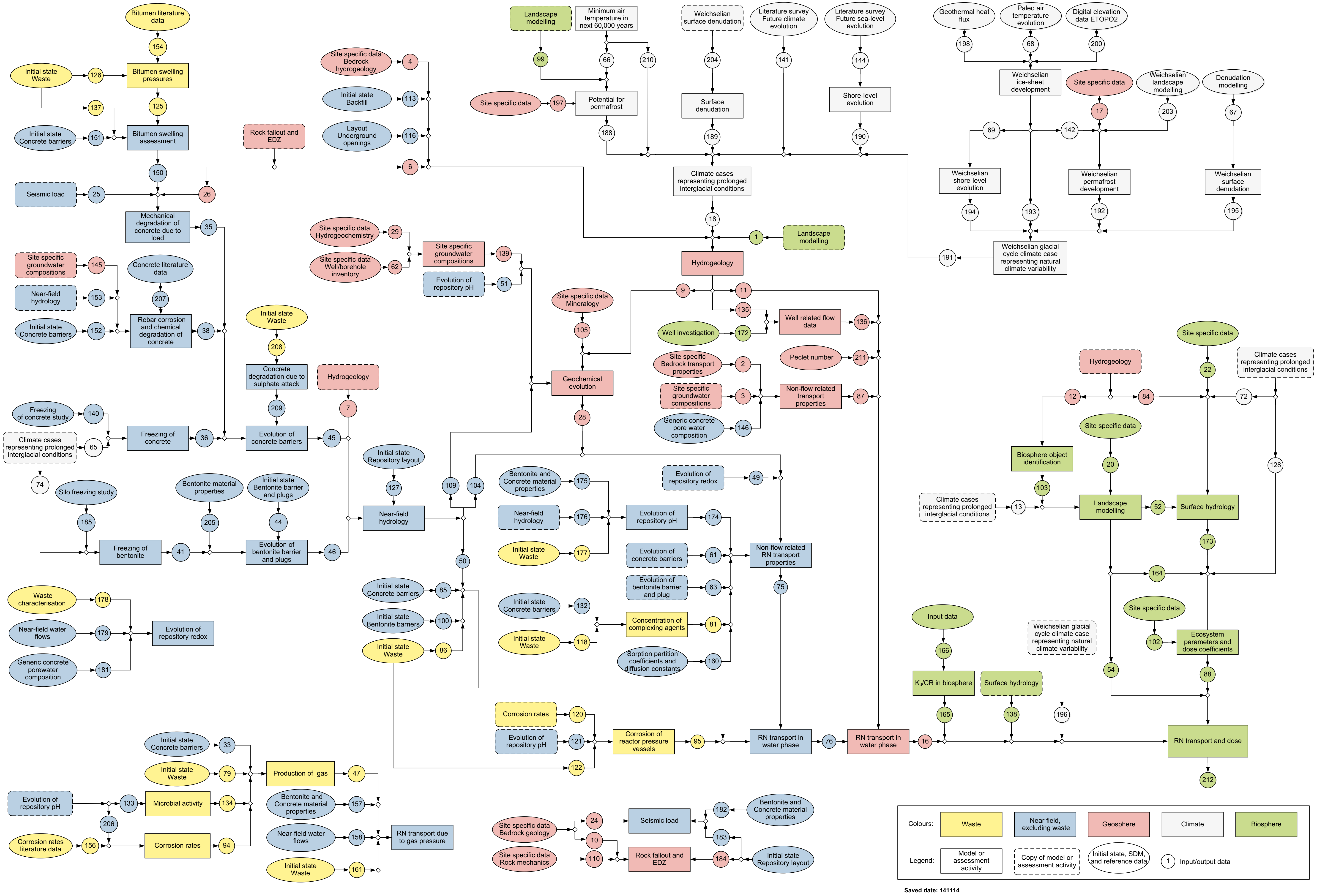
Biosphere interaction matrix showing processes interactions needed to considered in a safety assessment for a geological repository at Forsmark

	1	2	3	4	5	6	7	8	9	10	11	12
1	**GEOSPHERE (B.C.)**		a) Convection	a) Convection	a) Convection						b) Water supply	
2		**Regolith** *Geometry *Material composition *RN inventory *Stage of succession *Temperature *Water composition	a) Convection c) Reactions d) Sorption/Desorption e) Thresholding	d) Resuspension e) Sorption/desorption f) Thresholding	c) Decay e) Resuspension	a) Element supply b) Exposure c) Habitat supply f) Stimulation/inhibition	a) Element supply b) Exposure c) Food supply d) Habitat supply e) Stimulation/inhibition	a) Exposure b) Habitat supply c) Stimulation/inhibition	a) Exposure b) Habitat supply c) Stimulation/inhibition	a) Exposure b) Habitat supply c) Stimulation/inhibition	a) Exposure b) Food Supply c) Habitat supply d) Material supply e) Stimulation/inhibition	b) Thresholding
3	b) Convection	a) Phase transitions c) Saturation d) Sorption/desorption	**Water in regolith** *Geometry *Material composition *RN inventory *Stage of succession *Temperature *Water composition	a) Convection	a) Decay b) Phase transitions	a) Element supply b) Exposure d) Stimulation/inhibition e) Water supply	a) Element supply b) Exposure d) Stimulation/inhibition	a) Exposure b) Stimulation/inhibition	a) Exposure b) Stimulation/inhibition	a) Exposure b) Stimulation/inhibition	a) Exposure b) Stimulation/inhibition c) Water supply	a) Export
4	b) Convection	a) Deposition b) Relocation c) Resuspension d) Saturation e) Sorption/desorption	a) Convection	**Surface water** *Geometry *Material composition *RN inventory *Stage of succession *Temperature *Water composition	a) Covering b) Phase transition	a) Element supply b) Exposure c) Habitat supply d) light-related processes f) Stimulation/inhibition g) Water supply	a) Element supply b) Exposure d) Habitat supply f) Stimulation/inhibition	b) Exposure c) Food supply d) Habitat supply f) Stimulation/inhibition	a) Element supply b) Exposure c) Habitat supply e) Stimulation/inhibition	a) Element supply b) Exposure c) Habitat supply e) Stimulation/inhibition	a) Exposure b) Habitat supply c) Stimulation/inhibition d) Water supply	a) Export
5			a) Convection	a) Convection b) Deposition c) Phase transitions d) Wind stress	**Local atmosphere** *Geometry *Material composition *RN inventory *Stage of succession *Temperature *Water composition	a) Element supply b) Exposure d) Stimulation/inhibition	b) Exposure c) Stimulation/inhibition	b) Exposure	b) Exposure c) Stimulation/inhibition	b) Exposure c) Stimulation/inhibition	c) Exposure d) Stimulation/inhibition	a) Export
6		a) Bioturbation c) Death	b) Excretion e) Sorption/desorption f) Uptake	d) Death e) Excretion f) Interception j) Sorption/desorption k) Uptake	a) Acceleration c) Excretion g) Sorption/desorption h) Uptake	**Primary producers** *Geometry *Material composition *RN inventory *Stage of succession *Temperature *Water composition		a) Food supply	a) Food supply		a) Food supply b) Material supply	a) Export
7		a) Bioturbation b) Consumption d) Death e) Decomposition f) Excretion	c) Excretion f) Sorption/desorption g) Uptake	b) Consumption c) Death d) Decomposition e) Excretion j) Sorption/desorption k) Uptake	a) Excretion e) Sorption/desorption f) Uptake		**Decomposers** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a) Food supply		a) Food supply	a) Food supply	
8		c) Death f) Sorption/desorption	b) Excretion e) Sorption/desorption	b) Consumption c) Death d) Excretion g) Particle release/trapping h) Sorption/desorption i) Uptake		a) Consumption	a) Consumption	**Filter feeders** *Geometry *Material composition *RN inventory *Stage of succession *Temperature *Water composition		b) Food supply	a) Food supply	
9		c) Death d) Excretion g) Sorption/desorption h) Uptake	b) Excretion e) Sorption/desorption f) Uptake	b) Death c) Excretion h) Sorption/desorption i) Uptake	a) Excretion e) Sorption/desorption f) Uptake	a) Consumption			**Herbivores** *Geometry *Material composition *RN inventory *Stage of succession *Temperature *Water composition	a) Food supply	a) Food supply	
10		d) Excretion g) Sorption/desorption h) Uptake	b) Excretion e) Sorption/desorption f) Uptake	b) Excretion g) Sorption/desorption h) Uptake	a) Excretion e) Sorption/desorption f) Uptake		a) Consumption	a) Consumption	a) Consumption	**Carnivores** *Geometry *Material composition *RN inventory *Stage of succession *Temperature *Water composition	b) Food supply	
11	a) Intrusion	a) Anthropogenic release b) Consolidation g) Material use h) Relocation	a) Anthropogenic release d) Uptake e) Water use	a) Acceleration b) Anthropogenic release i) Uptake j) Water use	b) Anthropogenic release c) Convection h) Uptake	a) Consumption d) Stimulation/inhibition	c) Species introduction/extermination		a) Consumption c) Species introduction/extermination d) Stimulation/inhibition	d) Species introduction/extermination	**Humans** *Geometry *Material composition *RN inventory	
12	a) Change in rock surface location	a) Change in rock surface location b) Import c) light-related processes	a) Import b) Light-related processes c) Saturation	a) Convections b) Import c) Light-related processes d) Sea-level change	a) Import b) Light-related processes	a) Import b) Light-related processes c) Stimulation/inhibition	a) Import b) Stimulation/inhibition	a) Import b) Stimulation/inhibition	a) Import b) Stimulation/inhibition	a) Import b) Stimulation/inhibition	b) Stimulation/inhibition	**External conditions**

Assessment Model Flowchart, AMF



Appendix C

Parameter values

In the modelling the same parameter values were used as in the SR-PSU modelling of radionuclide transport in the biosphere. However, the parameter values for Lake Fiskarfjärden had to be calculated and this was done using the same approach as for the SR-PSU biosphere objects. The parameters are all described and presented in Grolander (2013). In the long-term modelling of 157_1 the time dependent parameters presented in C-1 were all changing over time. These are not presented here, but described in Grolander (2013).

Table C-1. Generic parameters independent of lake/mire object, which do not change over time.

Parameter	Value	Unit
biom_pp_ter	2.3	kgC m^{-2}
conc_C_atmos	0.0002	kgC m^{-3}
conc_C_regoLow_D	0.062	kgC m^{-3}
conc_C_upstream	0.029	kgC m^{-3}
conc_Corg_upstream	0.0019	kgC m^{-3}
conc_PM_lake	0.0011	kgDW m^{-3}
D_water	0.0378	m^2 $year^{-1}$
dens_regoGL	673	kgDW m^{-3}
dens_regoLow	2,115	kgDW m^{-3}
dens_regoPeat	100	kgDW m^{-3}
dens_regoPG	182	kgDW m^{-3}
dens_regoUp_lake	61	kgDW m^{-3}
dens_regoUp_ter	100	kgDW m^{-3}
f_C_peat	0.46	kgC $kgDW^{-1}$
f_H2CO3_lake	0.013	Bq Bq^{-1}
f_H2CO3_ter	0.46	Bq Bq^{-1}
f_refrac_macro_lake	0.3	kgC kgC^{-1}
f_refrac_micro_lake	0.01	kgC kgC^{-1}
f_refrac_plank_lake	0.01	kgC kgC^{-1}
f_refrac_ter	0.3	kgC kgC^{-1}
f_rootUptake	0.02	kgC kgC^{-1}
minRate_regoPeat	0.00088	$year^{-1}$
minRate_regoPG_lake	0.000065	kgC kgC^{-1} $year^{-1}$
minRate_regoPG_ter	0.000065	kgC kgC^{-1} $year^{-1}$
minRate_regoUp_lake	0.03	kgC kgC^{-1} $year^{-1}$
minRate_regoUp_ter	0.0029	kgC kgC^{-1} $year^{-1}$
minRate_water_PM_lake	0.8	kgC kgC^{-1} $year^{-1}$
NPP_ter	0.32	kgC m^{-2} $year^{-1}$
piston_vel_lake	201	m $year^{-1}$
piston_vel_ter	50	m $year^{-1}$
poro_regoGL	0.75	m^3 m^{-3}
poro_regoLow	0.21	m^3 m^{-3}
poro_regoPeat	0.9	m^3 m^{-3}
poro_regoPG	0.92	m^3 m^{-3}
poro_regoUp_lake	0.97	m^3 m^{-3}
poro_regoUp_ter	0.9	m^3 m^{-3}
solubilityCoef_lake	1.14	(mol m^{-3})/(mol m^{-3})
solubilityCoef_ter	1.23	(mol m^{-3})/(mol m^{-3})
z_regoUp_lake	0.05	m
z_regoUp_ter	0.3	m

Table C-2. Water fluxes for 157_1 and Lake Fiskarfjärden.

Parameter	157_1 Value	Lake Fiskarfjärden Value	Unit
q_downstream	3.4	0.7	m^3 m^{-2} $year^{-1}$
q_gl_low_lake	0.0006	0.0109	m^3 m^{-2} $year^{-1}$
q_gl_low_ter	0.0018	0.0203	m^3 m^{-2} $year^{-1}$
q_gl_pg_lake	0.0175	0.0132	m^3 m^{-2} $year^{-1}$
q_gl_pg_ter	0.0433	0.1244	m^3 m^{-2} $year^{-1}$
q_low_gl_lake	0.0102	0.0132	m^3 m^{-2} $year^{-1}$
q_low_gl_ter	0.0222	0.0926	m^3 m^{-2} $year^{-1}$
q_peat_pg_ter	0.0112	0.0237	m^3 m^{-2} $year^{-1}$
q_peat_up_ter	0.1399	0.2347	m^3 m^{-2} $year^{-1}$
q_pg_gl_lake	0.0026	0.0109	m^3 m^{-2} $year^{-1}$
q_pg_gl_ter	0.0088	0.0203	m^3 m^{-2} $year^{-1}$
q_pg_peat_ter	0.0480	0.1368	m^3 m^{-2} $year^{-1}$
q_pg_up_lake	1.2934	0.7324	m^3 m^{-2} $year^{-1}$
q_up_peat_ter	0.1557	0.2833	m^3 m^{-2} $year^{-1}$
q_up_pg_lake	1.1884	0.2284	m^3 m^{-2} $year^{-1}$
q_up_wat_lake	1.2934	0.7324	m^3 m^{-2} $year^{-1}$
q_up_wat_ter	1.0506	0.1757	m^3 m^{-2} $year^{-1}$
q_wat_up_lake	1.1884	0.2284	m^3 m^{-2} $year^{-1}$
q_wat_up_ter	0.0011	0	m^3 m^{-2} $year^{-1}$

Table C-3. Time dependent parameters for 157_1 and Lake Fiskarfjärden in the short-term modelling representing 4700 AD and 2000 AD, respectively. *denotes object-specific values, which do not change over time.

Parameter	157_1 Value	Lake Fiskarfjärden Value	Unit
area_obj	103,600	750,000	m^2
area_obj_aqu	47,200	375,000	m^2
area_obj_ter	55,600	375,000	m^2
biom_pp_macro	0.022	0.022	kgC m^{-2}
biom_pp_micro	0.0038	0.0038	kgC m^{-2}
biom_pp_plank	0.000082	2.01E–05	kgC m^{-2}
NPP_macro	0.087	0.087	kgC m^{-2} $year^{-1}$
NPP_micro	0.056	0.056	kgC m^{-2} $year^{-1}$
NPP_plank	0.024	0.024	kgC m^{-2} $year^{-1}$
res_rate	0.00027	0.00022	m^3 m^{-2} $year^{-1}$
sed_rate	0.00041	0.00034	m^3 m^{-2} $year^{-1}$
z_regoGL*	2.3548	2.01	m
z_regoLow*	2.99	0.2	m
z_regoPeat	0.42	0.5	m

Table C-4. For some compartments the initial conditions of accumulated carbon were calculated and entered before simulation, due to a slow accumulation rate. Some compartments reached close to a steady state fast (≪100 years). In a few compartments a value had to be entered to avoid division by zero. The names of the compartments refer to the name in the Ecolego model (Saetre et al. 2013b) and are described in the last column. Compartments with the extension "org" and biotic compartments refer to compartments containing inorganic carbon, while the others contain dissolved organic carbon.

Compartment	Ecosystem	Lake Fiskarfjärden (KgC)	157_1 (KgC)	Description
PP	Mire	0	0	Biomass of mire vegetation
RegoUp_org	Mire	5,175,000	767,280	Oxic peat surface layer
RegoUp	Mire	1	1	Oxic peat surface layer
RegoPeat_org	Mire	11,902,500	1,074,192	Anoxic peat layer
RegoPeat	Mire	8,280	250	Anoxic peat layer
RegoPG_org	Mire	8,190,000	335,026	Post glacial clay
RegoPG	Mire	0	0	Post glacial clay
RegoGL	Mire	0	0	Glacial glay
Plank	Lake	0	0	Biomass of plankton
Micro	Lake	0	0	Biomass of microphytobenthos
Macro	Lake	0	0	Biomass of macroalgae
Water_org	Lake	0	0	Lake water
Water	Lake	4,000	1	Lake water
RegoUp_org	Lake	194,438	25,913	Oxic upper sediment layer
RegoUp	Lake	0	0	Oxic upper sediment layer
RegoPG_org	Lake	8,190,000	335,026	Post glacial clay
RegoPG	Lake	0	0	Post glacial clay
RegoGL	Lake	0	0	Glacial glay