R-06-82

The biosphere at Forsmark

Data, assumptions and models used in the SR-Can assessment

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October 2006

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Contents

1 Introduction

This is essentially a compilation of a variety of reports concerning the site investigations, the research activities and information derived from other sources important for the safety assessment. The main objective is to present prerequisites, methods and data used, in the biosphere modelling for the safety assessment SR-Can /SKB 2006a/ at the Forsmark site. A major part of the report focuses on how site-specific data are used, recalculated or modified in order to be applicable in the safety assessment context; and the methods and sub-models that are the basis for the biosphere modelling. Furthermore, the assumptions made as to the future states of surface ecosystems are mainly presented in this report. A similar report is provided for the Laxemar area /SKB 2006b/.

Many authors have provided the original texts for, commented upon, or edited this report:

- Rodolfo Avila, Facilia AB, section on landscape dose factors and doses to biota.
- Sten Berglund, SKB, hydrology modelling.
- Emma Bosson, SKB, hydrology modelling.
- Lars Brydsten, Umeå University, modelling of shoreline displacements, distribution of quarternary deposits and the future development of the site.
- Anna Hedenström, SGU, development of projections describing the site in the future.
- Sara Karlsson, SKB, site investigation Forsmark, site data compilation and editing, development of projections describing the site in the future.
- Ulrik Kautsky, SKB coordinator of the research program, the safety analysis of the biosphere, landscape development and dose modelling.
- Linda Kumblad, Department of Systems Ecology, marine ecosystems.
- Tobias Lindborg, SKB coordinator of analysis of site biosphere, landscape modelling, site data.
- Anders Löfgren, EcoAnalytica, terrestrial ecosystems, coordinator of compilation of site generic parameter data, editing.
- Helena Nyman, Sweco, GIS and figures.
- Jens-Ove Näslund, SKB, climate development.
- Björn Söderbäck, SKB, limnic ecosystems, future development of the site, surface water chemistry, editing.
- Erik Wijnbladh, SKB, marine ecosystems.

Sara Karlsson, Ulrik Kautsky, Anders Löfgren and Björn Söderbäck edited the text and, Mike Thorne (SIERG) and Regina Lindborg (Department of Botany, Stockholm University) suggested many improvements on earlier versions of this report.

2 Summary and guidance to the reader

This section serves both as a summary and guidance for the reader. The section put this report into a wider context and presents its aims, but perhaps more importantly, it describes how the sections in this report are related, and how they are used in the different steps of the biosphere safety assessment.

2.1 Overview

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co., SKB. Within SKB's programme for the management of spent nuclear fuel, an interim storage facility and a transportation system are today (October 2006) in operation. An application to build a final repository will be made at the end of 2009 according to current plans. In the proposed approach to spent fuel disposal, copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock. Around 9,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme, corresponding to roughly 4,500 canisters in the repository. SKB is currently pursuing site investigations for a final repository in the municipalities of Östhammar (Forsmark area) and Oskarshamn (Laxemar area). One critical issue is to be able to characterise the long-term safety for a deep repository and a safety report will be produced in order to support the application in 2009. A preliminary version for such a safety report is the SR-Can report /SKB 2006a/. The SR-Can report is based on a number of reports, of which the current report is one, describing the methodology and input data for those aspects of the safety assessment relating to the biosphere in the Forsmark area (Figure 2-1). A similar report for the Laxemar area is found in /SKB 2006b/.

2.2 Aims

The overall objective of this report is to describe the methodology and input data used in the biosphere modelling of radiation dose to biota and humans, and to present the results of this modelling. The report presents descriptions and estimates not presented elsewhere, as well as summaries of important steps in the biosphere modelling that are presented in more detail in separate reports. The intention is firstly, to give the reader a coherent description of the steps taken to calculate doses to biota and humans, including a description of the data used, the rationale for a number of assumptions made during parameterisation, and of how the landscape context is applied in the modelling, and finally also to present the models used and the results obtained. The major outputs can be summarised as:

- Current biosphere state: A description of the different ecosystem types found local to the Forsmark site, along with descriptions of their successional development.
- Historical and future development: A description of the landscape succession at the site over the period between 8,000 BC and 10,000 AD.
- Climatic change: A description of potential permafrost, glacial ice-margin and greenhouse conditions at the site.
- Spatial model development: A landscape model consisting of a number of hydrologically connected Biosphere Objects that are identified as recipients of potential discharge of radionuclides.
- Temporal model development: A description of the successional development of the Biosphere Objects within the landscape model during the specified time period.

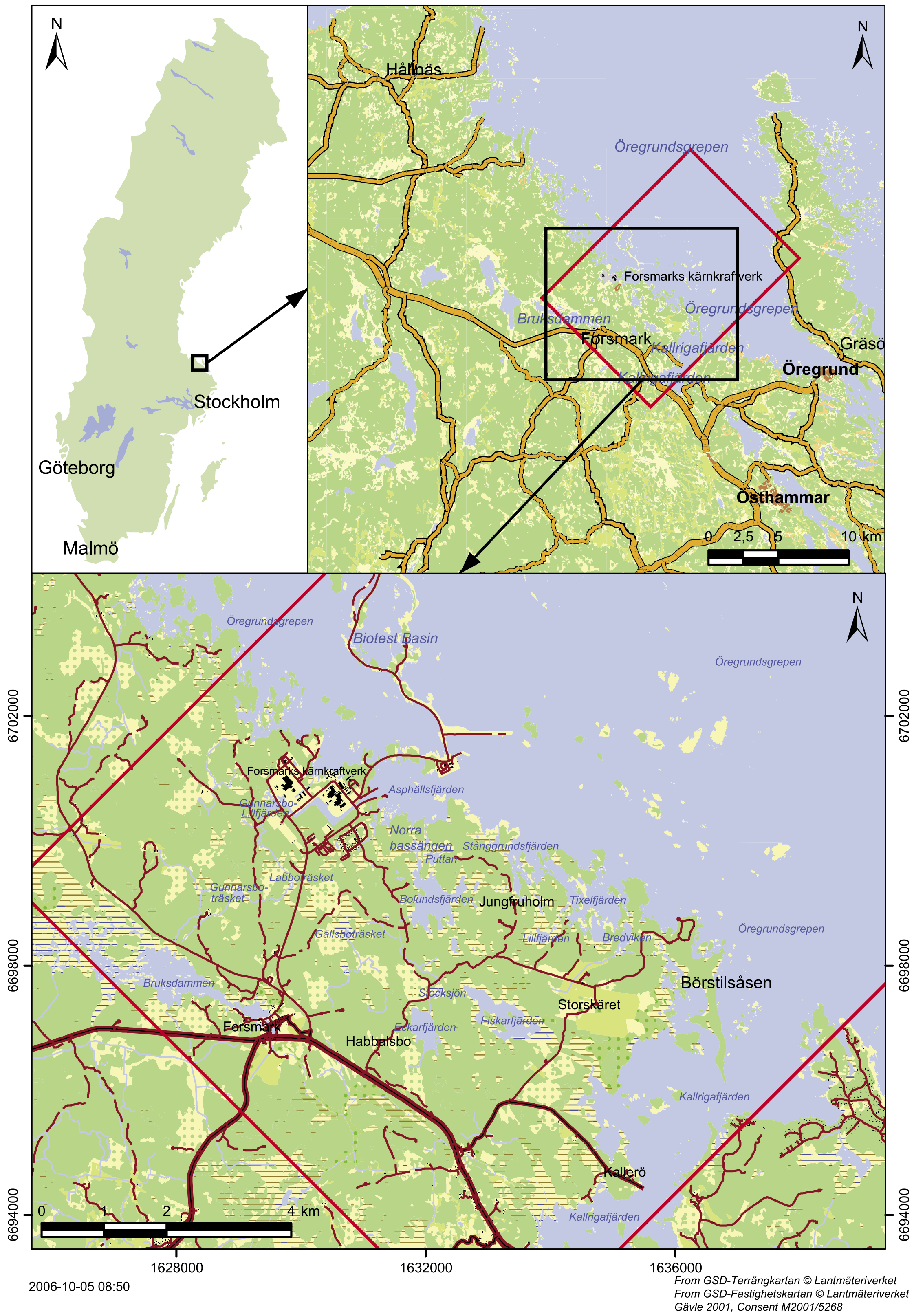


Figure 2-1. *The location of the Forsmark site, where the detailed map includes the geographical names used throughout this report, except for the names of some minor lakes in the area. The red rectangle shows the Forsmark regional model area.*

- The dose model input parameters: A presentation of the methodology, assumptions and calculations of the input data used in the description of the Biosphere Objects in the biosphere dose modelling.
- The dose model: A presentation of the methodology, assumptions and calculations underpinning estimates of doses to biota and humans.
- Conclusions: Presenting the overall conclusions from the dose-modelling.

2.3 Report content and the biosphere safety assessment approach

The report comprises a description of a number of distinct but related aspects of the integrated biosphere modelling approach. The relationships between the various components of the approach, and where they are discussed in the report, is illustrated in Figure 2-2. The assessment approach starts with the potential discharge points in the biosphere and ends with the calculation of landscape dose factors that is used to evaluate the potential doses to humans and biota. In the subsections below a general description of the content in the different sections is given along with the major references used.

2.3.1 The site

As an introduction to the site a short description of the abiotic and biotic conditions, from quaternary deposits to human activities, is presented (see Section 3). Generally, the overall site description puts the biosphere modelling into a site-specific context. More detailed information about the site conditions can be found in /Lindborg 2005/.

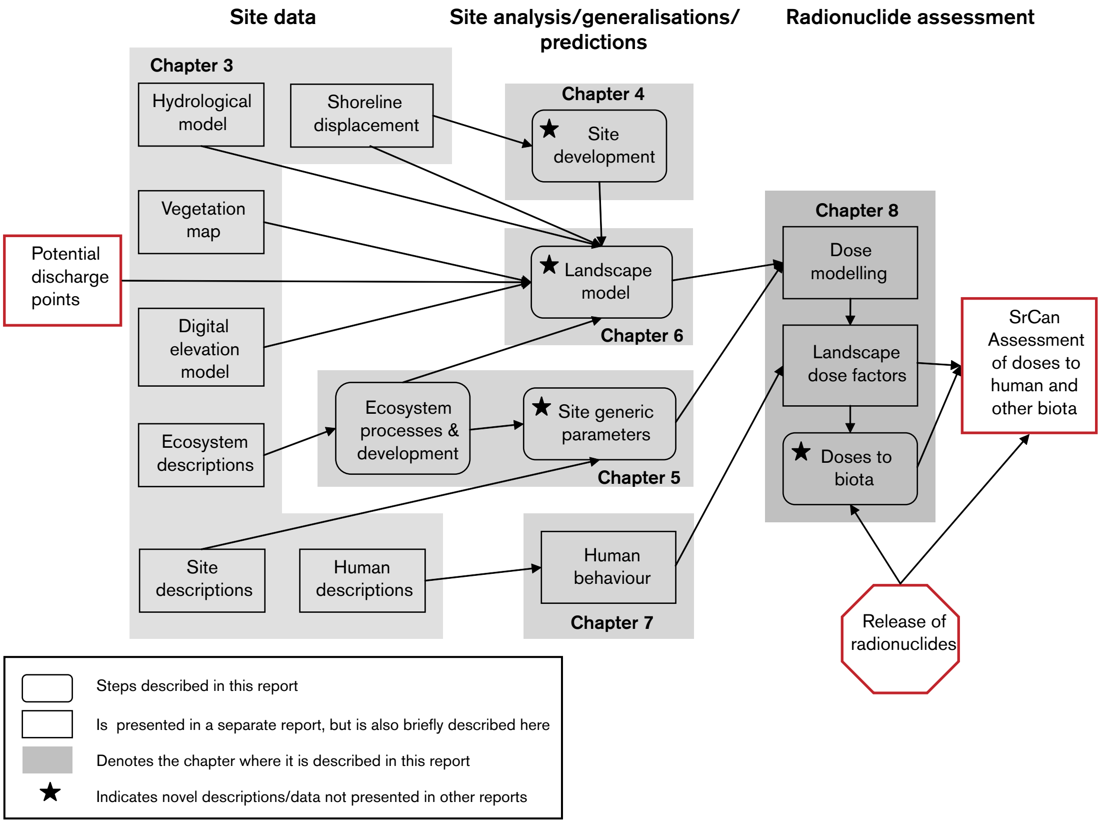


Figure 2-2. *A schematic picture of how the different sections in this report are related and where major input data feeds into the biosphere dose modelling. The grey shaded boxes are treated within this report, whereas the square boxes denote important data used in the different steps of modelling.*

2.3.2 Historical and future site development

An understanding of the historical and future development of the site is required as a basis for impact modelling in a long-term safety assessment. Consequently, Section 4 is devoted to a historical and projected future description of the site, starting at the time of the latest deglaciation in 8,000 BC and ending at approximately 20,000 AD. The description is based on a shoreline displacement model /Brydsten 2006b/ that is built upon a mathematical evaluation of shore displacement /Påsse 1997/. This section also includes a description of conditions during periods of permafrost and altered climatic conditions due to the influence of greenhouse gases released by human activities /SKB 2006c/. This section is based on studies from the site /Lindborg 2005/ but also projections of the future, which are described in the present report.

2.3.3 Ecosystems, biosphere objects and site generic parameters

The landscape at the site constitutes of a number of different terrestrial and aquatic environments that can be defined from their functional properties with regard to the biogeochemical cyclinf of elements, so called ecosystems. An ecosystem exposed to radionuclides is hereafter called a Biosphere Object, and is the smallest unit within the biosphere dose modelling. The different types of major ecosystems found at the site are described in sections /from Lindborg 2005/ together with their successional development through time. Moreover, a radionuclide transfer model is presented for each ecosystem /Avila 2006/, along with the different parameters that are used in the modelling of radionuclide transport and accumulation within the Biosphere Objects. Each ecosystem description is followed by a presentation of the data used in, and assumptions underlying the site generic parameterisation of the radionuclide model. All the site generic parameter values characterising the different ecosystems are presented in Appendix 1.

2.3.4 The landscape model

In the biosphere dose modelling, the Landscape model (represented by a box in Figure 2-2 and discussed in Section 6), describes the spatial distribution, connectivity and succession of biosphere objects in the landscape (Figure 2-3). The spatial extent of the landscape model is delimited by a number of potential discharge points, originating from a deep repository, at the regolith surface /Hartley et al. 2006/. These potential discharge points are used to identify the specific Biosphere Object associated with radionuclide release in the landscape. Assuming a hydrologically driven transfer process between objects, the biosphere objects are interconnected using a hydrological model, As the landscape changes over time, due to shore level displacement, the description of the Landscape model is updated for each 1,000 y step within the interglacial period using the shoreline displacement model /Brydsten 2006b/ together with a number of criteria describing ecosystem succession. During this process, a Biosphere Object may change from one ecosystem type to another, e.g. a marine basin turns into a lake, and must accordingly be assigned new object-specific parameters, such as area, water depth and water volume. Thus, this model provides the dose model with radionuclide recipients (Biosphere Objects), their spatial connectivity, successional development and Biosphere Object specific descriptions.

2.3.5 Human exposure

When modelling doses to humans from exposures to radionuclides, site–specific data on environmental conditions are of importance, but so also is information concerning human behaviour. Section 7 describes the methodology and the assumptions behind the calculations of doses to humans from exposures to radionuclides in environmental media, such as air, water, food and soil /Avila and Bergström 2006/. Dose to humans includes effective dose, in the ICRP publication 60 sense /ICRP 1991/, from external exposure and committed effective dose from ingestion and inhalation. To make certain that the annual average lifetime dose to humans is not underestimated the maximum dose conversion factor for any of the age classes considered

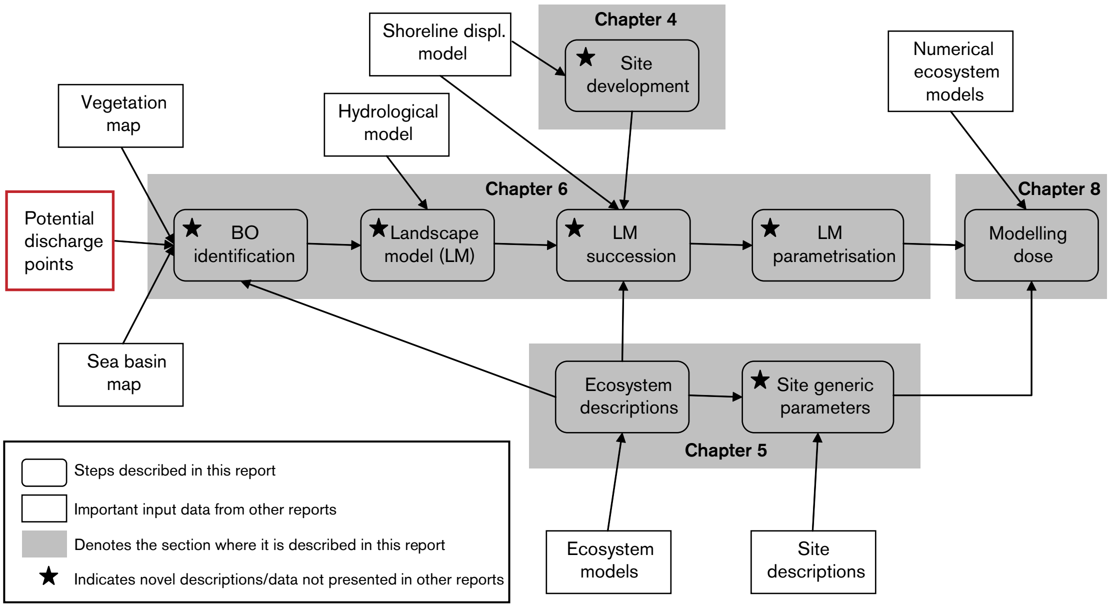


Figure 2-3. *A schematic picture of the major steps during the construction of the Landscape model (LM) presented in Section 6, and the major sources of input. This model provides the dose modelling with radionuclide recipients (Biosphere Objects), their spatial connectivity and successional development, and Biosphere Object specific descriptions, such as area and depth.*

is used. No assumptions have been made regarding human food preferences (see Chapter 7); instead the calculations are based on values of food energy intake. However, it is assumed that humans will exploit the contaminated landscape to a maximum, thus eating all potential edible food produced within the Biosphere Object. Thus, the number of persons that can be sustained by a Biosphere Object is constrained by the annual productivity of edible products and the size of the Biosphere Object. The production of natural food items is constrained by the primary production of the site and can be assessed separately. The adopted approach makes it possible to estimate not only the effective dose rate to individuals utilising a particular Biosphere Object, but also the number of individuals that the Biosphere Object can fully support. For the Biosphere Object giving the highest effective dose rate, this is the maximum number of people that could be associated with that effective dose rate. In practice, individuals would utilise resources from more than one ecosystem, so the effective dose rate that they received would be lower.

2.3.6 Biosphere modelling of doses to humans and biota

The radiological impacts are calculated for constant unit release rates of radionuclides to the surface environment. By using this approach, Landscape Dose Factors (LDFs), i.e. effective dose rates for unit flux of each radionuclide, are derived /Avila et al. 2006/. These LDF values can then be multiplied by radionuclide fluxes emerging from the geosphere for radiological impact estimation. The LDF values are calculated over the entire time period with a minimum time step of 1,000 years. A cautious approach is applied in which the maximum of the effective dose rate to the representative individual from the most exposed group over the reference times considered for each radionuclide is defined as the LDF for that radionuclide. As an example, in a developing landscape, as is represented in the landscape model, radionuclides can accumulate in marine or lacustrine sediments, but give rise to an increased radiological impact when, as a consequence of shore-level displacement, those sediments are converted to agricultural land /Avila 2006/. To allow for this, the LDF values used are the maximum values of effective dose rate that apply over the period of release.

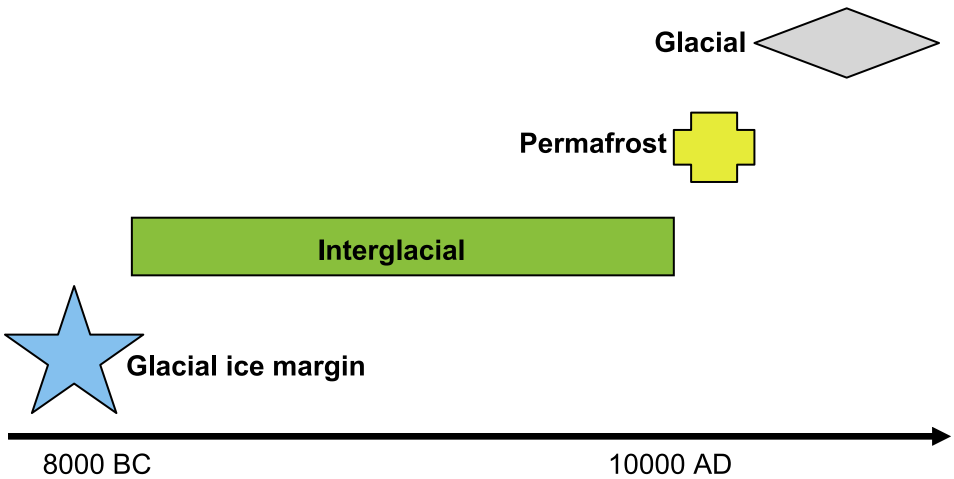
The modelling time-frame adopted for the base case covers a glacial cycle of 120,000 years and includes periods of glacial ice margin, interglacial, permafrost and glacial conditions (Figure 2-4). The interglacials are represented by the current interglacial as 8,000 BC to 10,000 AD. The different periods are integrated over the glacial cycle according to present knowledge of the Wechselian cycle (see Chapter 4). In addition, a greenhouse variant affecting future climate was modelled by prolonging interglacial conditions until 50,000 AD followed by the same conditions as in the base case after 50,000 AD.

The radiological impact on biota other than humans is calculated by estimating the concentration of radionuclides in water and regolith for the different ecosystems using the landscape model and the specified release of radionuclides. The concentrations are compared with the suggested screening limits from ERICA /ERICA 2006/. No further evaluation is performed if concentrations are below these screening limits, which they were found to be (see Chapter 8). If they, however, are above these screening limits refined calculations have to be undertaken on a case-by case basis.

2.4 Concluding remarks

This report summarises the method adopted for safety assessment following a radionuclide release into the biosphere. The approach utilises the information about the site as far as possible and presents a way of calculating risk to humans. The parameters are topography, where there is good understanding of the present conditions and the development over time is fairly predictable. The topography affects surface hydrology, sedimentation, size of drainage areas and the characteristics of ecosystems. Other parameters are human nutritional intake, which is assumed to be constant over time, and primary production (photosynthesis), which also is a fairly constant parameter over time. The Landscape Dose Factor approach (LDF) gives an integrated measure for the site and also resolves the issues relating to the size of the group with highest exposure.

If this approach is widely accepted as method, still some improvements and refinement are necessary, e.g. collecting missing site data, reanalysing site data, reviewing radionuclide specific data, reformulating ecosystem models and evaluating the results with further sensitivity analysis.



Figur 2-4. *The climate conditions that are modelled for the assessment of the biosphere during a glacial cycle. Glacial ice margin, interglacial, permafrost and glacial (as defined in /SKB 2006c/), are integrated over the glacial cycle according to present knowledge of the Wechselian cycle.*

3 Site description

This chapter provides a brief description of the biosphere in the Forsmark area. A more detailed description of the site can be found in the site description report /SKB 2005/ or in the surface description report /Lindborg 2005/.

3.1 Abiotic characteristics

Abiotic characteristics set the physical limits for the distribution of ecosystems and biota within these, and, accordingly, these characteristics are an important part of the site descriptive models. Moreover, the abiotic characteristics are important input parameters in the radionuclide transport modelling.

3.1.1 Geometry

SKB has developed a Digital Elevation Model (DEM) to describe the terrain relief. The model shows the current site conditions (see Figure 3-1), and it can, together with other models, be used to describe both past and projected future conditions. The DEM is a central tool for the site characterisation, and it has been used as input to most of the descriptions and models produced for the surface system. A comprehensive description of it is provided in /Brydsten and Strömgren 2004/.

3.1.2 Regolith

Data describing the regolith is an important input when modelling the transport of water, as well as of various elements and compounds, between the geosphere and the biosphere, through the soil and sediments. Data describing accumulation of matter in sediments have been used in the aquatic ecosystem models, whereas soil data is strongly associated to the classification of vegetation types in the terrestrial ecosystem model of the site.

The ground surface in the Forsmark area is flat and the land area is dominated by glacial till /Sohlenius et al. 2004/. The extent of different deposits and of exposed areas of bedrock is presented in Table 3-1.

Three different kinds of till are represented in the Forsmark area; a sandy till with medium boulder frequency (dominant), a clayey till with low boulder frequency (Storskäret) and a clayey till with high boulder frequency (Börstilåsen) /Sohlenius et al. 2004/. Clay, gyttja clay, sand and peat occur frequently as the superficial Quaternary deposits and cover many small (less than 50×50 m) areas. Peat accumulations are restricted to the south-western part of the investigated area, which is the most elevated and has been situated above the sea level long enough for peat to develop /Fredriksson 2004/.

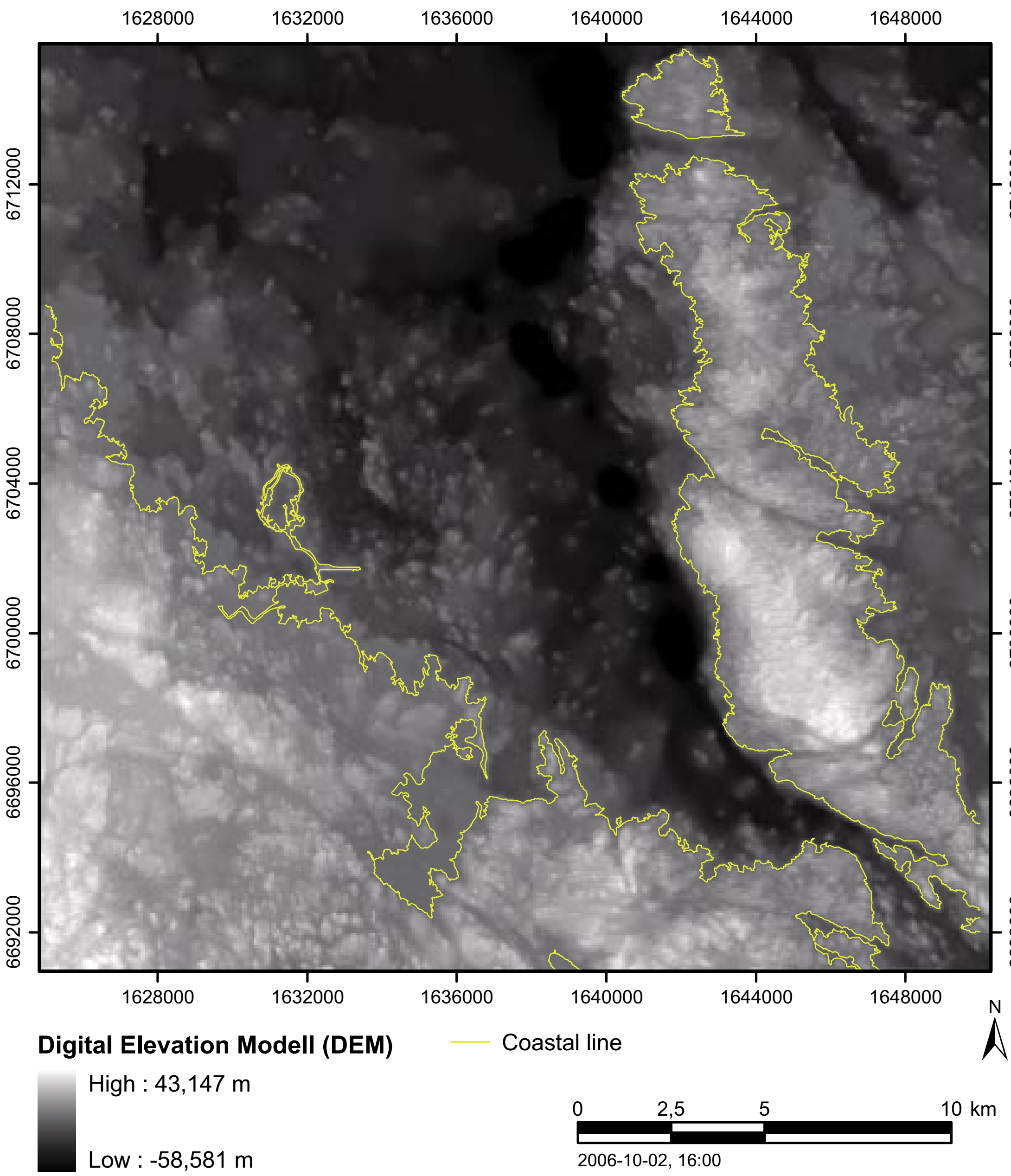


Figure 3-1. *The Digital Elevation Model for the Forsmark area /Brydsten and Strömgren 2004/, with the coastal line indicated in yellow.*

In a majority of the investigated lakes, the total thickness of the sediments (not including glacial till) was less than 2 m and only two lakes contained sediments thicker than 4.5 m /Hedenström 2004/. A generalised stratigraphical distribution of marine and lacustrine sediments in lakes is presented in Table 3-2. Offshore Quaternary deposits are dominated by glacial and post-glacial clay, together covering c 55% of the sea floor /Elhammer and Sandkvist 2005/.

Table 3-1. Areal coverage (%) of the different types of Quaternary deposits and exposed bedrock in the different subareas. The first column relates to the regional model area (cf Figure 2-1) and the calculations are based both on the detailed mapping performed within the site investigations /Sohlenius et al. 2004/ and the initial geological map from /Persson 1985, 1986/. The second column is based solely on the detailed mapping of the central part of the regional model area (cf /Sohlenius et al. 2004/), and the third column is based on the marine geological mapping /Elhammer and Sandkvist 2005/.

	Forsmark land, total	Forsmark land, detailed	Forsmark sea
Bedrock exposures	13	5	6
Glacial clay	4	4	41
Post-glacial clay (including gyttja clay and gyttja)	4	4	17
Post-glacial sand and gravel	2	4	2
Post-glacial fine sand	–	–	4
Till	65	74	30
Glaciofluvial sediment	1	2	0
Peat	8	3	–
Artificial fill	3	4	–

Table 3-2. Generalised stratigraphical distribution of marine and lacustrine sediments in lakes.

Environment	Lithology	
Freshwater lakes	Calcareous gyttja	Youngest
Freshwater lakes and coastal lagoons	Algal gyttja	
Postglacial Baltic Basin	Clay gyttja	↑
Shallow coast	Sand and gravel	
Postglacial Baltic Basin	Postglacial clay	↑
Late glacial Baltic Basin	Glacial clay	Oldest

The thickness of the Quaternary deposits, as recorded in corings in land areas, varies between 0 and 17 m within the investigated area /e.g. Johansson 2003/. A soil depth model (Figure 3-2), further described in /Vikström 2005/, has been created using data from several different kinds of investigations.

The glacial till and clay in the Forsmark area are characterised by their high content of calcium carbonate. The calcite originates from Ordovician limestone present at the sea bottom north of the Forsmark area. Due to chemical weathering of the calcite the groundwater has high carbonate content. It also influences the soil conditions. The soil types in the area are typically poorly developed soils (a result of young age due to the shore line displacement) on till or sedimentary parent material /Lundin et al. 2004/. The soil is nutrient-rich, which results in rich vegetation and an abundant soil fauna.

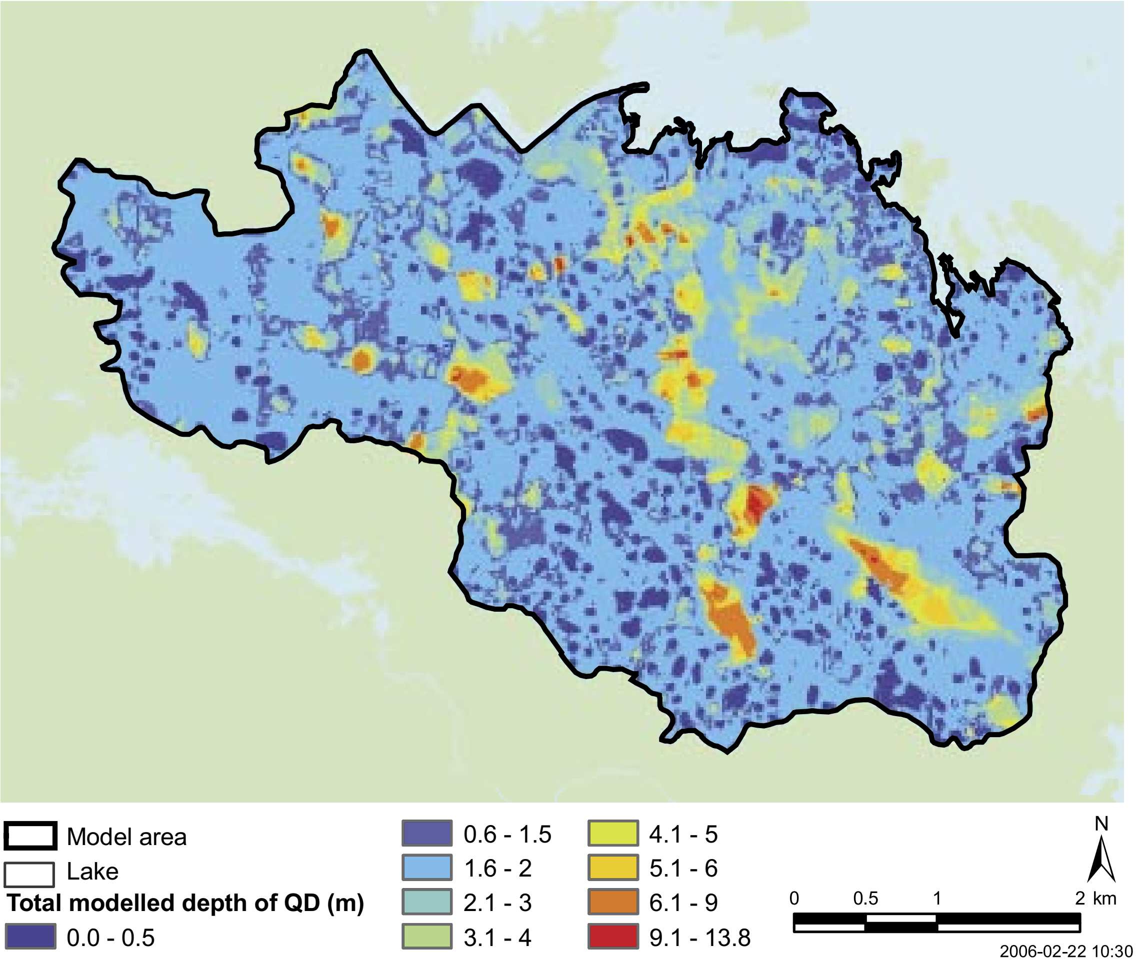


Figure 3-2. *Map showing the depth to bedrock in the drainage area of Lake Bolundsfjärden, based on the soil depth model /Vikström 2005/.*

3.1.3 Climate and surface hydrology

Climate data sets the framework for many processes and is an important input for the surface hydrological modelling. As water is the main transport medium in the system models, the magnitude of different flows in the hydrological cycle are an important factor.

The conceptual and descriptive modelling of the meteorological, surface hydrological and near-surface hydrogeological conditions in the Forsmark area is presented in /Johansson et al. 2005/. The model area is characterised by low relief and small-scale topography; almost the whole area is located below 20 m above sea level.

Climate

The meteorological conditions in north-eastern Uppland, where the Forsmark area is situated, are summarised in Table 3-3. Two meteorological stations were established in the Forsmark area in May 2003, and additional meteorological data from these stations can be found in /Johansson et al. 2005/.

Table 3-3. Some climate characteristics for the Forsmark area, based on data from meteorological stations in north-eastern Uppland.

Mean annual temperature 2004 (°C) [1]	6.0
Mean annual temperature 1961–90 (°C) [2]	5.5
Min – max annual temperature 1961–90(°C) [2]	3.4–7.4
Mean annual precipitation 1961–90 (mm) [3]	758
Min – max annual precipitation 1961–90 (mm) [3]	411–1,252
Growing season	May–September
Growing season (No of days > 5°C) [4]	180

1) /SMHI 2004/.

2) From Örskär 1961–1990 /Larsson-Mcann et al. 2002/.

3) From Lövsta 1961–1990 /Larsson-Mcann et al. 2002/.

4) From Örskär 1988 /Larsson-Mcann et al. 2002/.

Surface groundwater

In order to provide input to the ecological system modelling, the hydrology extension in ArcGIS 8.3 was used to calculate flow directions and mean discharges in the regional model area, based on topographical information (DEM) and regional data on the specific discharge /Johansson et al. 2005/. The detailed locations of recharge and discharge areas are strongly influenced by the local topography, which creates a small-scale recharge-discharge pattern. In "intermediate" areas, the results show that the extent of recharge and discharge areas varies during the year, due to the temporal variability in meteorological conditions /Johansson et al. 2005/. The GIS modelling illustrated the importance of incorporating features such as ditches, diverted water courses and other man-made structures in some catchments, as the flat topography in the model area implies that the results could be sensitive to the representation of such objects in the model.

The groundwater in northern Uppland is, as is the case of the surface waters, characterised by relatively high pH and high calcium concentrations /Naturvårdsverket 1999/. The chlorine concentrations are also higher than the average concentration in Sweden, an effect of relict brackish water, remaining since the area was covered by seawater. The groundwater salinity in the area will probably decrease with time as the area is further uplifted.

Surface water

In total, 25 "lake-centered" catchment areas, ranging in size from 0.03 km^2 to 8.67 km^2 have been delineated and described within the model area /Brunberg et al. 2004/, see Figure 3-3. The 25 mapped lakes range in size from 0.006 km^2 to 0.752 km^2. The lakes are very shallow with maximum depths ranging from 0.4 m to 2.0 m. No major watercourses flow through the model area, but east of the Forsmark area, two rivers enter the shallow bay Kallrigafjärden. Wetlands are frequent and cover 10–20% of the areas of the three major catchments, and up to 25–35% of some sub-catchments.

The lakes and streams in the Forsmark model area are, like most surface waters in the north-eastern parts of Uppland, characterised by high pH, high concentrations of major ions and high electrical conductivity. This is a combined effect of the calcium-rich deposits in the area and of the recent emergence from the Baltic Sea. Due to both chemically and biologically induced processes in the lake water, the amount of phosphorus available in the lakes is effectively reduced by precipitation of calcium-rich particulate matter. Because of this, the phosphorous concentration in lakes and streams is generally low. The nitrogen concentration, on the other hand, tends to be high, or even very high, due to a combination of high input and low biotic utilisation /Brunberg and Blomqvist 1999, 2000/. Taken together, these conditions give rise to a unique type of lake in the Forsmark area, the oligotrophic hardwater lake.

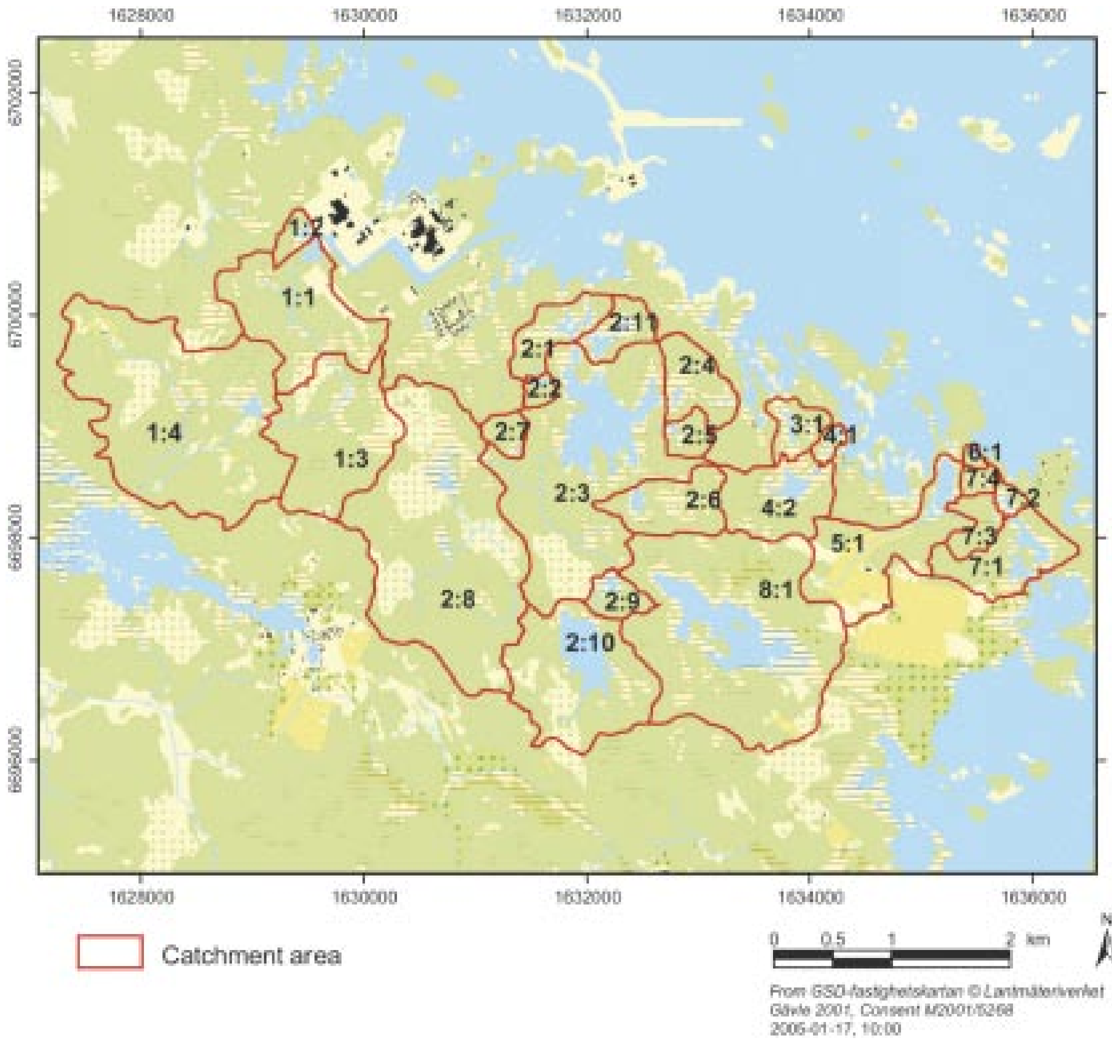


Figure 3-3. *Delineated catchment areas in the Forsmark area /Brunberg et al. 2004/.*

Generally, the chemical conditions in both the fresh and marine surface waters in the Forsmark area are relatively unaffected by anthropogenic influence. Several of the Forsmark lakes are still not completely isolated from the Baltic Sea because of the small altitude differences in the area.

3.1.4 Coastal oceanography

Oceanographic data are used when estimating water exchange times for the different basins in the coastal area (input data to the marine ecosystem model). The Forsmark area is located in Öregrundsgrepen that comprises a funnel-like open-ended embayment with the wider end toward the north. The narrow southern end is also shallower with a threshold at approximately 25 m. There are notable density fluctuations over an annual cycle, mainly due to the collective discharge of all the rivers into the Bothnian Bay. In order to estimate water exchange times for the coastal area a number of models describing oceanographic conditions were set up /Lindborg 2005/. The coastal area was partitioned into nine non-overlapping sub-basins based on consideration of present underwater structures that, in the future, will define distinct catchment areas when terrestrial conditions prevail. The locations of the sub-basins are shown in Figure 3-4. The calculated Average Age (AvA) for each basin is presented in Table 3-4. The AvA measure is computed as the average time the comprised water parcels have spent in a particular basin since entering, with the average taken over the basin volume

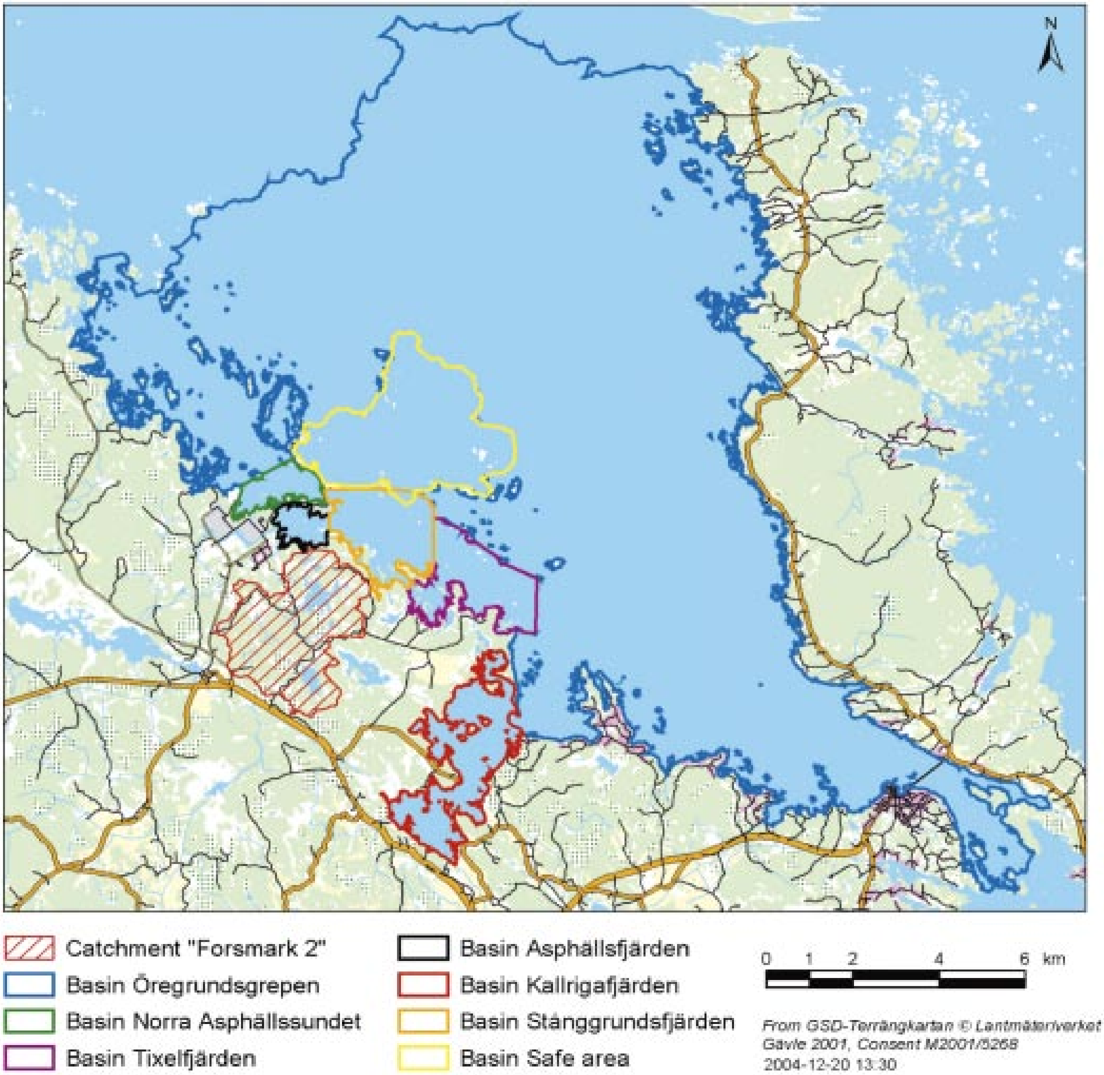


Figure 3-4. *The location of marine sub-basins. The major coastal sub-basin encompasses most, but not all, of the Öregrundsgrepen embayment.*

Table 3-4. Average Age (days) estimates for seven of the nine sub-basins (SB) in the Forsmark area. SB2 is the major coastal basin that to a large extent coincides with Öregrundsgrepen. These AvA data are thus computed for the individual basins with the water of the adjacent basins considered as exogeneous, i.e. having their AvA measure equal to zero. The vertically integrated (averaged by volume) statistics for SB15 through SB19 are calculated directly from 3D-model results, which have a temporal resolution of one hour. Two of the SBs were not sufficiently resolved by the 3D grid and the corresponding calculation has been deferred until their basin and strait hypsographies are available.

	Common name	Min	Mean – S D	Mean	Mean + S D	Max
SB1	Kallrigafjärden	0.48	1.29	1.67	2.05	2.45
SB2	Öregrundsgrepen (major coastal sub-basin)	1.88	4.46	6.32	8.19	10.40
SB15	Asphällsfjärden	0.30	0.73	0.82	0.92	1.10
SB16	Norra Asphällssundet	0.34	0.38	0.45	0.52	1.06
SB17	Stånggrundsfjärden	0.07	0.24	0.29	0.34	1.00
SB18	Tixelfjärden	0.03	0.12	0.15	0.19	1.00
SB19	SAFE-area	0.08	0.35	0.66	0.96	1.63

3.2 Biotic characteristics

This section presents a general description of the biota in the Forsmark area. Detailed information on biomass, production, turnover of tissue and carbon content used in the ecosystem models can be found in /Lindborg 2005/.

3.2.1 Terrestrial biota

Forest represents 73% of the land area in Forsmark. The terrestrial vegetation is strongly influenced by the characteristics of the Quaternary deposits and by human land use. Most of the Forsmark land area is covered with conifer forests. Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) dominate. The field layer is characterised by herbs and broad-leaved grasses along with a number of orchid species. The area has had a long history of forestry and this is also seen today, as a fairly high percentage of younger and older clear-cuts occur in the landscape. The wetlands in the Forsmark area are characterised by moderate to extreme rich fens /Jonsell and Jonsell 1995/, due to a high calcareous influence. However, bogs are also present at higher locations. The spatial distribution of different vegetation types is presented by /Boresjö Bronge and Wester 2002/.

The most common larger mammal species in the Forsmark regional model area is roe deer (9.4 deer km^{-2}) /Cederlund et al. 2004/. Moose is also fairly common (1.2 moose km^{-2}), but unevenly distributed, which is normal for this part of Sweden. European and mountain hare are fairly low in abundance, compared with other regions. A comprehensive description of the mammals in the Forsmark area is found in /Cederlund et al. 2004/. In total, 96 bird species have been found in the Forsmark area /Green 2004/. The most common species were, as in the rest of Sweden, Chaffinch (sw. Bofink) and Willow warbler (sw. Lövsångare).

3.2.2 Limnic biota

Since all lakes in the area are shallow (see above), the dominant habitat in the larger lakes is the littoral with submerged vegetation. All bottom areas in the lakes are reached by daylight and, accordingly, no profundal habitat exists in the Forsmark lakes. Phytoplankton and bacterioplankton biomasses are low, and the microbial community is mainly confined to the sediments where a 10–15 cm thick microbial mat, mainly consisting of cyanobacteria, is found. Preliminary primary production measurements in Lake Eckarfjärden show that whereas the production in the pelagial is always low, the production in the microbial mat may potentially be very high /Blomqvist et al. 2002/.

An important group of underwater plants in the lakes of the Forsmark area is the stoneworts (*Chara spp.*). Large parts of the bottoms of the larger lakes are covered with *Chara*. The biomass of benthic fauna is low compared with other Swedish lakes /Andersson et al. 2003/ and the benthic fauna is dominated by herbivores, both in terms of number of individuals and in terms of biomass.

Benthivorous fish is generally the dominant functional group among fish species in the Forsmark lakes. Their biomass ranges from 68% of the total fish biomass in Lake Eckarfjärden to 89% in Lake Fiskarfjärden. The biomass contribution of planktivorous fishes is generally low, ranging from 0.1% in Lake Bolundsfjärden to 8% in Lake Fiskarfjärden.

3.2.3 Marine biota

The marine system in the Forsmark area is a relatively productive coastal area in a region of otherwise fairly low primary production. This is due to upwelling along the mainland /Eriksson et al. 1977/. The species that contribute most to the macrophyte biomass of the benthic community in Forsmark are the red alga *Polysiphonia nigrescens*, the brown algae *Fucus vesiculosus* and *Sphacelaria arctica* and the vascular plant *Potamogeton filiformis* /Kautsky et al. 1999/.

The most common fish species in Öregrundsgrepen are herring (*Clupea harengus*), roach (*Rutilus rutilus*) and perch (*Perca fluviatilis*) /Neuman 1982/. Small-sized species such as sticklebacks (*Gasterosteidae*) and gobies (*Gobiidae*) are also common /Heibo and Karås 2005/.

3.3 Humans in the Forsmark area

The Forsmark area has no permanent residents, but there are five holiday houses and three farms situated within the area /Miliander et al. 2004/. The only agricultural enterprise in use today is situated at Storskäret. The area used for agricultural purposes (pastures, meadows, fields) is 4% of the total area. The enterprise at Storskäret is focused on meat production and the cattle graze outdoors during the vegetation periods.

The data assessment by /Miliander et al. 2004/ can be summarised as follows:

- The main employment sector is within electricity supply. There is a clear net daily in-migration to the parish of Forsmark due to the dominant employer; the Forsmark nuclear power plant.
- The land use is dominated by forestry; wood extraction is the only significant outflow of biomass from the area.
- The dominant leisure activity is hunting. Besides this, the area is only occasionally used for leisure. This is probably a result of both the scarce population and the relative inaccessibility of the area and distance from major urban areas.
- The agriculture in the parish is limited in extent and the major crop is barley.

4 Site development

In this chapter, the long-term development of the Forsmark landscape is described. The historical description is mainly based on the elevation model, the shoreline displacement equation /cf Påsse 1997/, old cadastral maps and site-specific information on Quaternary deposits. Prediction of the future development is associated with more uncertainties than the historical description. The future development of the area may be different than expected due to e.g. greenhouse gas-induced warming inducing a climate change which cannot be predicted today. Such changes are expected to influence important characteristics of the biosphere, such as the hydrological cycle, sea level, and salinity of the Baltic Sea. In SR-Can this uncertainty has been handled through the definition of a number of scenarios /SKB 2006a/.

It should be noted that the descriptions of the future development in the following text are based on existing knowledge of the past, known processes (e.g. shoreline displacement) and knowledge about the current situation e.g. existing ecosystems, climate, geometry and geology of the seafloor etc. All these descriptions have their uncertainties. Thus, the descriptions presented here are a sketch of the future, which is logical coherent, but the exact dates and spatial extent of the various domains are uncertain because of limitations in the underlying data and conceptual models.

The text in the sections describing periods with permafrost and glaciation are not site-specific, and describes only in broad outline how the biosphere appears during such conditions. These descriptions are the base for how those time periods have been treated in the model calculations in SR-Can /SKB 2006a/. Thus, the descriptions relate only to processes that may be important for the distribution of radionuclides.

Land uplift and the resulting shore-line displacement have strongly influenced the biosphere conditions in the past and will do so also in the future, e.g. succession on newly exposed land and sediment redistribution (sedimentation and resuspension/erosion). The estimated rate of shore-line displacement is shown in Figure 4-1. In the future ecosystems, today's early successional stages of vegetation and associated fauna are assumed to gradually move in the landscape, following the shore-line displacement.

4.1 Interglacial period

The latest deglaciation in Forsmark took place during the Preboreal climatic stage, c 10,800 years ago /Strömberg 1989, Persson 1992, Fredén 2002/. The closest shore/land area at that time was situated c 80 km to the west of Forsmark. The Forsmark area was initially covered with approximately 150 m of Yoldia Sea water. Since the main part of the Forsmark area has been situated below the Baltic until the last 2,000 years or so, the post glacial development of the area is mainly described by the shore displacement and the development in the Baltic basin.

The past salinity in the Baltic Sea since the onset of the Littorina period has been reviewed by /Westman et al. 1999/ and /Gustafsson 2004a/ with updated chronology from /Fredén 2002/. From proxy data, they estimated a range within which the salinity of the Baltic Proper (the Baltic Sea south of Åland) can be described over time. They also presented a model, which uses knowledge of the sills in the southern Baltic Sea together with river runoff, to estimate past and future salinity changes. The model can also be used to evaluate differences in salinity between the different basins of the Baltic Sea /Gustafsson 2004ab/, cf Table 4-1 and Figure 4-2.

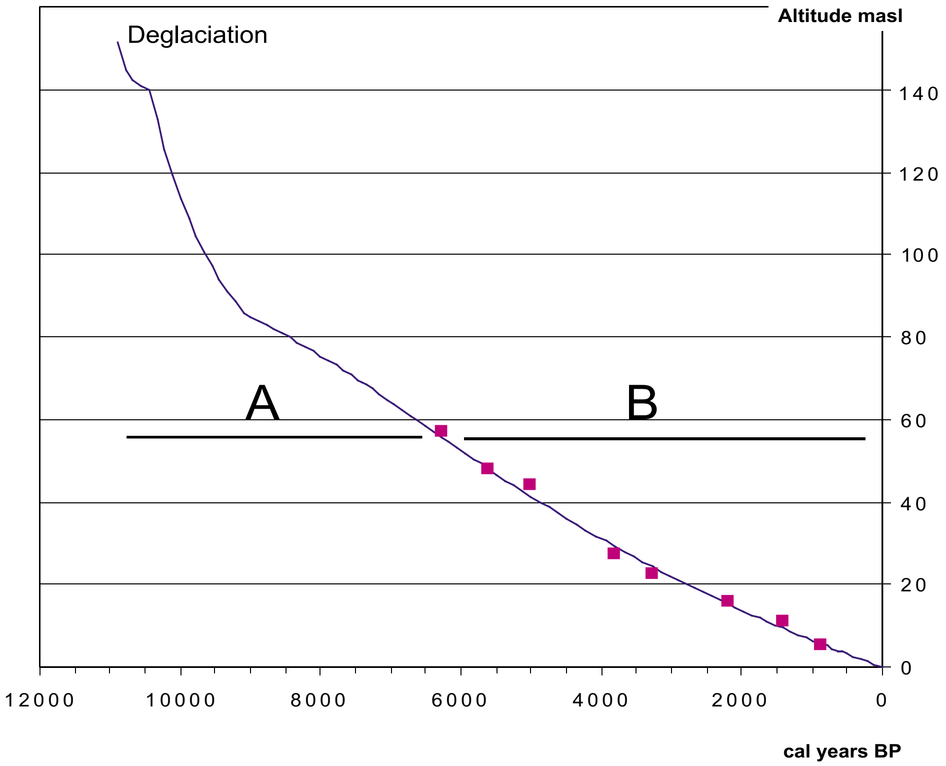


Figure 4-1. *Shore-line displacement curve for Forsmark. The purple squares are ages and altitude of dated isolation basins /Hedenström and Risberg 2003, Risberg et al. 2005/. The solid black line is the mathematically modelled shore displacement /Påsse 1997/. The older part of the curve, marked with A, has a larger uncertainty than the younger part, marked with B.*

Table 4-1. Summary of the stages of the Baltic Sea /Fredén 2002, Westman et al. 1999/. Note that the altitudes and ages are approximate values, based on regional extra- and inter-polations. BP = Before Present.

Baltic stage	Calendar year	Salinity	Environment in Forsmark
Baltic Ice Lake not applicable in Forsmark	15,000–11,550 BP (13,050–9,600 BC) not applicable in Forsmark	Glacio-lacustrine not applicable in Forsmark	Covered by inland ice
Yoldia Sea	11,500–10,800 BP (9,550–8,850 BC)	Lacustrine/Brackish /Lacustrine	Deglaciation, regressive shoreline from c 150 m.a.s.l. Minor (or no) influence of brackish water.
Ancylus Lake	10,800–9,500 BP (8,850–7,550 BC)	Lacustrine	Regressive shoreline from c 140–75 m.a.s.l.
Littorina Sea sensu lato	9,500 BP–present (7,550 BC–present)	Brackish	Regressive shoreline from 75–0 m.a.s.l. Most saline period 6,500–5,000 calendar years BP. Present Baltic Sea during approximately the last 2,000 years.

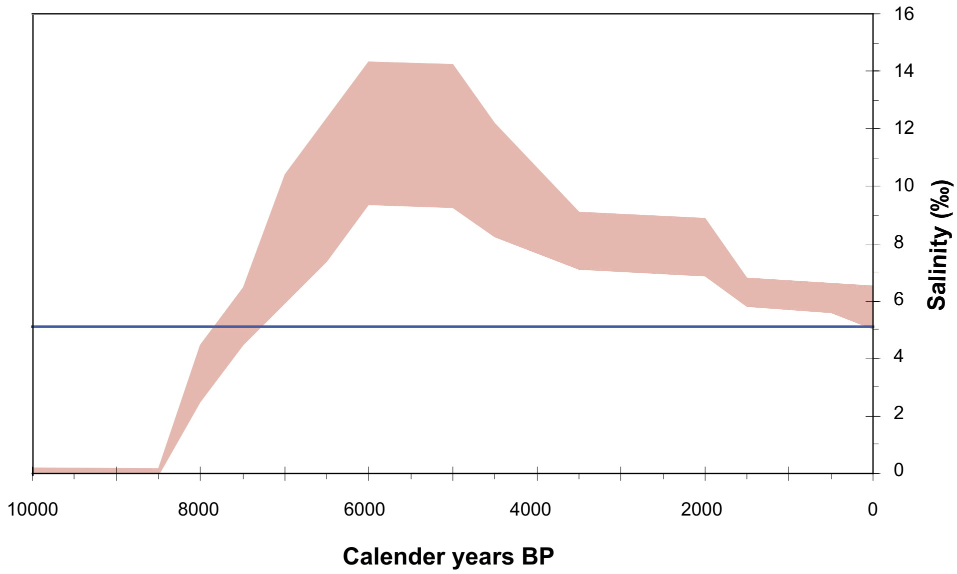


Figure 4-2. *Estimated range for the salinity of Baltic Sea water in the Forsmark area from the onset of the Littorina period until today. Maximum and minimum estimates are derived from /Westman et al. 1999/ and /Gustafsson 2004ab/. The present salinity in the area is shown as a horizontal reference line.*

The model by /Gustafsson 2004ab/ has, together with proxy records of salinity in the Baltic Proper, been used to make a rough estimation of the likely range of past salinity in the Bothnian Sea, i.e. the basin where the Forsmark area is situated (Figure 4-2). The difference in estimated salinity between the Baltic Proper and the Bothnian Sea back in time is generally low (< 1 ppt), due to the low sill in the Åland Sea. The shoreline displacement in northern Uppland during the last 10,000 years has been studied with stratigraphical methods by /e.g. Robertsson and Persson 1989, Hedenström and Risberg 2003, Risberg et al. 2005/. Påsse has made a mathematical model of the shoreline displacement /Påsse 1997, 2001/, and his curve is similar to the curve presented by /Hedenström and Risberg 2003/, based partly on site-specific data. Påsse's mathematical model, however, continues back to the deglaciation, whereas the stratigraphical investigations only cover the last 6,500 years. The curve in Figure 4-1 shows that the shoreline in Forsmark has been continuously regressive since the deglaciation. During the first c 2,000 years after the deglaciation, the regression rate in Forsmark was fast, in the order of 3.5 m/100 years. During the following c 9,000 years the regression rate has been slower, in the order of 0.9 m/100 years (Figure 4-1). The present land uplift rate in Forsmark is c 6 mm/year /Ekman 1996/.

Preliminary results from a sediment core collected from the sea floor east of Forsmark, indicate only minor influence from brackish water during the deglaciation /Risberg 2006/. Thus, the transition to the next Baltic stage, the Ancylus Lake, was characterised by continuous freshwater conditions and a regressive shore line. Global eustatic sea level rise, in combination with a reducing isostatic rebound in the southern Baltic basin, enabled marine water to enter the Baltic basin through the Danish straits, marking the onset of the Littorina Sea *sensu lato*. This stage includes an initial phase when the salinity was stable and low, the Mastogloia Sea, that lasted for approximately 1,000 years in Southern Uppland before the onset of the brackish water Littorina *sensu stricto* /Hedenström 2001/. Preliminary results from the site show that the most saline period was between 7,000 and 4,500 years ago /Risberg 2006/.

4.1.1 1,000–0 BC

The major part of the Forsmark regional model area was still covered by water until c 2,500 years ago. The first islands started to form at c 500 BC (Figure 4-3). A few scattered islands, situated close to the present location of the church of Forsmark, were the first land areas to emerge from the brackish water of the Bothnian Sea. The surface of the first islands was covered by sandy till and exposed bedrock, i.e. similar to the present situation on the islands outside Forsmark. Palaeo-ecological studies from the Florarna mire complex, situated c 30 km west of the regional model area, indicate a local humid and cold climate at approximately this time /Ingmar 1963/.

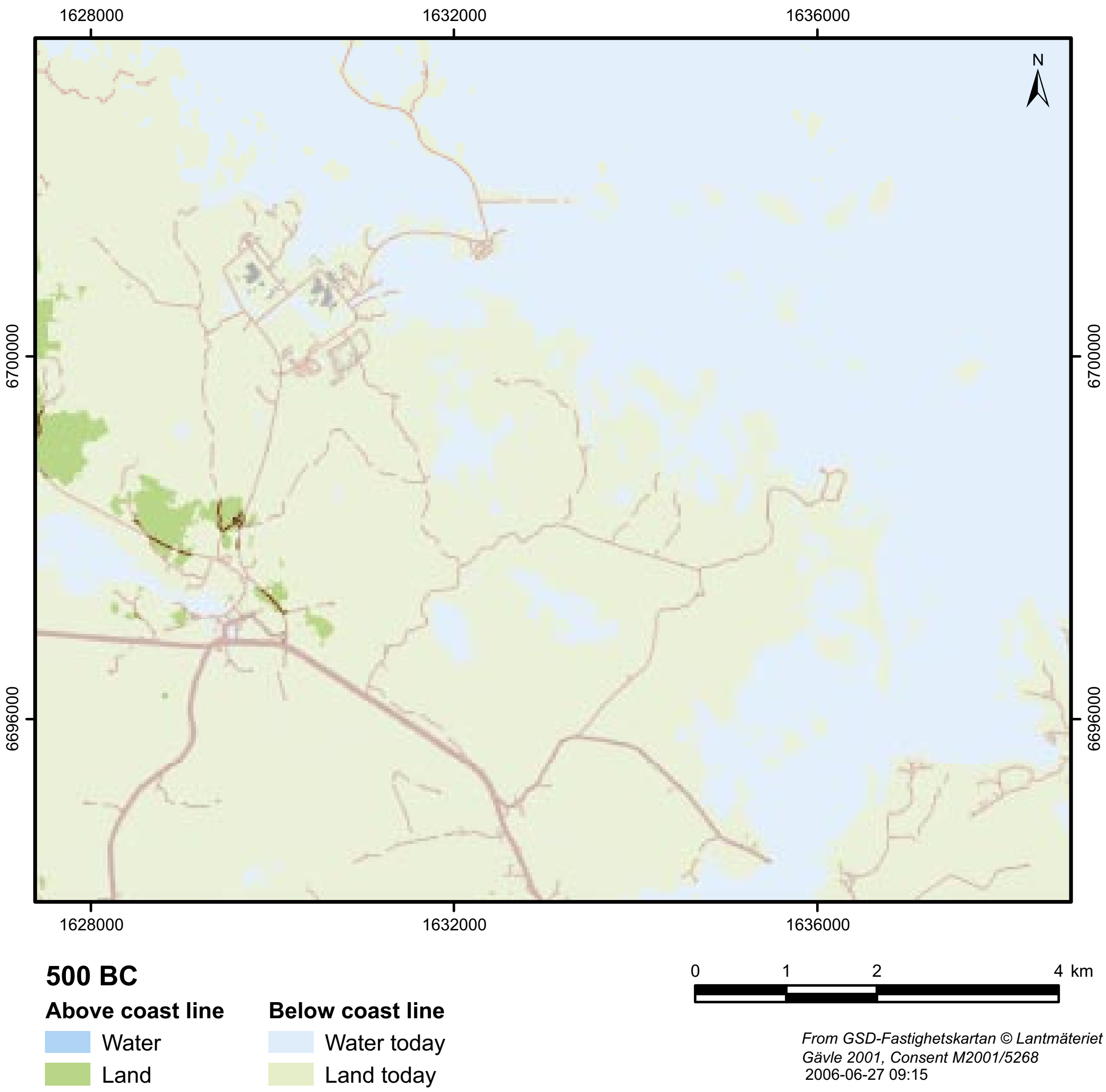


Figure 4-3. The distribution of land and sea in the Forsmark area at c 500 BC.

4.1.2 0 BC – 950 AD

At 0 BC, the Bothnian Sea still covered the Forsmark candidate area (Figure 4-4), whereas the islands in the area close to Forsmark church had expanded in size. Land-areas presently covered by peat had emerged and, at that time, these basins were newly isolated from the Bothnian Sea, and most probably a number of small and shallow freshwater lakes/ponds existed in the archipelago. At the same time, the isolation process of the first larger lake, Lake Bruksdammen, had started in the western part of the area.

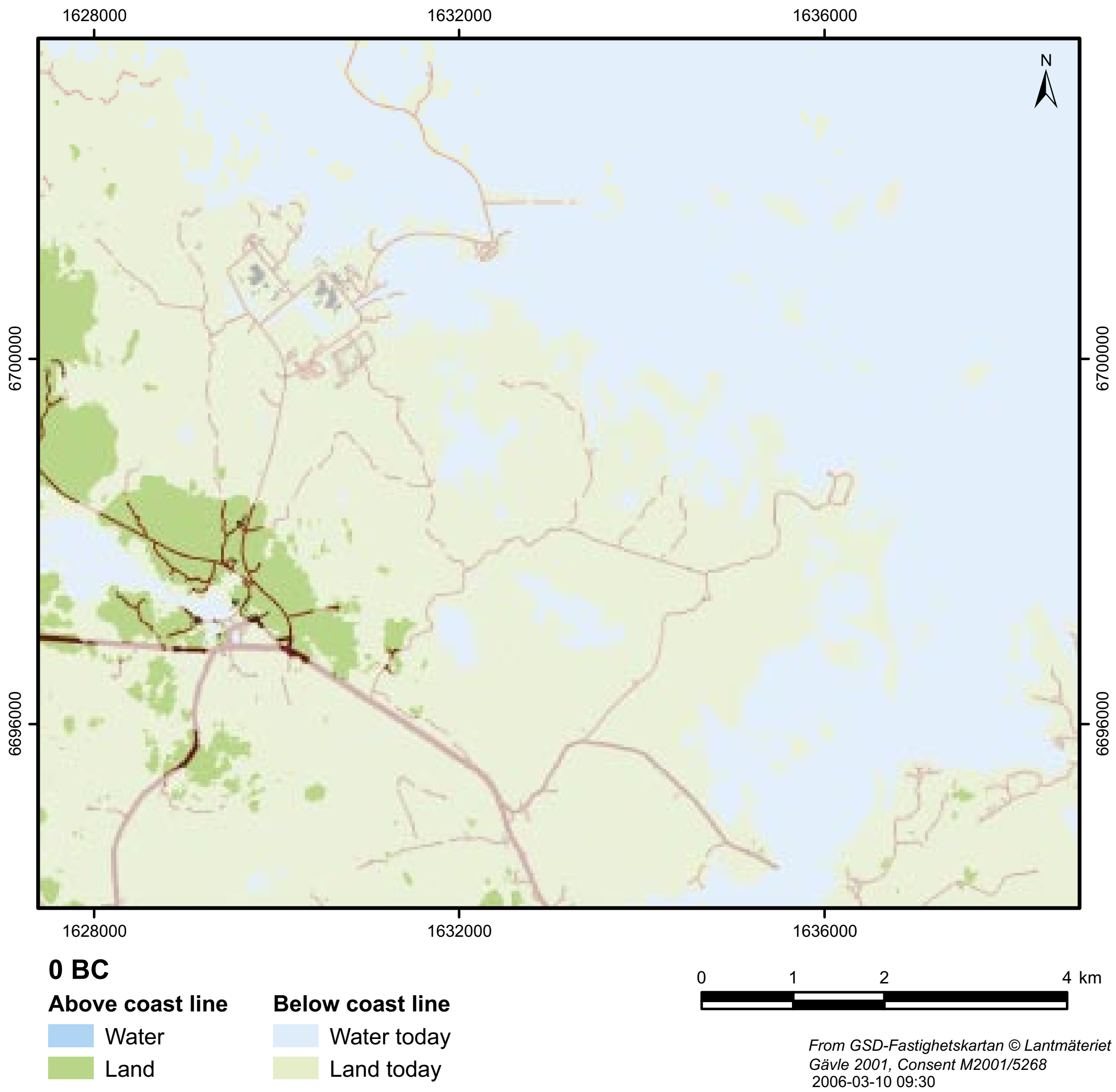


Figure 4-4. *The distribution of land and sea in the Forsmark area at c 0 AD.*

4.1.3 950–1,450 AD

At c 950 AD, the mainland had expanded further in the south-western part of the area (Figure 4-5). The isolation process of the Lake Eckarfjärden basin had been initiated, but the bay still had an open connection to the Baltic through the threshold area at the north /cf Hedenström and Risberg 2003/. The area presently occupied by the Stenrösmossen mire had emerged and a short lake phase was succeeded by infilling of reed /cf Fredriksson 2004/. The Börstilåsen esker and the most elevated areas at Storskäret constituted some small islands in the east, exposed to waves and erosion.

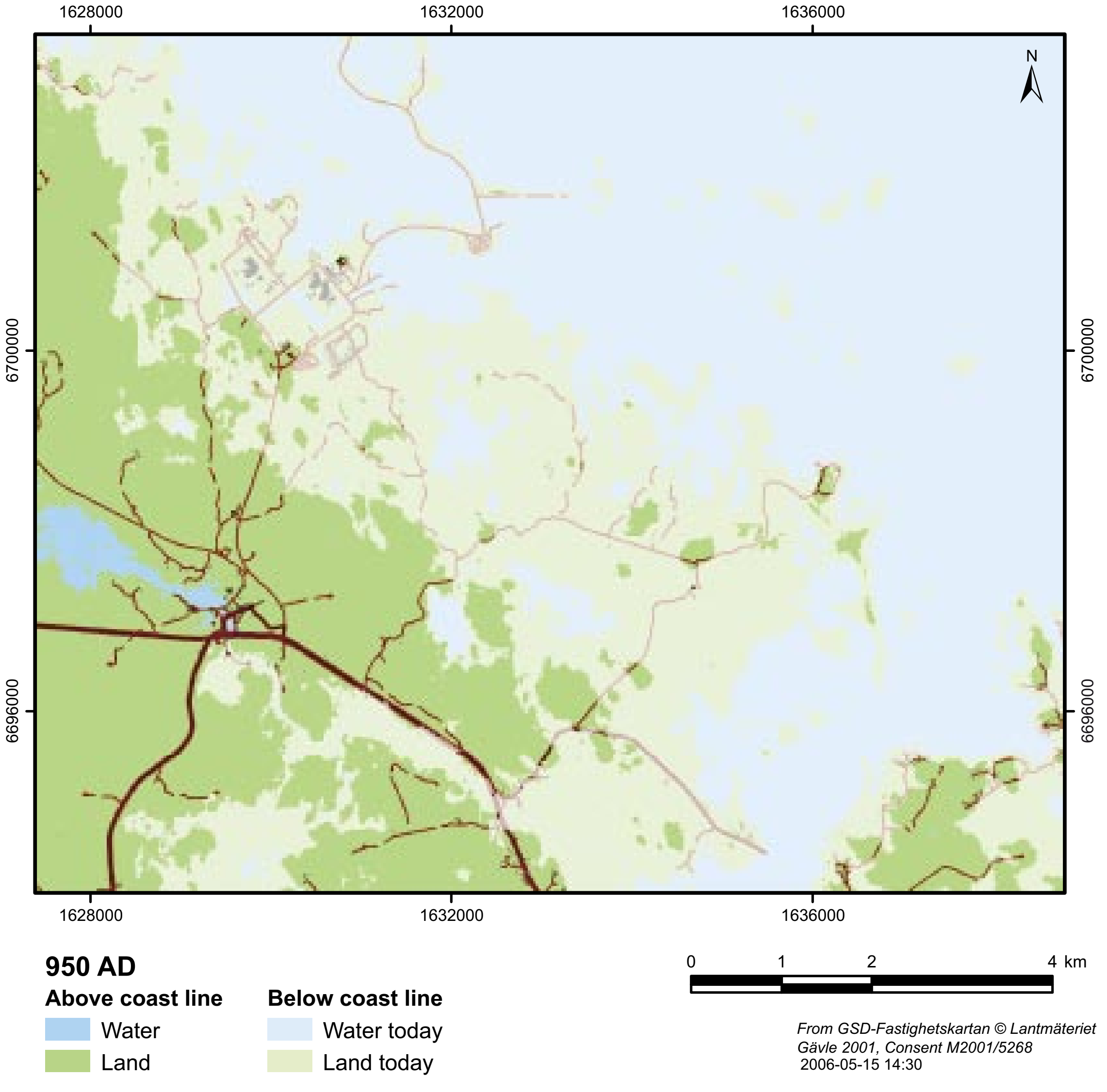


Figure 4-5. *The distribution of land and sea in the Forsmark area at c 950 AD.*

4.1.4 1,450 AD until present

At 1,450 AD, the candidate area comprised shallow, restricted waters and an exposed archipelago, see Figure 4-6. A shallow strait covered the area that today is Lake Fiskarfjärden and Lake Bolundsfjärden. A considerable part of the overall study area had emerged and several freshwater lakes were isolated from the Baltic, e.g. Eckarfjärden and Gällsboträsket. The area covered by clayey till at Storskäret formed a large island, partly protected from wave exposure by the esker Börstilåsen.

At 1,550 AD the strait mentioned above had been cut off and Lake Fiskarfjärden and Lake Bolundsfjärden were separate bays with different conditions. In contrast to the exposed situation of Bolundsfjärden, the conditions in the Fiskarfjärden bay were favourable for sediment accumulation. The small Lake Stocksjön had been isolated and was at that time considerably larger than the present lake.

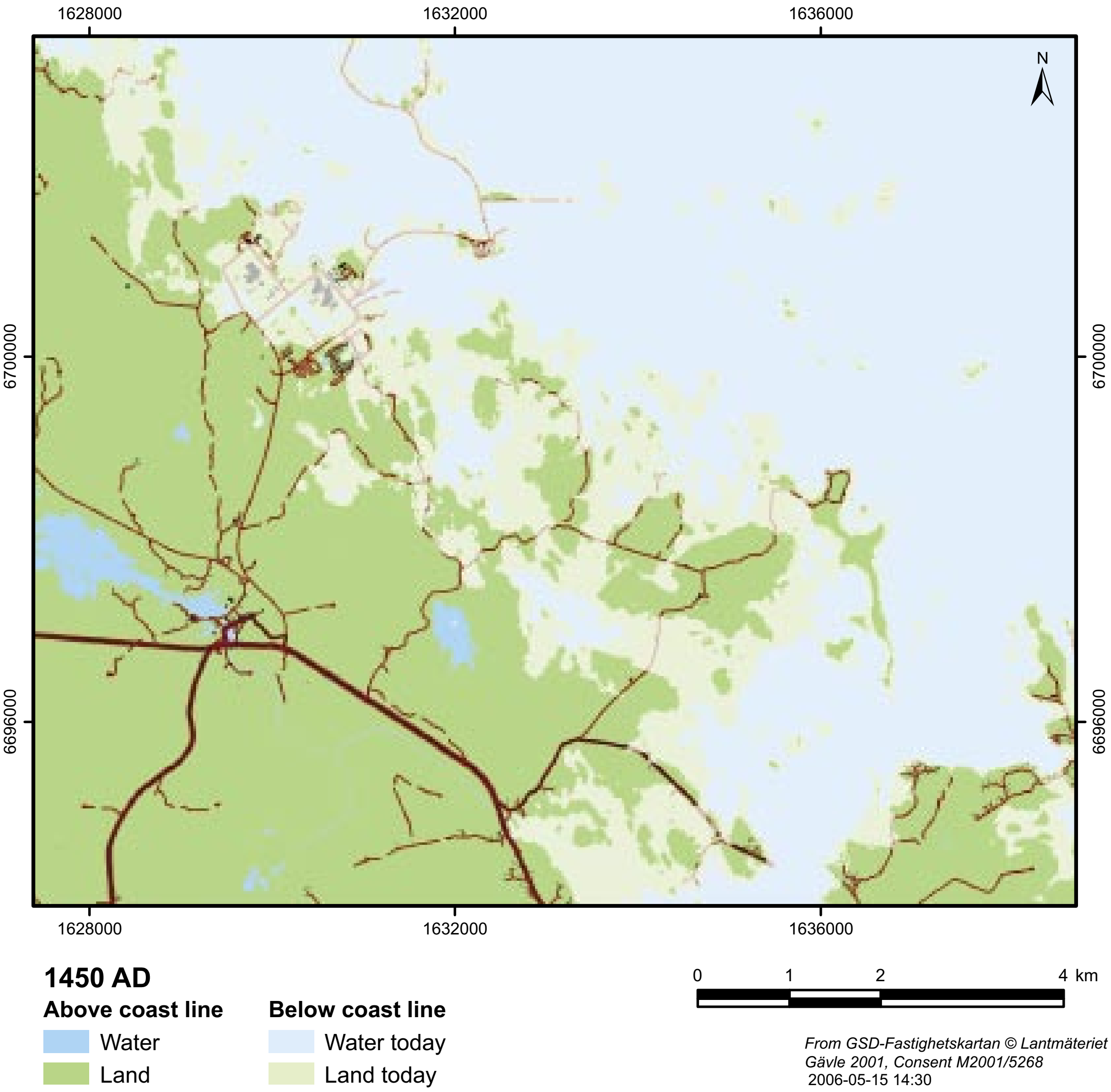


Figure 4-6. The distribution of land and sea in the Forsmark area at c 1,450 AD.

At 1,650 AD the major part of the candidate area was situated above sea level. Lake Bolundsfjärden was in contact with the Baltic through the exposed strait at Puttan. The land area north of Lake Fiskarfjärden had emerged and this transformed the previously exposed lake basin into a sheltered position, favouring sedimentation. In the western part of the area, clay and peat areas were used for cultivation and pasture. Cultivation was predominant on clay areas, whereas pasture dominated on peat, sand and till areas.

The increase in land areas continued, and by 1,735 AD the shores of the shallowest bays at the eastern side of Bolundsfjärden were utilized as pastures. The clayey till at Storskäret was used partly for cultivation and partly for pasture.

At 1,850 AD the Börstilåsen esker had established contact with the main land (Storskäret). The small lake Fräkengropen was isolated. Cultivation and pasture continued on clay and peat areas. The cultivated areas at Storskäret had expanded and included also areas formerly used for pasture (Figure 4-7).

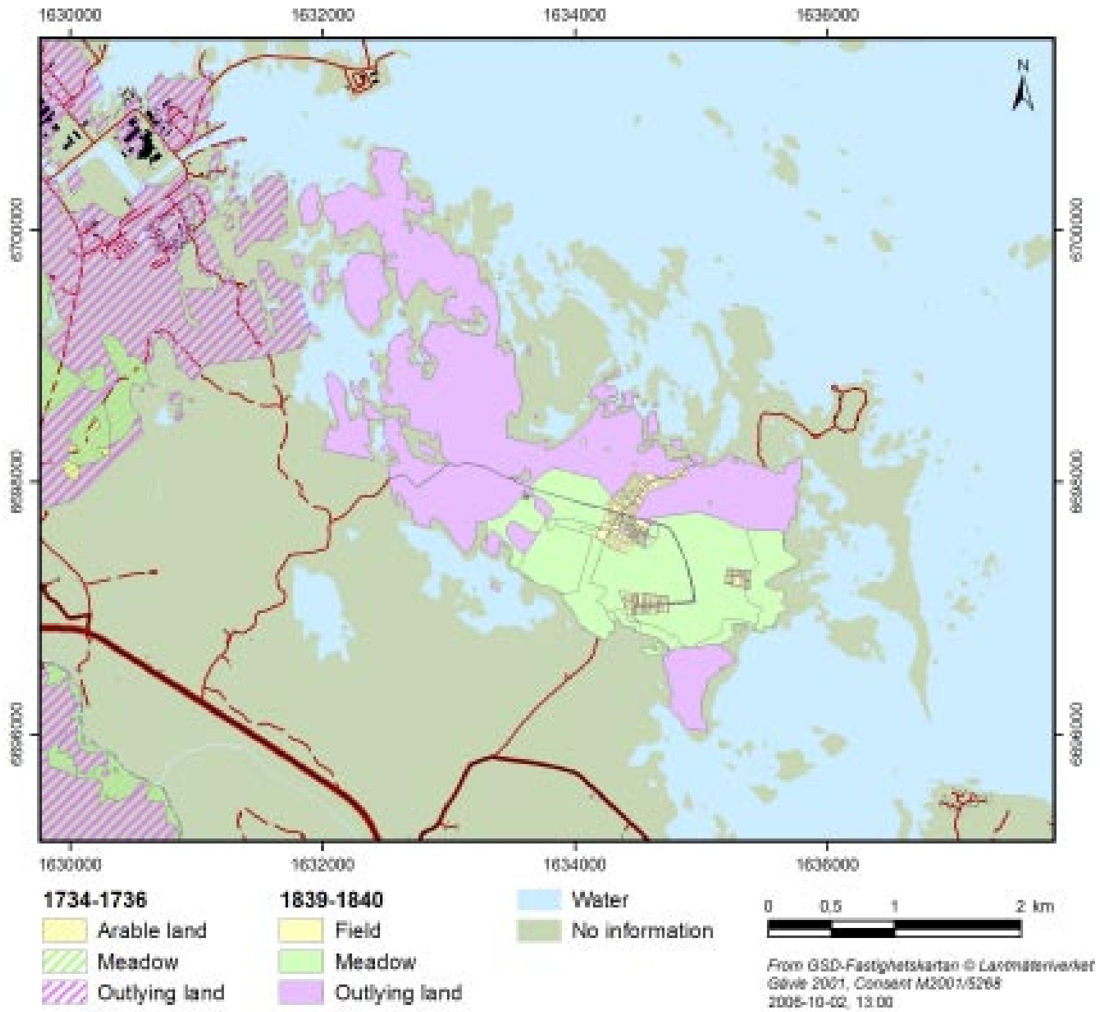


Figure 4-7. *Distribution of agricultural land based on historical maps, ca 1,735 and 1,840 AD. The map is a combination of two non-overlapping maps for the different stages. Thus, the eastern part of the map gives no information on land use during the earlier stage, and the western part of the map gives no information on the latter stage.*

4.1.5 Present to 2,500 AD

A number of lakes in the area, e.g. Lake Bolundsfjärden, Lake Norra Bassängen, Lake Puttan, Lake Fiskarfjärden and Lake Lillfjärden, are currently isolated from the Baltic Sea. The human impact in the area today is dominated by the construction of the nuclear power plants and the circulation of their cooling water. For example, a very deep channel has been created and the water circulation has been considerably changed by construction of new islands and the Biotest Basin. Most of the area is forested and includes a fairly high rate of younger and older clear-cuts /Lindborg 2005/. Active cultivation and pasturage occur at Storskäret only.

During the next 500 years, the shallowing process will continue and new land areas will be created, predominantly in the northern part of the area (Figure 4-8). At 2,400 AD, Lake Tixelfjärden will be isolated. The inner parts of Kallrigafjärden will also become land. At 2,500 AD, the channel for cooling water will become isolated into a deep freshwater lake. Lake Stocksjön will be totally filled with sediment and transformed into a mire, Table 4-2. The land areas will expand around the sea bay west of Biotest basin, but the basin will still be a part of the Baltic Sea.

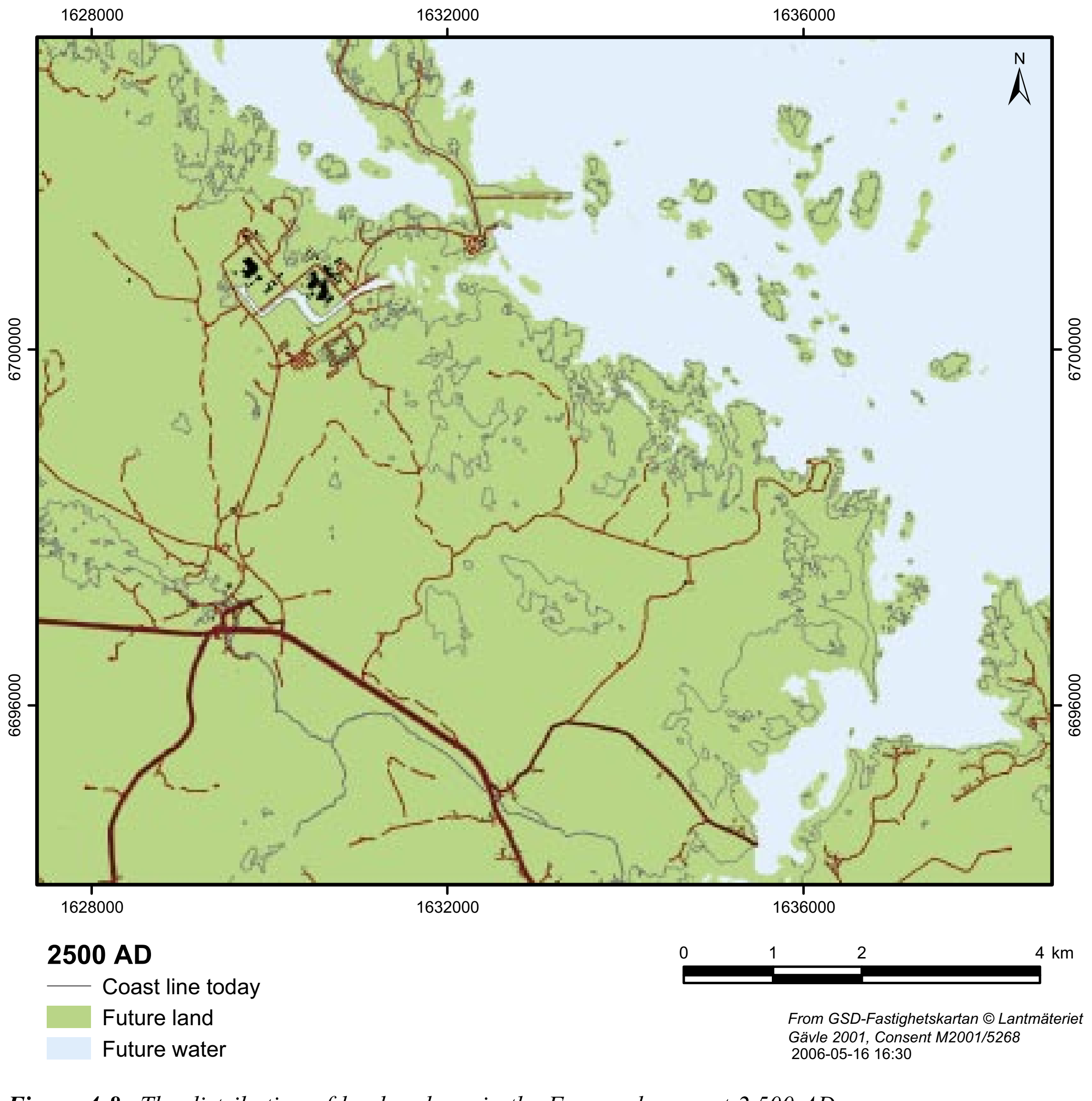


Figure 4-8. The distribution of land and sea in the Forsmark area at 2,500 AD.

Table 4-2. Dates when present lakes in the Forsmark area will have been completely transformed into mire (based on the sedimentation model in /Brydsten 2004/). The location of the larger lakes is shown on the detailed map in Figure 2-1, whereas the smaller lakes (denoted by an asterisk in the table) are situated within the regional model area, but are not shown on the map.

Lake	Year (AD) of complete transformation
Simpviken*	2,200
Kungsträsket*	2,200
Gunnarsbo-Lillfjärden, north part	2,300
Märrbadet*	2,300
Stocksjön	2,400
Gällsboträsket	2,500
Graven*	2,500
Tallsundet*	2,600
Gunnarsbo-Lillfjärden, south part	2,900
Gunnarsboträsket	2,900
Vambörsfjärden*	3,000
Puttan	3,200
Norra bassängen	3,400
Lillfjärden	3,700
Labboträsket	3,700
Bredviken	3,900
Fiskarfjärden	4,700
Eckarfjärden	5,400
Bolundsfjärden	5,600

The ongoing change in the distribution of land and sea will continue with the emergence of new land areas, forming new and larger islands. The distribution of minerogenic Quaternary deposits will be affected by soil-forming processes at the surface, but no major redistribution will take place after the area has been isolated from the Baltic. The most notable change will be observed in the distribution of organic soils, for example the sedimentation of gyttja in the lakes and the formation of peat in the wetlands (cf the lake sedimentation model /Brydsten 2004/).

4.1.6 2,500 AD until permafrost

The coastal period, over which the candidate area is situated at the coast, will continue until about 4,000 to 5,000 AD. A semi-enclosed archipelago northeast of the area is expected from approximately 3,000 to 5,000 AD. At 5,000 AD most straits in this archipelago are expected to become closed and the lakes so formed will become isolated from the sea. The transformation of the landscape from 5,000 AD is dominated by a general regression of the sea and the current lakes in Forsmark will all be filled in and transformed into mires by 5,600 AD, see Table 4-2. These mires are later assumed to be transformed into forests or, if they are managed as such by humans, to agricultural land. In the Landscape model (cf Chapter 6), a cautious approach is adopted in which a transformation to agricultural land is assumed,unless factors such as boulder density imply that this would be very difficult. In the period to 7,000 AD, the coast extends along the island of Gräsö, the coastline is about 7 km from the central Forsmark area and the bay gradually shrinks to form two large and 20–30 m deep lakes. Most of the new lakes are expected to quite quickly be transformed into mires. Only a few deeper lakes are projected to exist for more than 1,000 years. However, the large lakes near Gräsö are expected to last for a period of around 10,000 years. The salinity of the sea is expected to decrease to 3–4 ppt at 6,000 AD due to the shallower sills between Ålands hav and the Baltic Proper /Gustafsson 2004b/. This means that an ecosystem similar to the Northern Quark, with a low abundance of marine species, will develop. Around 10,000 AD, freshwater is predicted for the entire Bothnian Sea. Öregrundgrepen will consist of freshwater anyhow due to the shore-level displacement. The terrestrial period of the Forsmark area is assumed to end at 10,000AD, where a permafrost period starts (see below).

4.2 Periglacial period (permafrost)

In the SR-Can main scenario /SKB 2006a/, covering a time span of 121,000 years after repository closure, permafrost conditions prevail at Forsmark for a total duration of 41,000 years (34% of the time). Temperate- and glacial conditions prevail for 31,000 years (26%) and 30,000 years (24%) respectively, whereas the site is submerged for 19,000 years (16% of the time) (Figure 4-9).

The first periglacial period, with shallow permafrost, occurs after approximately 8,000 years (10,000 AD) (Figure 4-9). After that, temperate conditions and permafrost conditions will alternate until the first glacial period occurs at around 50,000 AD. During this interval, the periglacial periods get longer and the permafrost grows progressively deeper.

In the SR-Can greenhouse scenario, the present warm interglacial climate will prevail for about 60,000 years after repository closure before the first period of permafrost conditions occurs /SKB 2006c/. After that, the same alterations between temperate and permafrost conditions follow as after the first permafrost period in the base case (Figure 4-9). Another possibility with a generally warming climate, due to an increased greenhouse effect, is that the thermohaline circulation in the North Atlantic is affected, so that less heat is transported towards Fennoscandia by the North Atlantic Drift. This would lead to a regional cooling over Fennoscandia, a cooling that would occur earlier than the cooling described in the base variant of the main scenario /SKB 2006c/. In such a case, permafrost conditions at Forsmark would occur earlier than at 10,000AD.

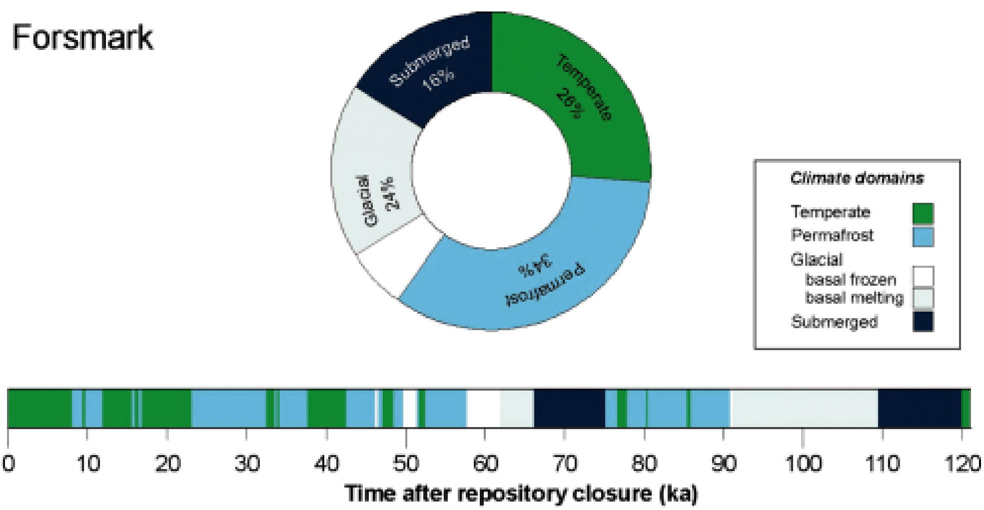


Figure 4-9. *Duration of climate domains at Forsmark, expressed as percentage of the total time for the base variant of the SR-Can main scenario. The bars below the pie charts show the development of climate-related conditions for the base variant as a time series of climate domains and submerged periods. From /SKB 2006c/.*

The permafrost periods are characterized by a tundra ecosystem. The tundra is devoid of forests. The precipitation is often less than 200 mm/year due to low evaporation transporting water through the atmosphere. The low evaporation makes the climate humid and surplus water is unable to seep into the ground because of the permafrost. This would lead to extensive swamps, but the amount of peat formed would be negligible because plant productivity is low. Even if there is a snow cover of 50 cm during winter, raised parts are blown free of snow where intensive erosion occurs by the blowing ice crystals. The vegetation consists of herbs and shrubs, at raised dryer places lichens, whereas on wet ground mosses dominate. The vegetation period is short and the species present are those adapted to this climate, i.e. they flower and set buds in different years. Most of the plants develop thick roots, which serve as storage and the plants can live up to 200 years. No plants produce berries for their dispersal of seeds /French 1996/.

The major part of the vertebrate fauna of the tundra migrates south during winter. The birds, which are abundant during summer, migrate long distance to subtropical areas. During the summer they thrive on the enormous amount of mosquitos. Rodents, e.g. lemmings, do not migrate and spend most of their life under the isolating snow-cover. Specialised mammals like reindeer can utilize lichens in snow-free areas in winter or they migrate into forested land.

Even on gentle slopes, the soil moves downhill with the peat cover on top, i.e. solifluction. Other processes are upfreezing of stones causing patterned ground, such as tundra-polygons. Thus, there are several processes disturbing the soil and also exposing it to erosion. When the upper soil thaws during summer, large quantities of water are available.

Taliks, i.e. unfrozen windows in the permafrost region beneath lakes and rivers, are potentially places that animals and humans can settle nearby. The taliks can be a result of discharge of warmer groundwater that could include some water coming from a repository. However, even if taliks can be a potential waterhole, the low productivity in the permafrost region requires a large foraging area. During summer, surface water will be abundant in the landscape, which means that taliks will not be the only waterholes.

4.3 Glacial period

In the SR-Can main scenario, the first major ice advance that covers Forsmark occurs after 58,000 years (Figure 4-9). It is preceded by two minor ice advances over the site. During these glacial periods, the site will be covered by an ice sheet. Periods when the site is submerged under the sea follows after the two major periods of ice coverage (Figure 4-9). During the glacial periods, contact between biosphere and geosphere will occur only during the very short periods when the ice sheet is thin over the site. At these times, elevated parts can protrude above the ice surface where lichens or occasional herbs can occur. The productivity will, however, be low and due to their elevated positions, there will be no contact with groundwater in the protruding areas.

On the ice surfaces, microbes, algae and some insects can exist. At the ice margin, a productive aquatic community can occur. This can sustain a rich fish population, which can be exploited by the animals living on the ice (e.g. polar bears, birds) and by humans. The populations of vertebrates migrate over a large area to avoid winter climate or to exploit the resources to a maximum extent. In most cases, the human population would probably be occasional, due to the hostile environment and the variable ice configuration. It is possible that a population can exist for longer periods at ice-free spots along the coast and live on fish. However, at such coastal locations the water-turnover is most likely to be rapid (otherwise the water would be frozen) which would give a larger dilution-rate. During periods of glacial domain, no long-term accumulation of contaminants can occur in sediments or soils, due to rapid turnover of these potential reservoirs.

Between the two major glacial phases, during a period around 70,000–90,000 years from present, Forsmark is in the SR-Can main scenario subjected to interstadial ice-free conditions. This period is dominated by periglacial conditions with permafrost (Figure 4-9).

4.4 Greenhouse variant

A greenhouse variant is included in the description of the future climate. There are two main reasons for doing this; 1) modelling studies of the climate response to increased greenhouse gas emissions, mainly CO_2, indicate that global temperatures will increase in the future under such scenarios /e.g. IPCC 2001/, and 2) climate cycles are believed be driven by changes in insolation. The coming 100,000 year period is initially characterised by exceptionally small amplitudes of insolation variations /Berger 1978/, possibly making the present interglacial exceptionally long. /Berger and Loutre 2002/ and others suggest it may not end until ~ 50,000 years from now, even in the absence of significant human-induced greenhouse-gas, warming.

In the greenhouse variant, it is assumed that the temperate domain will prevail for another 50,000 years until the first, restricted, ice advance takes place. After that, the first 70,000 years of the reference evolution is assumed to follow. The first major ice advance will, therefore, occur after ~ 90,000 years. This scenario is in line with results simulated for two greenhouse-warming cases within the BIOCLIM project /BIOCLIM 2003/.

Noting the uncertainties and assumptions used in the climate modelling undertaken in the BIOCLIM and SWECLIM projects /BIOCLIM 2003, Rummukainen 2003/, and the limited range of greenhouse-gas emission scenarios used, the results of these climate modelling studies suggest that the climate in the Forsmark region will experience increased summer temperatures of 2–3 ºC within the initial long period of temperate conditions. The climate model results also suggest increased winter temperatures in these regions. Precipitation is also predicted to increase, especially in summer /SKB 2006c/.

Climate change or variability due to greenhouse gas-induced warming over the coming 1,000 years is also expected to influence important parameters in the biosphere such as the hydrological cycle, sea level, and salinity of the Baltic Sea. In respect of the hydrological cycle, increased precipitation could lead to higher runoff, if it was not balanced by increased evapotranspiration due to higher temperatures. The projected changes of sea level would reduce, negate or reverse the shore-level displacement and thus maintain the sites and surface ecosystems close to the sea. Thus, the water turnover rates would be dominated by the sea for the ecosystems closest to the repository. The salinity of the sea is dependent on the runoff to the Baltic Sea /Gustafsson 2004/, and might decrease if the runoff increases.

Due to higher winter temperatures in a greenhouse-warming scenario, the vegetation period would increase and thus give higher productivity and a shift in species composition. However, this would have a minor impact on the safety assessment, as is shown by considering the impact the north-south gradient of climate in Sweden has on vegetation today.

5 Ecosystems, biosphere objects and site-generic parameters

The biosphere in Forsmark is described using an ecosystem approach, where differences in important ecosystem functions, such as accumulation of organic matter or presence or absence of functional groups, define the ecosystem type and its spatial extent. Six ecosystem types, commonly found in the Forsmark area, are described in the following sections; sea, lake, running water, mire, agriculture land and forest. In addition, one section describes a well, which is a potential transport route for radionuclides to humans. The following descriptions of the six ecosystems and the well are the basis for delimiting and for the parameterisation of Biosphere Objects (further described in Chapter 6). Biosphere Objects are specific areas in the landscape potentially exposed to radionuclide releases and are the smallest unit in the modelling of radionuclide transport and accumulation in the landscape (radionuclide transport modelling is described in Chapter 8 and in /Avila 2006/).

The description of each ecosystem type comprises the most important fluxes of matter and water, extracted from the descriptive ecosystem models in /Lindborg 2005/. The descriptive ecosystem models relate to the pools and fluxes of carbon, but carbon can also be used as a proxy for organic matter and energy /Chapin et al. 2002/. This approach may be useful to describe the behaviour of a wide range of bioavailable radionuclides assimilating into living tissue. The development or succession of the different ecosystems is also described in terms of transitions to other ecosystems over longer temporal scales. This description is followed by a presentation of the conceptual models used to represent the transfer and accumulation of radionuclides (further described in /Avila 2006/). These conceptual models show how the different parameters characterising the systems are related and used to describe transfer and accumulation. There are two types of parameters presented in this report; the parameters characterising a specific type of ecosystem within the site, termed site-generic parameters (described in this chapter), and parameters that are regarded as unique for the identified biosphere object, termed object-specific parameters, such as area and water volume (described in Chapter 6). The site-generic parameters in the models have been estimated using site-specific data or models in most cases, but when such were lacking, data were taken from other sources from as similar areas as possible. Site-generic parameters describing biota, which is presented in this chapter, is not found in the conceptual models presented below, but are used in estimating potential effects on non-human biota from exposure to radionuclides (decribed in Section 8.2.3). The premises for estimation of each parameter are described in this chapter, and the parameter values are presented in Appendix 1, along with statistical descriptions, such as means, medians, maximum and minimum values, and standard deviation of the value. For some data, e.g. modelled or literature data, no statistical descriptions are available. In the section with the parameter descriptions, all reports initiated by SKB have been denoted with an asterisk (*).

5.1 Sea

The marine ecosystem in Forsmark has a varied bathymetry, with a few enclosed bays clearly affected by fresh water effluence, a shallow water, exposed archipelago and open sea areas heavily exposed to currents and wave action. As a result, contaminants discharged into the marine environment from the adjacent terrestrial and limnic environments will have a different fate depending on where they enter the marine system.

5.1.1 Major flows of matter

In basin Stånggrundsfjärden and in the Safe area (see map in Figure 3-4), the transport of organic carbon is dominated by the transport generated by water exchange between the basins and the Baltic Sea. The water exchange is large and the overall carbon retention time is calculated to be only 2–5 days in these basins /Lindborg 2005/. In the secluded basin Asphällsfjärden, on the other hand, the inflow of carbon is dominated (c 75%) by macrophyte primary production. Carbon is transported from the basin mainly by water exchange and only to a small extent by sedimentation or respiration. Carbon retention time in basin Asphällsfjärden is estimated to be c 23 years.

The largest fluxes of both water and carbon in the Forsmark area are driven by the exchange of water between the marine basins and between the basins and the open Baltic Sea /Lindborg 2005/. The estimated carbon fluxes from terrestrial areas to the marine basins, based on the measured concentrations of Total Organic Carbon (TOC) in the streams, are proportional to the water fluxes. A large fraction of the total carbon pool in the marine ecosystem is the storage of organic carbon in soil and sediment. A schematic view of the carbon budget set up for Stånggrundsfjärden /Lindborg 2005/ is shown in Figure 5-1.

Water is assumed to have no net annual storage. The highest fluxes are found in the coastal area. The runoff from the watersheds contributes about 10% of the total water flow into the first marine basin, Asphällsfjärden, and less than 2‰ into the basin Stånggrundsfjärden /Lindborg 2005/. Thus, any inflow of matter from the terrestrial and limnic systems to the marine basins will be highly diluted due to the large flows and fast water turnover in the coastal area.

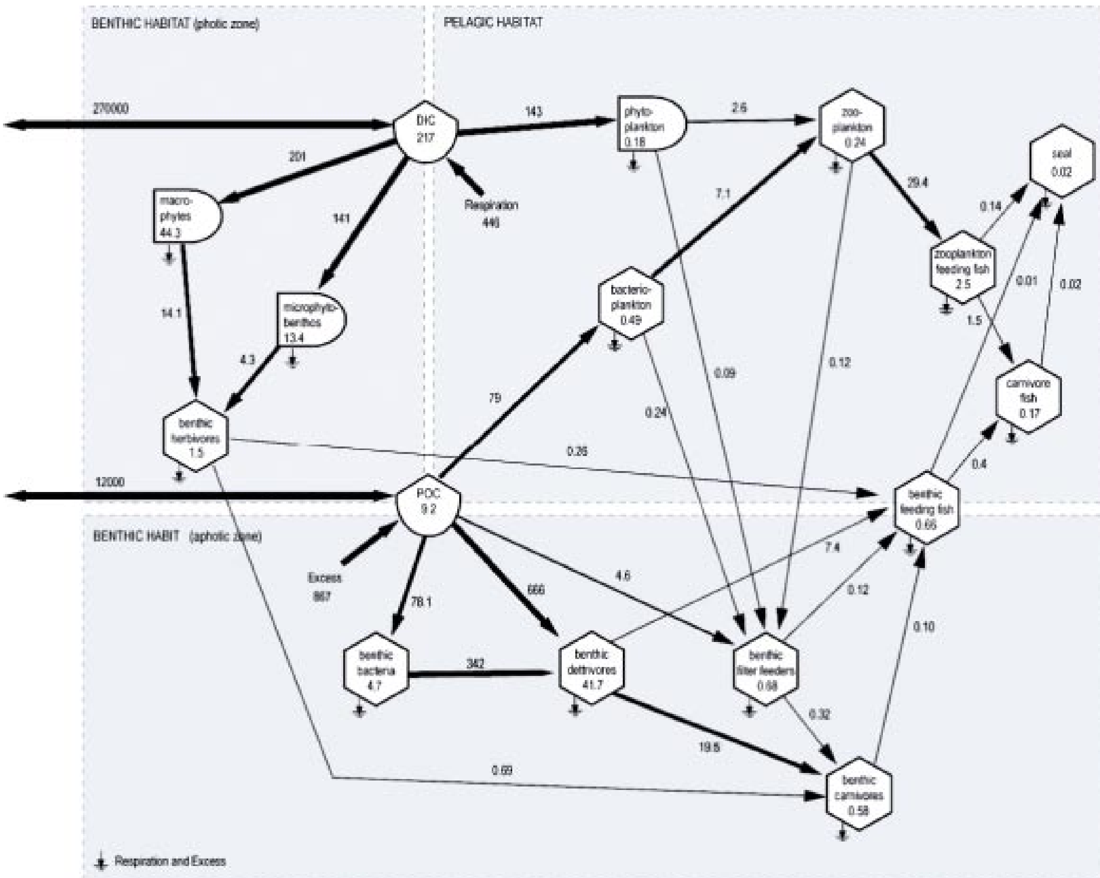


Figure 5-1. Carbon flow model for basin Stånggrundsfjärden in Forsmark. Biomass (10^6 gC) and flow of carbon between the functional groups, e.g. due to consumption (units of 10^6 gC y^{-1}) /Lindborg 2005/.

As a result of the difference in residence time between water and carbon, contaminants easily dissolved in water and with a low affinity to carbon will quickly be transported out of the area, whereas contaminants sorbing to or incorporated in organic matter will accumulate in the area for longer periods. The estimated residence time for carbon roughly sets limits for possible periods for the accumulation of radionuclides or other pollutants in the area. In bioavailable matter (organic matter and water), the accumulation can be, at most, some 10,000 years in this area.

5.1.2 Development over time

Shoreline displacement

Due to the land uplift process, the sea will continuously become shallower, provided that the isostatic recovery continues to outpace global sea-level rise. Bays will be formed in the coastal areas, and these bays will eventually be cut off from the sea and form new lakes (see Sections 4.1 and 5.2.2). The change over time in the emergence of land is most rapid at the beginning of the period from present-day until 7,000 AD. Half the water area in Öregrundsgrepen will become land within the next 2,000 years and, from about 4,500 AD, the sea in the area consists of a long and narrow bay /Brydsten 1999a/.

Sedimentation

Due to the positive shoreline displacement, sedimentation conditions have fluctuated and will continue to fluctuate over time. Areas with accumulation bottoms can switch to erosion bottoms and vice versa. /Brydsten 1999b/ has evaluated previous, present and future sedimentation conditions using a mathematical model that simulates the resuspension of fine particles caused by wave movement. The results of the simulation show that sedimentation conditions may change quickly, but normally a clear pattern is evident. Two opposing mechanisms determine the distribution of accumulation and erosion bottoms; the shoaling and wave energy filter effects of the coastal areas:

1. The shoaling effect is caused by the fact that the orbital movement of water in a wave decreases exponentially with the depth beneath the water surface. In other words, the shallower the water, the higher the horizontal orbital speed at the bottom and thus the greater the potential for resuspension. The shoaling effect alone causes gradually increasing extension of erosion bottoms as the positive shoreline displacement progresses.
2. The wave energy filter effect is determined both by the density of the islands in coastal areas and water depths in those areas. Waves with high energy generated in open sea breake on the island shores or loose energy when they pass shallow areas without breaking. The process results in high wave energies being filtered out whereas low wave energies are able to pass. Over time, the positive shoreline displacement results in increased density of islands and shallow areas becoming even shallower. Thus, the filter effect increases, which results in an increased extension of accumulation bottoms.

A third mechanism, the wave breaking effect, occurs only at bottoms where morphometry results in breaking waves when the depth of water is less than approximately 5 meters. The water movements occurring under a breaking wave are generally much higher than wave-induced near bottom horizontal orbital movements under non-breaking waves. The extent of accumulation bottoms may therefore decrease again at exposed, near-shore shallow bottoms, because the wave breaking effect dominates over the filter effect.

The predicted shift between the two types of bottoms over time for an outer and a near-shore model area in Forsmark is shown in Figure 5-2 below, for the period 5,000 BC to 3,000 AD /Brydsten 1999b/. Water movements will change drastically during the process of shoreline displacement, which leads to a change in sedimentation rates, i.e. water exchange slows down and sedimentation increases. Large parts of the present near-shore coastal area in Forsmark

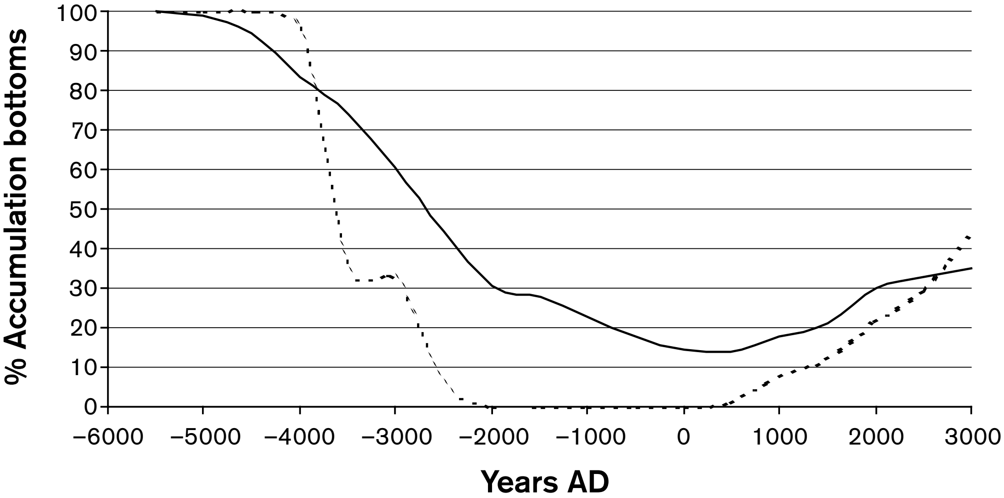


Figure 5-2. The change in % accumulation bottom over time for an outer (solid line) and a local (dotted line) model area in Forsmark /Brydsten 1999b/.

have recently shifted from erosion bottoms to accumulation bottoms, and this trend will continue until the whole area of Öregrundsgrepen becomes land /Brydsten 1999b/. The modelling of the sedimentation processes is described in detail in /Brydsten 2006b/.

Salinity

The vertical structure of the salinity in the future Baltic Sea is strongly dependent on saline-water inflow, freshwater inflow and turbulent mixing. A change in any of these factors can have a large impact on the vertical stratification. For example, with an increased inflow of ocean water, the halocline depth could decrease, forcing the Baltic Sea towards conditions similar to the Skagerrak or the Hudson Bay, with a thin brackish layer over a deeper saline layer. At the other extreme, with much reduced inflows, the Baltic Sea could become a lake with negligible salinity. The sensitivity of the Baltic Sea surface salinity to changes in freshwater inflow, wind and sea level fluctuations in the Kattegatt are shown in Figure 5-3. A 20% change in freshwater inflow has a strong impact on the surface salinity.

/Westman et al. 1999/ have developed a model to describe the importance of changes in the cross-section areas of the Öresund strait and the Darss sill compared with direct climatic influences (temperature and net freshwater input). A steady-state model for the salt exchange between the Baltic Sea and Kattegat /Gustafsson 1997/ has been used to study past changes of salinity during the Holocene. The model will be used to study future development of the salinity of Baltic Sea.

As described above, /Brydsten 1999a/ has modelled the shoreline displacement of Öregrundsgrepen. The modelling shows that from about 4,500 AD the sea in the area consists of a long and narrow bay (see Figure 6-6C). During this period it is likely that the sea in the model area has pronounced estuarine environment, i.e. low salinity, a sharp developed halocline, an estuarine water circulation and a sedimentation that is controlled by this water circulation.

Coastal ecosystem

The shoreline displacement will gradually shrink the coastal ecosystem in Öregrundsgrepen until the last bay is isolated from the sea at around 7,700 AD /Brydsten 1999a/. Future changes in properties of the coastal ecosystem during the land-rise process have been assessed by /Kumblad 2001/. The total biomass will decrease by 20% from year 2,000 AD to 4,000 AD

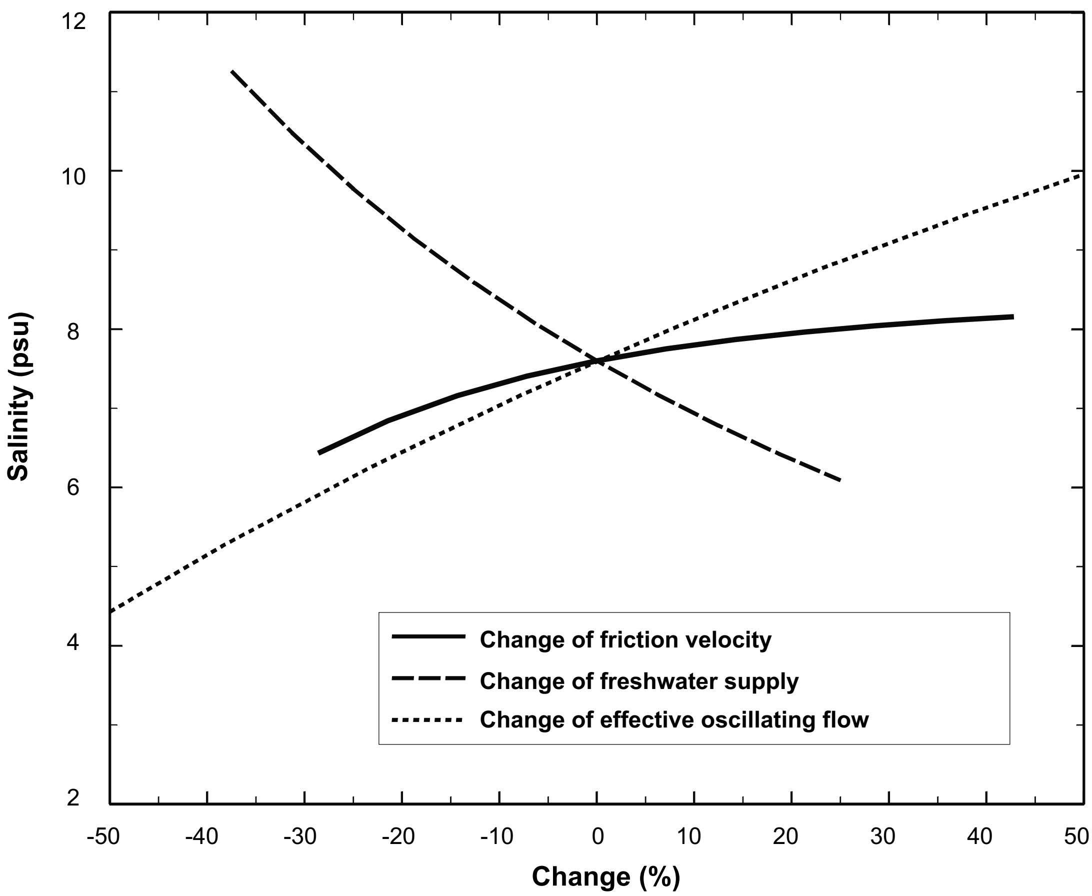


Figure 5-3. *Model results for the response of Baltic Sea salinity to changes in wind stress (solid line), freshwater input (dashed line) and effective flow oscillations (dotted line) /Westman et al. 1999/.*

due to decreased water surface in the future area. Since the water at 4,000 AD will be shallower than at present, the area of the photic zone will increase, even though the total water area decreases, which will result in increased dominance of benthic plants and grazers at the cost of benthic consumers. The biomass of benthophytes and grazers increases almost 50% and 25% respectively, whereas benthos decreases almost 80% /Kumblad 2001/. However, the species composition is assumed to be the same as today.

According to /Kumblad 2001/, the turnover of matter in the model area will change. The total primary production increases by almost 10% due to higher benthophyte biomass, and the decomposition is reduced by approximately 80% as a consequence of decreased biomass of benthos. This may result in a larger export of excess production from the area at 4,000 AD compared with 2,000 AD, but probably also in an increased sedimentation of organic matter due to the slower water exchange rate that is expected in the future ecosystem. Overall, this means a higher retention of organic matter in the coastal area at 4,000 AD compared with today, which in turn means that any radionuclides associated with organic matter will be buried in the sediment to a larger extent than at present.

5.1.3 Simplified radionuclide model

A schematic view of the numerical model that describes the transport and accumulation of radionuclides in marine basins is presented in Figure 5-4. The figure shows the different parameters and how these are related in order to describe fluxes of radionuclides. The site-generic parameters are presented in further detail below, whereas object-specific parameters are treated in Chapter 6.

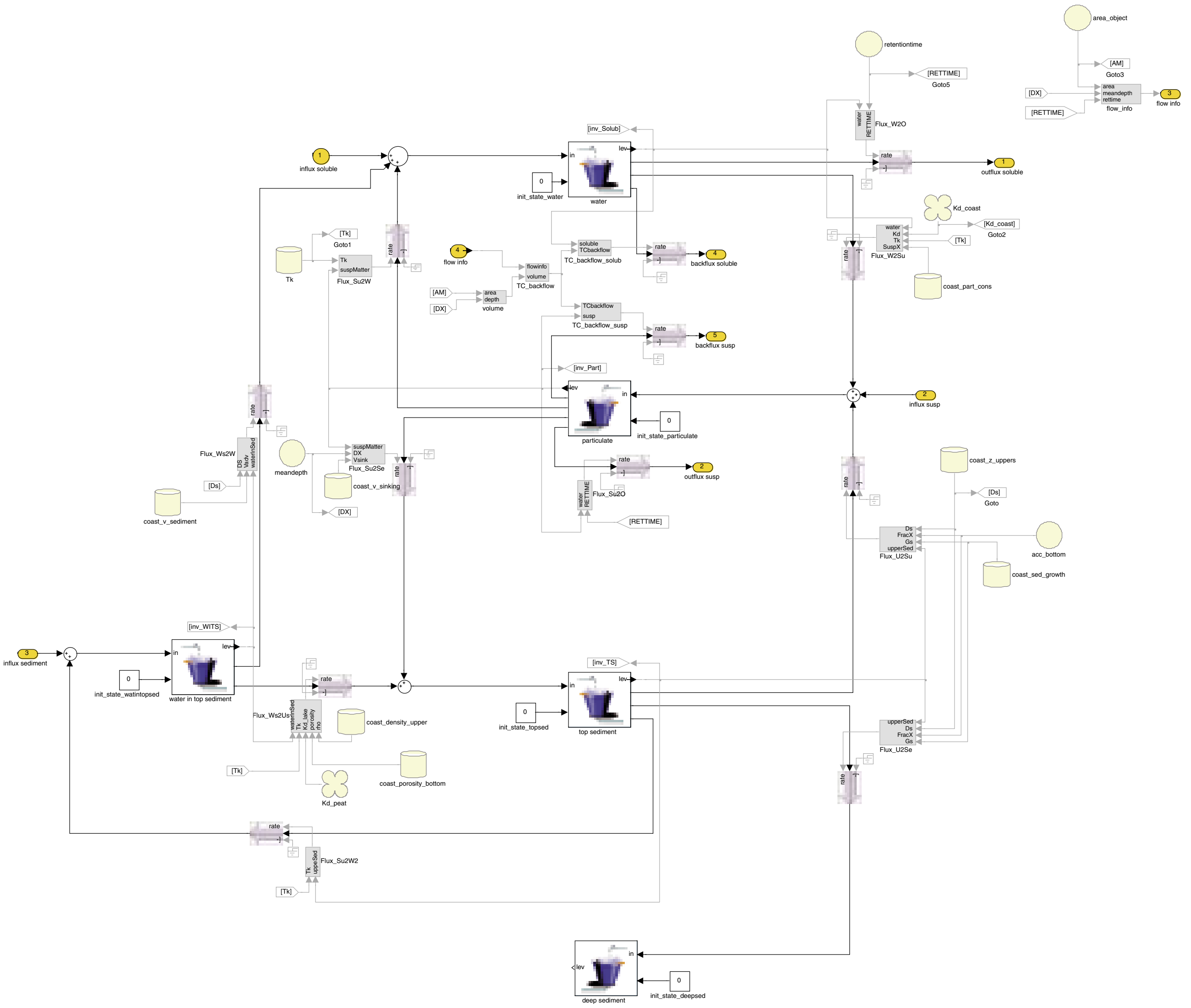


__Figure 5-4.__ The model that describes the transport and accumulation of radionuclides for a marine basin. Orange symbols are radionuclide fluxes into and out of the system. Large boxes denote the amount of radionuclides within the system, distinguished into soluble and particulate phases, whereas the smaller grey boxes are transfer coefficients used to calculate fluxes. Yellow circles show object-specific parameters, whereas yellow cylinders are site-generic parameters (but the Tk-cylinder is half-time to sorption equilibrium and is further treated in /Avila 2006/). Yellow propellers show radionuclide-specific parameters. Large arrows show fluxes of radionuclides between compartments, whereas small arrows show how functions and parameters are connected within the model. From /Avila 2006/.

5.1.4 Radionuclide model parameterisation

This section describes assumptions and data behind the parameterisation of the site-generic parameters in the conceptual radionuclide model (described above). The parameter name within brackets is the name in the radionuclide model. The parameter values are presented in Appendix 1.

Regolith

Depth of top regolith (z_uppers)

The value represents an estimation of the zone where bioturbation occur. The range 0.5–5.5 cm is given as the total variation in /Eckhéll et al. 2000/.

Porosity of top regolith (porosity_upper)

The value is based on a weighted average of the porosity of shallow sediments on accumulation bottoms /58%, Table 5-3, Lindborg 2005*/, comprising organic material, and erosion bottoms /42%, Table 5-3, Lindborg 2005*/, comprising mostly sand. The porosity was taken from /Talme and Almén 1975/ for accumulation bottoms (value 0.85) and from a grain size distribution curve in one sample (PFM004396) from a sandy bottom offshore from Forsmark /Risberg 2006*/ (value=0.25).

Density of top regolith (density_upper)

The value is based on a weighted average of the density of shallow sediments on accumulation bottoms /58%, Table 5-3, Lindborg 2005*/, comprising organic material, and erosion bottoms /42%, Table 5-3, Lindborg 2005*/, comprising mostly sand. The bulk density was an average of two measurements presented in /Borgiel 2003*/ for accumulation bottoms (92 $kg \cdot m^{-3}$) and from the upper 30 cm in a soil profile, located in a leaf forest on clayey till in Forsmark /Lundin et al. 2005*/ (1,770 $kg \cdot m^{-3}$).

Depth of deeper regoltih (z_deeps)

The value represents the mean depth of Quaternary sediments based on the marine geological investigations offshore from Forsmark /Elhammer and Sandkvist 2005*/.

Porosity of deeper regolith (porosity_bottom)

The value is based on the measured values of water content in till samples from two trenches in Forsmark /Lundin et al. 2005*/ and on calculated values from the grainsize distribution curves from clay, collected offshore from Forsmark /Risberg 2006*/.

Density of deeper regoltih (density_bottom)

The value is based on measurements of dry bulk density of till samples in two large trenches in Forsmark /Lundin et al. 2005*/.

Sediment growth rate (sed_growth)

The value is based on interpolations between dated levels in a sediment core collected offshore from Forsmark /Risberg 2006*/. The minimum value is negative since erosion is active on many bottoms.

Hydrology

Particle concentration in water (part_conc)

The estimate is based on the concentration of Particulate Organic Carbon (POC), sampled biweekly to monthly at one representative coastal sampling site (PFM000062) in the Forsmark area /Sonesten 2005*/.

Velocity of sinking fine particles (v_sinking)

/Estrum-Yuosef et al. 2000/ estimated the sinking velocity of particulate organic carbon to range between 0.01–0.32 m/day in inner coastal southern Baltic. The arithmetic mean of this range was used.

Advective transport in sediment (v_sediment)

Calculated values of water flows from the MIKE SHE model /Bosson and Berglund 2006*/ were used to describe advective transport in sediments. Modelling results representing the vertical water flow between the bedrock, the till and the sediments under the lakes have been used. The value presented in Appendix 1 is a mean value based on modelling results from four lakes in the Forsmark area. In abscence of other data it has been considered appropriate to use the same value also in the marine environment.

Biota

Productivity of food normally consumed (productivity_food)

The productivity of food is based on estimations of the productivity of fish in three basins offshore of Forsmark /Lindborg 2005*/.

5.2 Lake

Small lakes are common in the Forsmark area today. The lakes are very shallow, rich in calcium and oligotrophic /e.g. Brunberg and Blomqvist 1999/. The lake areas range between 0.01 and 0.75 km^2 /Brunberg et al. 2004/. As described earlier, all lakes were isolated from the Baltic Sea relatively recently and some of them occasionally receive brackish water from the marine area, during extreme weather conditions. The depth of the sediment differs and some of the lakes are underlain by a continuous layer of clay (e.g. Lake Eckarfjärden and Lake Fiskarfjärden) whereas clay is absent in others (e.g. Lake Bolundsfjärden) /Hedenström 2004/.

5.2.1 Major flows of matter

The largest carbon pool by far in the limnic system is that in the sediments /Lindborg 2005/. Production and biomass of primary producers is dominated by macrophytes (mainly reed) and macroalgae (*Chara spp*). The former bring in carbon to the lake ecosystem through the utilisation of DIC from the air. Lake respiration is strongly dominated by bacteria, both benthic and pelagic. The within-system transport of carbon (and other elements) to the top predator (piscivorous fish) may occur through two different pathways. The first and probably more important pathway is from benthic bacteria to benthic fauna, to benthic feeding fish and further to piscivorous fish. The other pathway is from bacterioplankton to zooplankton, to zooplankton feeding fish and further to piscivorous fish. A schematic view of the carbon budget set up for Lake Eckarfjärden /Lindborg 2005/ is shown in Figure 5-5.

5.2.2 Development over time

Ontogeny of oligotrophic hardwater lakes in the Forsmark area

The present-day oligotrophic hardwater lakes in the Forsmark area can, from at least two points of view, be regarded as being of an ephemeral nature /Brunberg and Blomqvist 2000/. First of all, like all lakes, they are successively being filled with material from the drainage area and material produced in the lake basin itself, the final stage being a wetland forest or a bog (see Figure 5-6). Secondly, the oligotrophic hardwater stage is also of ephemeral nature. The reason for this is that the exceedingly high concentrations of bicarbonates and cations, principally calcium, typically found at an early stage after the isolation of the lake basin from the Baltic Sea, originate from the calcium-rich glacial and post-glacial soils of the catchment basin. When isolated from the Baltic Sea and as the groundwater level fell, weathering of the soils began and this gave rise to large amounts of dissolved substances in the water. However, as the underlying bedrock consists of granites and gneisses, the storage of carbonates and base cations is restricted to the soils, which are a finite source of ions that will be depleted in a relatively

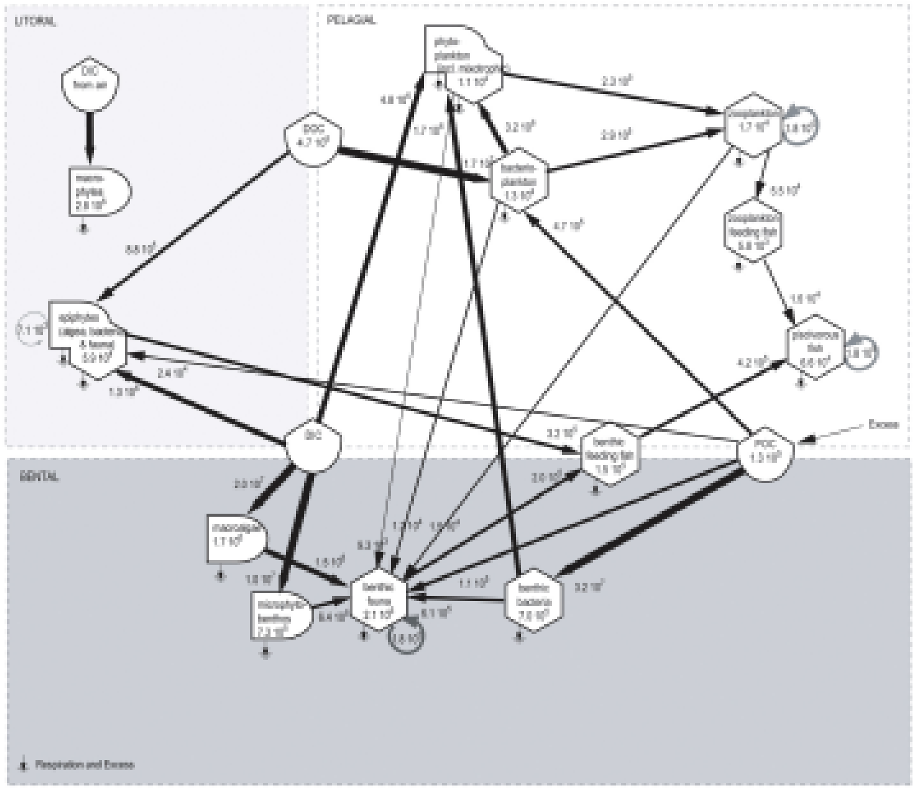


Figure 5-5. *Carbon budget for Lake Eckarfjärden. Arrow sizes indicate the magnitude of carbon flows between different functional groups /Lindborg 2005/.*

short geological perspective. Regardless of the duration of the hard-water stage, it is evident that the system sooner or later will reach a point when the precipitation of CaCO3 from the lake water will no longer take place. At that point, there will be no co-precipitation of important plant micronutrients (e.g. P) or essential trace elements (e.g. Fe, Mn). Instead, these elements, and especially P, will contribute to the production of organisms in the system and there will be a rapid change towards eutrophic conditions. This change will, in turn, lead to increased amounts of sedimenting organic matter (i.e. increased infilling), increased decomposition rates, at least until anoxic conditions are reached, and enhanced nutrient recycling.

However, due to the shallow depths of present-day lakes in the Forsmark area, it is unlikely that they will reach a stage of increasing eutrophication before they are filled with material. Instead, a likely ontogeny of the hardwater-lakes in the Forsmark area is towards a reed swamp, a fen, and finally a bog ecosystem. This idea is supported by the fact that mires constitute a large part of the Forsmark area today (10–20% of the area in the three major catchments). It is also supported by the fact that the riparian zone of most existing oligotrophic hard-water lakes in the area to a great extent is dominated by mires.

All present-day and future lakes in the Forsmark area have originated or will orginate as depressions in the bottom of the coastal systems. As the land-rise proceeds, these areas are successively transported upwards to become shallow bays along the coast (Figure 5-6A). Inflow of freshwater in the form of ground- or surface water begins and the system changes slowly from a brackish to a freshwater stage. In such coastal basins, there is a “threshold” in the mouth of the main part of the coastal basin. This threshold allows settling fine material to accumulate in the deepest part of the basin. At this stage, provided that the water depth is less than 2–3 m, different *Charales* (e.g. *Chara tomentosa*) colonise the illuminated soft-bottom sediments. Along the shore, *Phragmites* and other aquatic vascular plants also begin to colonise the system and a wind-sheltered littoral zone is develops. In both these habitats, the colonisation by plants reduces the water currents, resulting in increased sedimentation. Thus, two of the

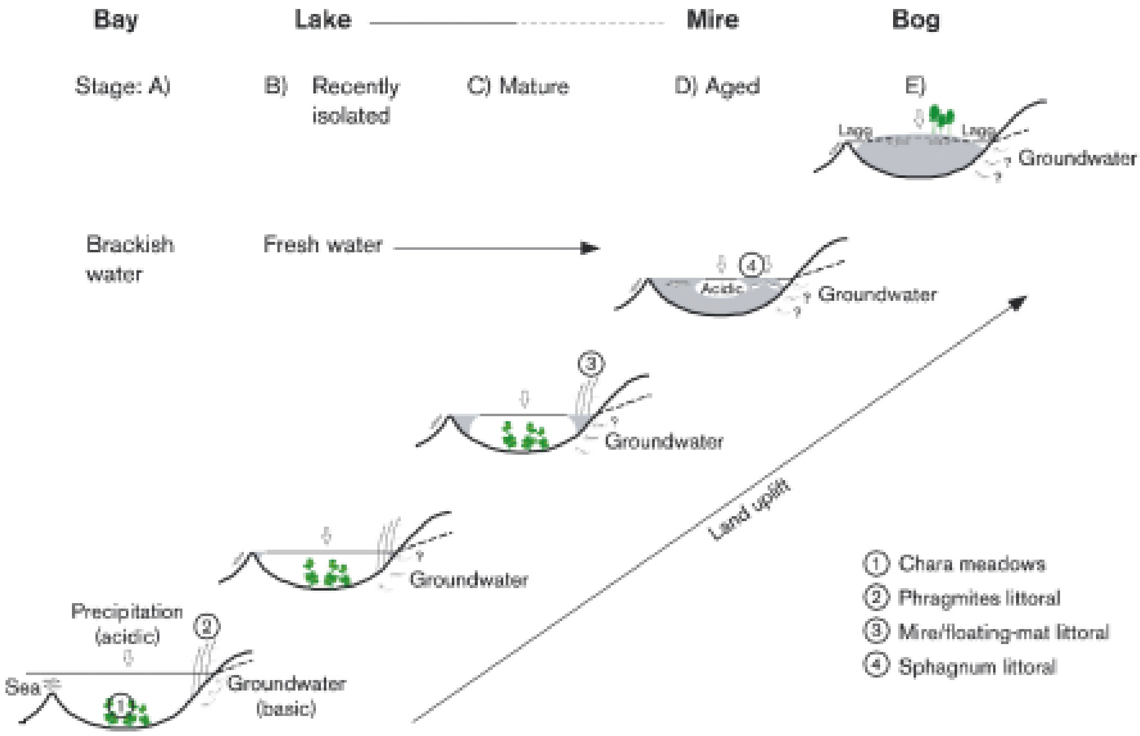


Figure 5-6. *Suggested ontogeny of the oligotrophic hardwater lakes in the Forsmark area. The numbers in the figure represent different major components of the ecosystem: 1 = Chara meadow, 2 = Phragmites littoral, 3 = mire/floating-mat littoral, 4 = Sphagnum littoral /Brunberg and Blomqvist 2000/.*

major components of the oligotrophic hardwater lakes start to develop when the basin is a brackish water system along the coast (Figure 5-6A). The water entering the bay from the catchment will be rich in dissolved substances and well buffered as a result of the new soils being rich in carbonates and associated ions.

As the basin successively becomes isolated from the Baltic Sea, the influence of the brackish coastal water decreases and so does the salinity of the system. In recently isolated lake basins which lack major tributaries, the inflowing groundwater becomes the only source of water to the system. It is probably at this stage that precipitation of $CaCO_3$ and co-precipitation of P, Fe, and Mn becomes pronounced. An oligotrophic clearwater system, in which the major components are the illuminated soft-bottom zone and the *Phragmites*-dominated sheltered littoral zone, establishes (Figure 5-6B).

During the ongoing succession towards a more mature oligotrophic hardwater lake stage, *Sphagnum* mosses start to colonise the macrophytes of the sheltered littoral. As the growth of *Sphagnum* proceeds in an outward direction and organic accumulation underneath these plants increases, a mire/floating-mat littoral zone is successively developed. This mire-littoral is important in that it alters the groundwater flow and/or chemistry of the inflowing water by turning the system increasingly acidic. Thus, the invasion of the sheltered littoral by *Sphagnum*, should, at least theoretically have a profound effect on the functioning of the lake ecosystem (Figure 5-6C), which still has two major key habitats both associated with the bottom area. In a later stage of succession, the accumulation of organic detritus in the lake basin completely covers the previous illuminated soft-bottom area (Figure 5-6D). At this stage, the *Sphagnum* littoral alone dominates the metabolism of the system, as the previous soft-bottom habitat has been lost through sedimentation of peat. The whole system; the mire-littoral as well as the open water, is now acidic. The final stage, the raised bog ecosystem (Figure 5-6E), represents an autonomous hydrological system which is exclusively fed by precipitation on the surface of the bog and which, through the capillary capacity of the *Sphagnum* necromass, is characterised by a raised groundwater surface in the bog and an outflow of water to the surrounding ecosystems /Brunberg and Blomqvist 1999/. In this situation, material from the groundwater in the catchment area is transported through the surrounding lagg.

Ontogeny of future brownwater lakes in the Forsmark area

In an investigation of lakes in the catchment of River Forsmarksån, /Brunberg and Blomqvist 2000/ concluded that lakes in the vicinity of the Forsmark area may develop to brownwater lakes without passing through the oligotrophic hardwater stage. From a historical and ontogenic point of view, the catchment of River Forsmarksån, and thereby also its lakes, may be divided into two parts with different ontogeny; the area upstream and downstream, respectively, of the 13 m high falls at Lövstabruk.

Paleoecological studies show that the upstream Lake Vikasjön passed through an oligotrophic hardwater stage after its isolation from the sea, during which "cyanophycée-gyttja" was settled. This corresponds to the present situation in the oligotrophic hardwater lakes along the coast. This stage lasted for about 1,000 years, and was followed by a period of 1,000–2,000 years when the lake basins successively were isolated from each other and partly were grown over by mires. The sediments in the remaining lake basins then switched to "dy" sediments due to the influence of humic compounds from the surroundings. Thus, most of the lakes in the upper parts of River Forsmarksån have a similar historical record in the sediments.

The lakes which are situated below the 13 m fall at Lövstabruk have a different history. Due to the substantial difference in the topography they were isolated from the sea at least 2,000–2,500 years later than the upstream lakes. At this time, the upstream lakes had passed the oligotrophic hardwater stage, and were already more or less brownwater systems. The inflowing water from the upstream areas to the newly formed lakes was thus less alkaline. This water from the main river constituted a major component of the inflowing water to the newly formed lake basins. The large flow of water dominated, and still dominates, the hydrology of the system, thus diluting and washing out the contributions from the land areas in the close vicinity of the newly formed lakes. Consequently, no oligotrophic hardwater stage occurred in the chain of lakes situated along the main river below Lövstabruk. Instead they developed to brownwater flow-through lakes more or less directly after isolation.

Ontogeny of future deep eutrophic lakes in the Forsmark area

The deepest parts of Öregrundsgrepen will in the future develop into a number of deep lakes, which will differ considerably from the present-day lakes in the Forsmark area. The first of these lakes will be isolated from the sea around year 5,400 AD, and the last around year 7,700 AD /Brydsten 1999a/. The ontogeny of two deeper lakes in the vicinity of the Forsmark area, Lake Erken and Lake Limmaren, over the next 10,000 years was assessed by /Brunberg and Blomqvist 2000/. For Lake Erken, the accumulation of lake sediments in the deepest parts of the basin is maximally 1 m over the 2,500 years that have passed since the lake was isolated from the Baltic Sea. Assuming the same rate of sediment deposition, the accumulation of sediments during the next 10,000 years would be 4 m. The accumulation of sediments in other parts of the lake would be considerably less. Thus, even 10,000 years from now, Lake Erken will be a large and, for the region, relatively deep lake (maximum depth c 16 m).

The situation in Lake Limmaren is different. First, the sedimentation rate over the past 1,000 years has been considerably higher than that in Lake Erken, with an accumulation of some 1.4 m of sediment in the deepest part of the lake. Secondly, Lake Limmaren is much shallower than Lake Erken. Over the next 10,000 years, the accumulation of sediments in Lake Limmaren would be about 14 m, so it seems reasonable to conclude that the basin will be completely filled with sediments in 5,000 to 10,000 years from now. A first transition to a reed-marsh seems very likely but whether the state will be a mire or a wetland forest (dominated by alders) is highly uncertain.

5.2.3 Simplified radionuclide model

A schematic view of the numerical model that describes the transport and accumulation of radionuclides in lakes is presented in Figure 5-7. The figure shows the different parameters and how these are related in order to describe fluxes of radionuclides. The site-generic parameters are presented in further detail below, whereas object-specific parameters are treated in Chapter 6.

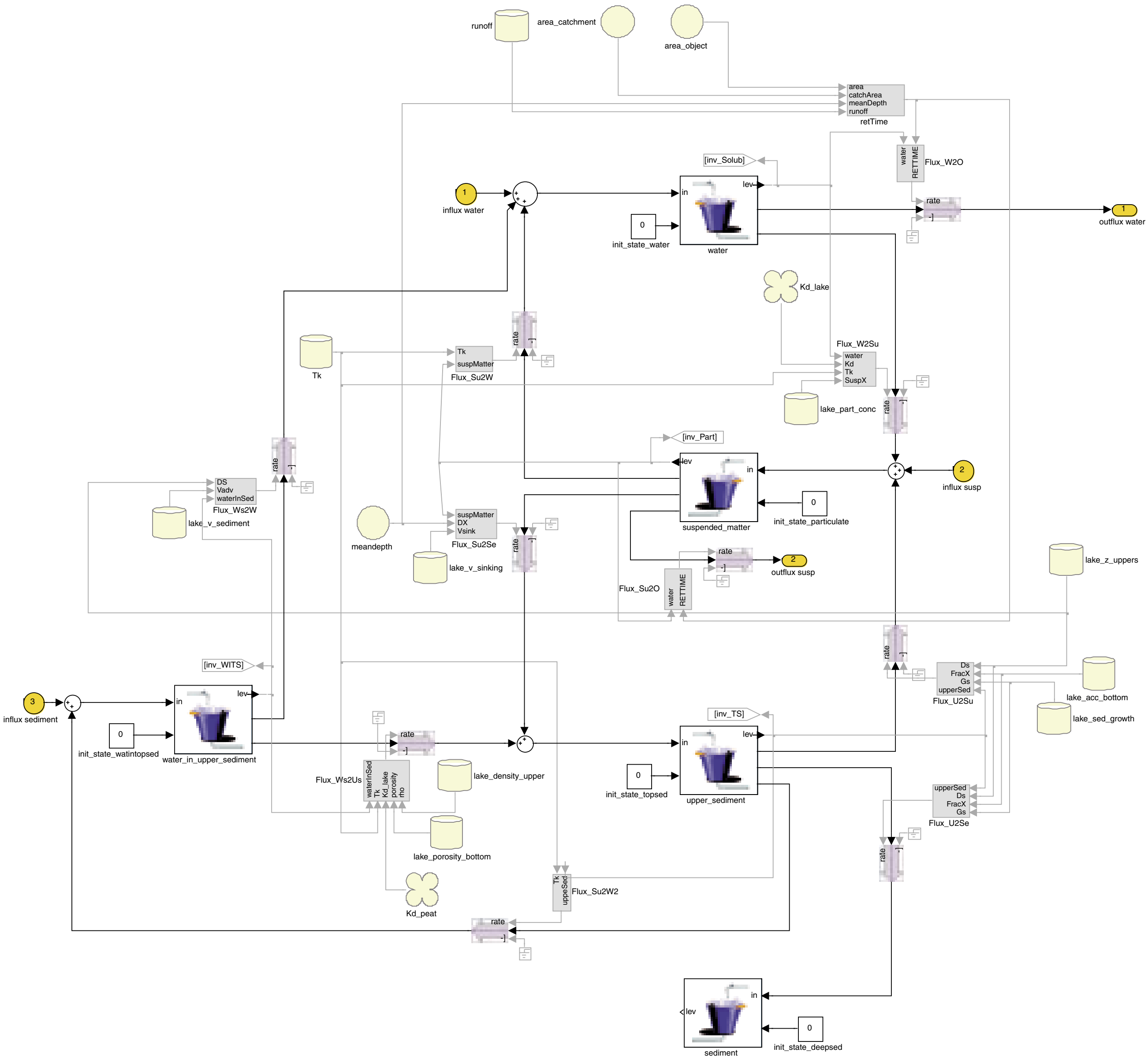


Figure 5-7. The model that describes the transport and accumulation of radionuclides for a lake. Orange symbols are radionuclide fluxes into and out of the system. Large boxes denote the amount of radionuclides within the system, distinguished into soluble and particulate phases, whereas the smaller grey boxes are transfer coefficients used to calculate fluxes. Yellow circles show object-specific parameters, whereas yellow cylinders are site-generic parameters (but the Tk-cylinder is half-time to sorption equilibrium and is further treated in /Avila 2006/). Yellow propellers show radionuclide-specific parameters. Large arrows show fluxes of radionuclides between compartments, whereas small arrows show how functions and parameters are connected within the model. From /Avila 2006/.

5.2.4 Radionuclide model parameterisation

This section describes assumptions and data relavant to the site-generic parameters in the conceptual radionuclide model (described above). The parameter name within brackets is the name in the radionuclide model. The parameter values are presented in Appendix 1.

Regolith

Depth of top regolith (z_uppers)

The value represents an estimate of the depth of the upper zone of the sediment that is biologically active. The value used is an estimate of the depth of the thickness of the microbial mat that covering most of the lake bottoms in the Forsmark area /Borgiel 2003*/.

Porosity of top regolith (porosity_upper)

Values are calculated from the measured water content in the upper 5 cm of sediments from seven lakes in and around the Forsmark region (Table 5-1, A-K. Brunberg, Uppsala univ., unpublished data*). The water content is assumed to be equivalent to the porosity.

Density of top regolith (density_upper)

The top regolith consists mainly of a ”fluffy” layer of organic matter often referred to as the microbial mat. Density estimates from this mat are not available, instead the mean bulk density is approximated by the density of lose to dense peat soils /Kellner 2003*/.

Depth of deeper regolith (z_deeps)

This depth is defined as the post glacial sediment depth, excluding the upper, loose and water saturated microbial mat. Accordingly, the till layer below the post glacial sediments is excluded from the depth. The statistics are based on calculated mean depth of post-glacial sediment in 6 lakes in the Forsmark area. Data from sediment corings in the lakes, which were used for the calculation of mean depth of post-glacial sediment in each lake is presented in /Hedenström 2004*/.

Porosity of deeper regolith (porosity_bottom)

The value was calculated from the water content in post-glacial sediments (20–100 cm sediment depth) in Lake Eckarfjärden (Table 5-2, A-K. Brunberg, Uppsala univ., unpublished data*), where water content was set equal to porosity.

Table 5-1. Water content in the upper 0.05 m of the lake sediment for seven lakes (A-K. Brunberg, Uppsala univ., unpublished data*).

Lake	Water content (%)
Fiskarfjärden	97.8
Bolundsfjärden	96.9
Stocksjön	97.7
Labboträsk	98.0
Hällefjärd[1]	98.1
Eckarfjärden	98.3
Landholmssjön[1]	98.1

[1] in the table denotes oligotrophic hardwater lakes not located within the Forsmark area.

Table 5-2. Water content at different depth intervals in the sediments of Lake Eckarfjärden (A-K. Brunberg, Uppsala univ., unpublished data*).

Depth (cm)	Water content (%)
20–25	94.6
25–30	96.5
30–35	96.0
35–40	96.6
40–45	96.8
45–50	96.8
50–55	95.7
55–60	95.1
60–65	94.3
65–70	93.7
70–75	93.7
75–80	92.9
80–85	91.8
85–90	89.5
90–95	83.0
95–100	80.7

Fraction of accumulation bottom (acc_bottom)

The shallow lakes in the Forsmark area are characterised by small depth variations and an almost complete lack of erosion bottoms. Therefore, the fraction of accumulation bottom is assumed to be 1, i.e. the whole lake area is regarded as accumulation bottom.

Sediment growth rate (sed_growth)

/Brydsten 2004*/ calculated sedimentation rates in six lakes in the northern part of Uppsala County as the measured sediment depth divided by the estimated age of the sediment. Due to difficulties in distinguishing between sediments originating from the shallow gulf phase and the lake phase, the sedimentation rate was calculated as an average for both these phases. Lake Eckarfjärden, which is the lake most recently isolated from the Baltic and also the only one of the six investigated lakes situated within the regional model area, shows the highest sedimentation rate. However, here the estimate is based on data from all six lakes.

Hydrology

The water balance data presented in this report are based on calculated values from the near-surface hydrological model for Forsmark /Bosson and Berglund 2006*/ The physically based and spatially distributed modelling tool MIKE SHE was used for the near-surface hydrological modelling. The model is driven by local meteorological data from the Forsmark area for the period 2003 to 2004. Meteorological input data to the model are temperature, potential evapotranspiration and precipitation. The actual evapotranspiration and its different components (transpiration, evaporation from soil, interception etc) is calculated in timesteps less than periods of twenty-four hours during the simulation.

Particle concentration in water (part_conc)

The estimate is based on average concentrations of Particulate Organic Carbon (POC) in five lakes in the Forsmark area, sampled biweekly to monthly during 2002–2004 /Sonesten 2005*/.

Velocity of sinking fine particles (v_sinking)

There are no site data available for the velocity of sinking fine particles. The estimate used is based on the estimated velocity given in Table 4-1 in /Karlsson et al. 2001*/.

Advective transport in sediment (v_sediment)

Calculated values of water flows from the MIKE SHE model /Bosson and Berglund 2006*/ were used to describe the advective transport in sediments. Modelling results representing the vertical water flow between the bedrock, the till and the sediments under the lakes have been used. The value presented in this report is a mean value based on modelling results from four lakes in the Forsmark area.

Biota

Productivity of primary producers weighted over the area of the object (productivity_plants)

Productivity of all primary producers, i.e. macrophytes, phytoplankton and benthic algae, was calculated for one lake in the Forsmark area, Lake Eckarfjärden, in /Lindborg 2005*/. The calculations are based on site data from Lake Eckarfjärden presented in /Andersson et al. 2003*/ (phytoplankton and microphytobenthos) and /Andersson and Kumblad 2006*/ (macroalgae and macrophytes), and on generic data on epiphytic algae /Meulemanns 1988/.

Productivity of secondary producers (productivity_animal)

Productivity of secondary producers, i.e. all heterotrophic production, was calculated for one lake in the Forsmark area, Lake Eckarfjärden, in /Lindborg 2005*/. Production of bacterioplankton and benthic bacteria was obtained from /Andersson and Brunberg 2006*/, and the production of epiphytic bacteria was obtained from /Meulemanns 1988/. The productivity of the remaining secondary producers was calculated from site-specific data on biomass, using conversion factors given in /Kautsky 1995/ and measured temperature variations in Lake Eckarfjärden /Sonesten 2005*/.

Productivity of food normally consumed (productivity_food)

Productivity of food normally consumed, i.e. all fish production, was calculated for two lakes in the Forsmark area, Lake Eckarfjärden and Lake Bolundsfjärden, in /Lindborg 2005/. Productivity was calculated from site data on fish biomass from these two lakes /Borgiel 2004*/, using conversion factors given in /Kautsky 1995/ and measured temperature variations /Sonesten 2005*/.

Productivity of edible products (productivity_edible)

Productivity of edible products, i.e. fish and macroinvertebrate, was calculated for one lake in the Forsmark area, Lake Eckarfjärden, in /Lindborg 2005/ from site-specific data on biomass /Andersson et al. 2003*, Borgiel 2004*/, using conversion factors given in /Kautsky 1995/ and measured temperature variations in Lake Eckarfjärden /Sonesten 2005*/.

5.3 Running water

In the Forsmark area, the running waters are mainly streams confined to dug ditches /Carlsson et al. 2005/. The water flow varies very much over the year and during dry years many streams may cease to flow for long periods.

5.3.1 Major flows of matter

The flow of matter in running waters has not been studied explicitly at Forsmark. There are, however, certainly processes that will affect turnover of elements and accumulation of matter. For example, due to the flat topography in Forsmark, wetland areas adjacent to streams will regularly be flooded during periods of high discharge. There may potentially be a significant accumulation of matter in such areas.

5.3.2 Development over time

Running waters are located in lows of the environment. An important factor for the existence and size of watercourses is the runoff in the area upstream. Assuming no changes in climate, the amount of water in watercourses in the Forsmark area will decrease over time due to the process of lakes turning into wetlands. This leads to increased evapotranspiration and slower water turn-over resulting in lower water flows. The running waters in the Forsmark area today will continue in their present courses in the area unless ditching by humans occurs. New watercourses will develop in the areas uplifted above sea level by the ongoing land elevation.

5.3.3 Simplified radionuclide model

For rivers a compartment model was not used. Instead, instantaneous and complete missing of the released radionuclides with the river water was assumed. The flow of water was calculated using the depth and width, and the run-off from the catchment area above a specific point (further described in /Avila 2006/.

5.3.4 Radionuclide model parameterisation

This section describes assumptions used in the specification of the site-generic parameters in the conceptual radionuclide model (described above). The parameter name within brackets is the name in the radionuclide model. The parameter values are presented in Appendix 1.

Hydrology

The water balance data presented in this report are based on calculated values from the near-surface hydrological model for Forsmark /Bosson and Berglund 2006*/ The physically based and spatially distributed modelling tool MIKE SHE was used for the near-surface hydrological modelling. The model is driven by local meteorological data from the Forsmark area for 2003–2004. Meteorological input data to the model are temperature, potential evapotranspiration and precipitation. The actual evapotranspiration and its different components (transpiration, evaporation from soil, interception etc) is calculated in timesteps less than periods of twenty-four hours during the simulation.

Runoff (runoff)

The parameter “runoff” represents the annual amount of water leaving the model domain (see above) in the watercourses and as direct runoff to the sea.

5.4 Mire

Wetlands are frequent in the Forsmark area and cover 10–20% of the area in the three major catchments and up to 25–35% of some sub-catchments. The wetlands are characterised by a high calcareous influence resulting in the extremely to moderate rich fen types common in this area /Jonsell and Jonsell 1995/. These fen types lack the dominance of *Sphagnum* species in the bottom layer and are instead dominated by brown mosses e.g. *Scorpidium scorpioides*. However, bogs are also present and are continuously created as land rise and mineral and nutrient leaching progresses. Bogs are not yet so numerous in this area, partly because of the young age of the terrestrial environment. Roughly, there are two types of wetlands identified; those that accumulate peat and those where decomposition is fairly high thereby minimising peat formation. The latter has a more or less thick humus layer on mineral soil, hence having less carbon in the soil organic carbon pool (SOC) /Lundin et al. 2004/.

The stratigraphy of the wetlands has not been investigated in detail, but peat has developed in the more elevated areas with a thickness of less than one metre. In more low-lying areas, the peat layer is very thin or missing. The peat is underlain by gyttja and sometimes also by sand and clay layers. From existing borings /Johansson 2003, Werner and Lundholm 2004/ it is known that the peat in the wetlands can rest directly on till or be underlain by gyttja and/or clay above the till.

5.4.1 Major flows and processes

The wetlands in Forsmark can either be in direct contact with the groundwater zone and constitute typical discharge areas or be separate hydrological systems with tight bottoms having little or no hydraulic contact with the groundwater zone /Lindborg 2005/.

The largest flux of carbon is the gross primary production in the field and bottom layer, where approximately 50% is the net primary production (NPP). A large part of the NPP is turned into litter from both above-ground and below-ground plant functional parts, whereas the rest is stored in perennial plant tissue. C-mineralisation is the largest flux of carbon leaving the mire and the difference between litter input and C-mineralisation is the accumulation of organic matter. The position of the water table is the principal factor affecting CO_2 fluxes from boreal wetlands /Silvola et al. 1996/, which have consistently shown a strong positive relationship between CO_2 fluxes and water-table depth. For wetlands, there are data describing the accumulation of carbon based on the age of the site and the thickness of the peat layer (Table 5-3), suggesting that wetlands on peat soils accumulate on average 60 $gC{\cdot}m^{-2}y^{-1}$. Unfortunately, there are few references describing carbon cycling from forested wetlands, especially fen-like wetlands.

Table 5-3. A rough estimate of accumulation rate of carbon in four wetlands in the Forsmark area. These values are calculated using information of the depth of the peat soil and the approximate time since the wetland emerged from the sea. From /Lindborg 2005/.

Locality in Forsmark	g $Cm^{-2}y^{-1}$	Reference
Stenrösmossen	43.2	/Fredriksson 2004*/
Lersättermyran	66.3	/Fredriksson 2004*/
T1	58.3	/Lundin et al. 2004*/
T2	73.8	/Lundin et al. 2004*/
Mean	**60.4**	

The anaerobic conditions created in the inundated soil lead to emission of methane gas during decomposition. This emission rate is low compared with the carbon dioxide emitted during heterotrophic respiration (e.g. a boreal bog, 1–2 $gCm^{-2}y^{-1}$ /Alm et al. 1999/ and 4 $gCm^{-2}y^{-1}$ /Waddington and Roulet 2000/).

/Brydsten 2004/ found that data from six investigated lakes in the Forsmark area suggested that sediments had a high degree of material of autochtonous origin. Several other factors supported this conclusion, such as small topographic variation (small watersheds), low current velocities and low abundance of fine-grained sediments. This pattern suggests that a similar pattern would be likely for wetlands in the Forsmark area. Studies of DOC exports to lakes, as a function of vegetation types, in a drainage area have shown that wetlands export more DOC than other vegetation types /e g Canhem et al. 2004, Humborg et al. 2004/. /Canhem et al. 2004/ calculated the export from temperate conifer wetlands, "emergent marches" and forests to be 17.5 $gC{\cdot}m^{-2}{\cdot}y^{-1}$, 12.5 gC $m^{-2}{\cdot}y^{-1}$ and 3.5 gC $m^{-2}{\cdot}y^{-1}$ respectively, using a predictive model based on 2,750 lakes and their drainage areas in Canada. /Waddington and Roulet 2000/ estimated the lateral transport from a boreal bog in Sweden to be 4.2 $gC{\cdot}m^{-2}$ and 6.7 $gC{\cdot}m^{-2}$ in two consecutive years. Consequently, import and export of carbon are small in comparison with the local wetland carbon budgets, see /Lindborg 2005/, but their impact on the recipient ecosystem may be large depending on the size of the drainage area and the number of wetlands.

5.4.2 Development over time

Mires are formed basically through three different processes; terrestrialisation, paludification and primary mire formation /Rydin et al. 1999, Kellner 2003/. Terrestrialisation is the filling-in of shallow lakes. Paludification, which is the predominant way of mire formation in Sweden, is an ongoing water logging of more or less water-permeable soils, by expanding mires or beaver activities. Primary mire formation is when peat is developed directly on soils exposed after post glacial land uplift. All three types of processes are likely to occur in the Forsmark area. The richer types of mires will undergo a natural long-term acidification, when turning into a more bog-like mire. It seems that the final result of mire development, in the boreonemoral and southern boreal areas of Sweden, is the bog /Rydin et al. 1999/. The bog can, however, have Scot pines if the peat can support their weight and some studies (e.g. /Gunnarsson et al. 2002/ and references therein) indicate that Scots pine have established and become more common in recent years on bogs. The mires can be drained for forestry and such activities peaked in the 1930's in Sweden. Mires have also been used for haymaking and, in this context the rich fens were more important than the poor fens. Haymaking slows down or stops the succession of the rich fen resulting in poorer fen-like stages due to the inhibition of peat formation /Elveland 1978/. Mires have also been used for agriculture purposes and such use was during the 1850's and subsequently, often preceded by ditching activities to ensure the best possible conditions for the crops cultivated. This resulted in lowering of the water table induceing a switch from anaerobic conditions to aerobic conditions, initiating decomposition and erosion of peat-dominated soil.

5.4.3 Simplified radionuclide model

A schematic view of the numerical model that describes the transport and accumulation of radionuclides in mires is presented in Figure 5-8. The figure shows the different parameters and how these are related in order to describe fluxes of radionuclides. The site-generic parameters are presented in further detail below whereas object-specific parameters are treated in Chapter 6.

5.4.4 Radionuclide model parameterisation

This section describes assumptions used in specification of the site-generic parameters in the conceptual radionuclide model (described in the section above). The parameter name within brackets is the name in the radionuclide model. The parameter values are presented in Appendix 1.

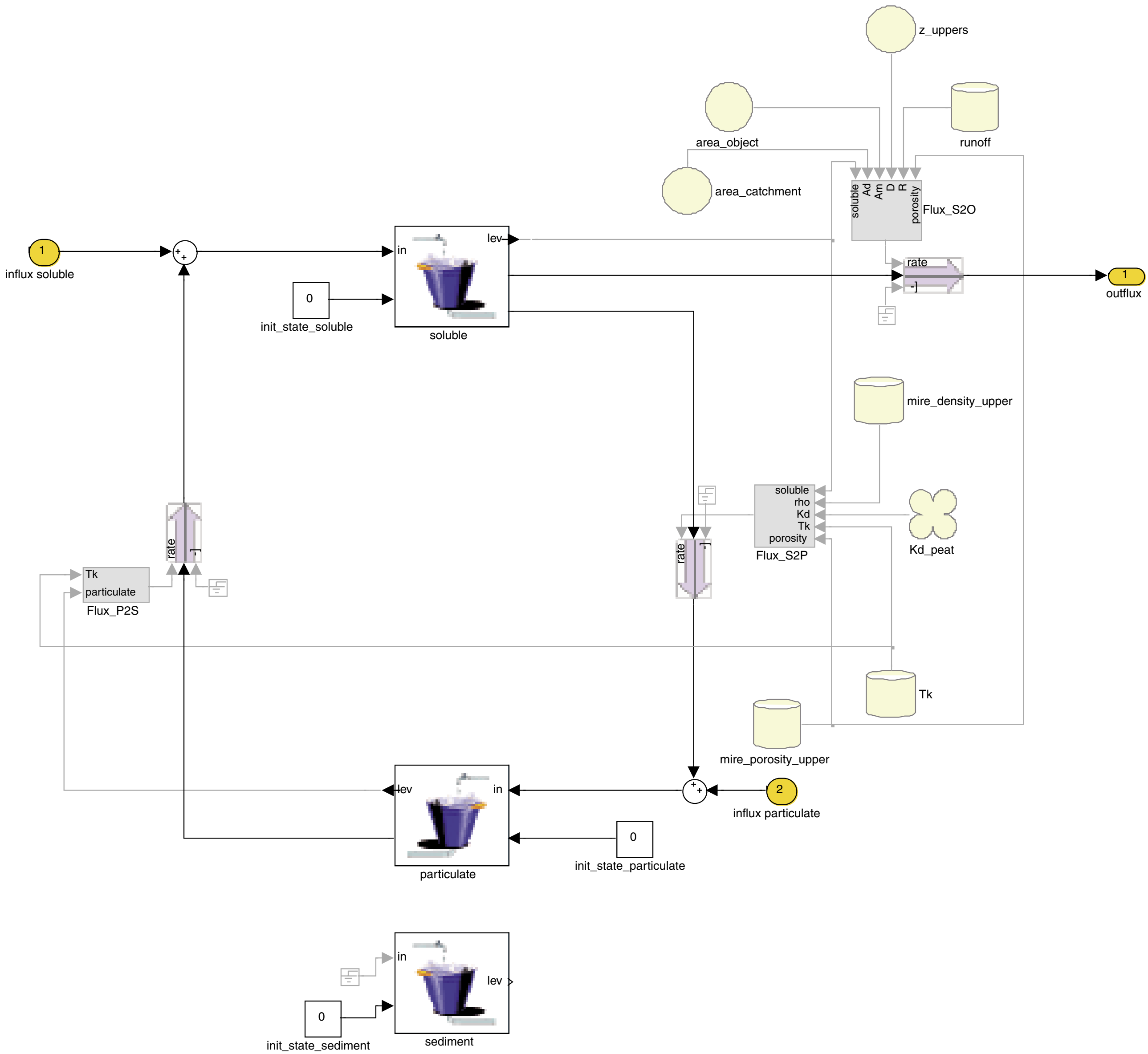


Figure 5-8. *The model that describes the transport and accumulation of radionuclides for a mire. Orange symbols are radionuclide fluxes into and out of the system. Large boxes denote the amount of radionuclides within the system, distinguished into soluble and particulate phases, whereas the smaller grey boxes are transfer coefficients used to calculate fluxes. Yellow circles show object-specific parameters, whereas yellow cylinders are site-generic parameters (but the Tk-cylinder is half-time to sorption equilibrium and is further treated in /Avila 2006/). Yellow propellers show radionuclide-specific parameters. Large arrows show fluxes of radionuclides between compartments, whereas small arrows show how functions and parameters are connected within the model. From /Avila 2006/. The parameter z_uppers is objects-specific in the figure for future conditions (see Chapter 6), but is treated as site-generic in the text below for present conditions.*

Regolith

Depth of top regolith (z_uppers)

The depth of the peat layer, is based on 16 corings from two mires in the Forsmark area /Fredriksson 2004*/ and the depth of the organic layer (peat and gyttja) in 25 corings made in the vicinity of Lake Bolundsfjärden, /Lokrantz and Hedenström 2006*/. Descriptive statistics was calculated from these three locations regarded as three independent samples, except for max and min were the highest and lowest depth of all the 31 corings were used. Standard deviation was from the mire with the highest standard deviation.

Porosity of top regolith (porosity_upper)

Peat porosity varies with depth but in this model this is not considered and the value is based on the water content in peat, measured on 31 samples from Forsmark /Fredriksson 2004*/.

Density of top regolith (density_upper)

The peat density (kg dw/m^3) varies with depth but in this model this is not considered, instead an average density for the whole thickness of peat is used. This value is from /Karlsson et al. 2001*/.

Hydrology

The water balance data presented in this report are calculated values from the near-surface hydrological model for Forsmark /Bosson and Berglund 2006*/ The physically based and spatially distributed modelling tool MIKE SHE was used for the near-surface hydrological modelling. The model is driven by local meteorological data from the Forsmark area for 2003–2004. Meteorological input data to the model are temperature, potential evapotranspiration and precipitation. The actual evapotranspiration and its different components (transpiration, evaporation from soil, interception) was calculated in timesteps less than periods of twenty-four hours during the simulation.

Runoff (runoff)

The parameter "runoff" represents the annual amount per unit of area of water leaving by the network of watercourses and as direct runoff to the sea.

Biota

Productivity of food normally consumed (productivity_food)

The mire produces berries, mainly cloudberry and cranberry that may be consumed. The estimation is from three years and comprises collected cloudberries from Sweden /Berggren and Kyläkorpi 2002*/. The collected amount is estimated to be 5% of the production. The abundance of cloudberries is, however, low in the Forsmark area in comparison with the northern part of Sweden. This estimate, therefore is adopted for cloudberry and cranberry, but is probably an overestimate of the actual production. Due to lack of better data the carbon content in bilberries (7.0% of the fresh weight in /Section 3.10, Lindborg 2005*/) was used as an estimate of the carbon content in cloudberries. Berry production was divided by the total mire area in Sweden /Statistics Sweden 1998/. Estimates of wild game production (moose and roe deer) is from /Lindborg 2005*/ and these figures were adjusted, as the densities were estimated after the hunting season, by increasing the density figures by a value corresponding to the loss from hunting in the area using local hunting statistics /Lindborg 2005*/.

5.5 Agricultural land

The agriculture land is the arable land and the seminatural grassland. Arable land and seminatural grassland are found close to settlements. The seminatural grassland was earlier intensively used but is today mainly a part of the abandoned farmland following the nation-wide general regression of agricultural activities. The largest arable land unit in the Forsmark area is found on clayey till.

In Sweden, the cultivated area which is irrigated, is very small, 3–4% /Bergström and Barkefors 2004/. Potatoes and vegetables are the crops that are most often irrigated. According to /Bergström and Barkefors 2004/ approximately 80% of the irrigation water is drawn from lakes and rivers and 15% is groundwater (mostly in Skåne and Halland).

A smaller version of arable land is a garden plot, where vegetables and root crops can be grown for personal use. There are no permanent residents in the Forsmark area, but five cottages are situated there. It has not been investigated if the residents have garden plots and the degree of self-sustainability concerning different kind of crops is unknown. Although the extent of irrigation of garden plots is not known, the figures in /Bergström and Barkefors 2004/ indicate a general need in drier summers.

5.5.1 Major flows and processes

The arable land is subjected to regular harvest that either provides humans with crops or cattle with fodder. In both cases, the final products are destined for human consumption. The cattle produce manure that may be used as fertiliser on arable land. The soil of the arable land is constantly being disturbed by ploughing, which makes well mixed and aerated down to ploughing depth. Depending on fertilisation, litter quality, and initial nutrient and carbon status, the decomposition and accumulation of carbon and nitrogen may vary /e.g. Hyvonen et al. 1996/.

Irrigation water supplies the arable land not only with water, but also with its contents of soluble and particulate matter. The water may be retained on the crop (interception) or land on the soil surface and infiltrate. The water in the soil may be taken up by the crop or leave the upper soil horizon by downward percolation. Some elements may accumulate in the soil, whereas others follow the water into the crop or down to the groundwater.

5.5.2 Development over time

The arable land in Sweden had its maximal extent in the 1920s and over-production in the 1940s led to a decrease in arable land and the number of cattle. In 1989 had 25% been taken out of production /Bernes and Grundsten 1992/. This pattern is also evident in the Forsmark area /Berg et al. 2006/.

Before agricultural modernisation, only fairly dry soils could be cultivated, heavy clays and wetlands were used for mowing and stone ridden tills and bedrock were grazed. In Nynäs in Södermanland, it was found that thin soils on bedrock were used for cultivation close to the villages in the 17th and 18th centuries /Cousins 2001/.As management intensity and population increased, more of the medium fertile soils were used for agriculture while the poorest soils were assigned to the livestock /Rosén and Borgegård 1999/. However, this trend came to an end as management was rationalised by using fertilisers and better equipment in the early 20th century. This development of farming and the development of forest tools and machinery altered the utilization of land-covers and thus their association with different soils. The distribution of agricultural land in Sweden is today largely associated with postglacial deposits /Angelstam 1992, Sporrong et al. 1995/. The largest arable land unit in the Forsmark area is, however, found on clayey till.

The seminatural grassland was earlier intensively used, but is today mainly a part of the abandoned farmland following the nationwide general regression of agricultural activities. If these areas are left unattended, they will eventually develop into forests that in most cases will be dominated by Norway spruce. During the latter parts of the 1900's, farmers have been encouraged to plant coniferous trees on arable land, thereby accelerating the succession into forest.

5.5.3 Simplified radionuclide model

A schematic view of the numerical model that describes the transport and accumulation of radionuclides in agricultural land is presented in Figure 5-9. The figure shows the different parameters and how these are related in order to describe fluxes of radionuclides. The site-generic parameters are presented in further detail below, whereas object specific parameters are treated in Chapter 6.

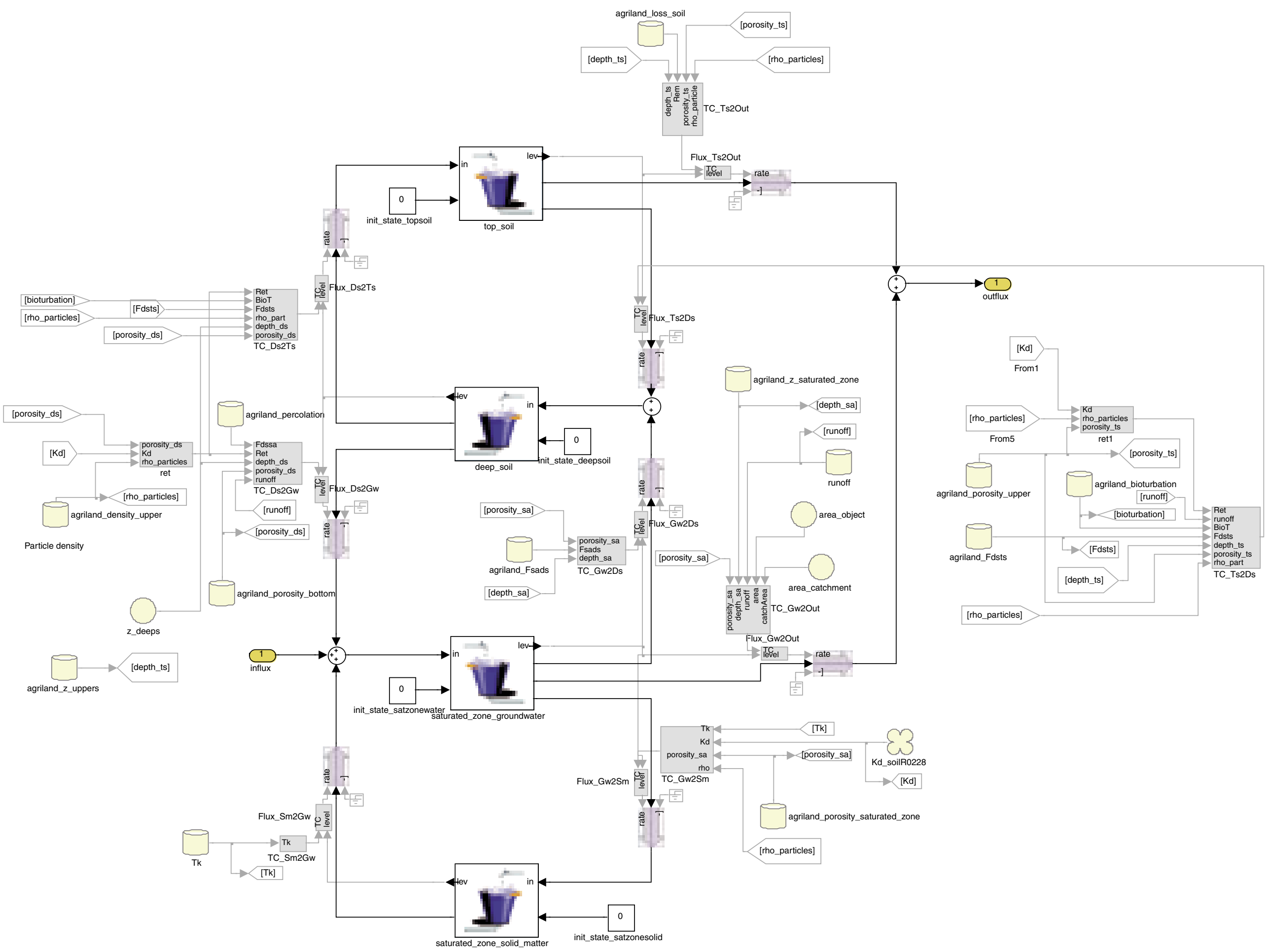


__Figure 5-9.__ The model that describes the transport and accumulation of radionuclides for an agricultural land. Orange symbols are radionuclide fluxes into and out of the system. Large boxes denote the amount of radionuclides within the system, distinguished into soluble and particulate phases, whereas the smaller grey boxes are transfer coefficients used to calculate fluxes. Yellow circles show object-specific parameters, whereas yellow cylinders are site-generic parameters (but the Tk-cylinder is half-time to sorption equilibrium and is further treated in /Avila 2006/). Yellow propellers show radionuclide-specific parameters. Large arrows show fluxes of radionuclides between compartments, whereas small arrows show how functions and parameters are connected within the model. From /Avila 2006/. The parameter z_deeps is objects-specific in the figure for future conditions (see Chapter 6), but is treated as site-generic in the text below for present conditions.

5.5.4 Radionuclide model parameterisation

This section describes assumptions relating to parameterisation of the site-generic parameters in the conceptual radionuclide model (described above). The parameter name within brackets is the name in the radionuclide model. The parameter values are presented in Appendix 1.

Regolith

Depth of top regolith (z_uppers)

Defined as the depth of the plough layer in agricultural soils. The value is from /Karlsson et al. 2001*/.

Porosity of top regolith (porosity_upper)

The value is from measurements from two trenches in Forsmark /Lundin et al. 2005*/. In the Forsmark region, a majority of the agricultural land is situated on till. Therefore, the porosity of till is used, even though the values are from a forest area instead of an agricultural area. The value is calculated as the average porosity in six samples from the upper 25 cm of a soil profile.

Density of top regolith (density_upper)

The value is from measurements of dry bulk density from a large trench in a forest on clayey till /Lundin et al. 2005*/.

Depth of deeper regolith (z_deeps)

The value is the calculated median depth to bedrock in a soil depth model of Forsmark /Vikström 2005*/. The data to the model was information from bore holes, probings and machine-cut trenches as well as interpreted soil depths from geophysical investigations.

Porosity of deeper regolith (porosity_bottom)

The value is based on 22 measurements of pore volume in samples collected at > 80 cm depth. The data are from two large trenches in Forsmark /Lundin et al. 2005*/.

Density of deeper regolith (density_bottom)

The value is the dry bulk density from 14 samples collected at > 80 cm depth in two large trenches in Forsmark /Lundin et al. 2005*/.

Depth of saturated zone (z_saturated_zone)

This estimate is based on data from an agricultural land on Storskäret, Forsmark /Werner and Lundholm 2004*/.

Porosity of saturated zone (porosity_saturated_zone)

The porosity in aquifers may vary considerably between 30 to 60% in unconsolidated deposits /Grip and Rodhe 1985/. In order not to underestimate the upward transport of radionuclides 30% was selected as a reference value, with a selected range from 25 to 40%. The reference value is based on /Karlsson et al. 2001*/.

Soil removal (loss_soil)

The soil erosion value is based on studies presented in /Karlsson et al. 2001*/.

Hydrology

The water balance data presented in this report are calculated values from the near-surface hydrological model for Forsmark /Bosson and Berglund 2006*/ The physically based and spatially distributed modelling tool MIKE SHE was used for the near-surface hydrological modelling. The model is driven by local meteorological data from the Forsmark area for 2003–2004. Meteorological input data to the model are temperature, potential evapotranspiration and precipitation. The actual evapotranspiration and its different components (transpiration, evaporation from soil, interception) was calculated in timesteps less than periods of twenty-four hours during the simulation.

Precipitation (precipitation)

The precipitation is based on local meteorological data from the Forsmark area from 2003–2004 /Bosson and Berglund 2006*/.

Runoff (runoff)

The parameter "runoff" represents the annual amount of water leaving the model domain (see above) in the river network and as direct runoff to the sea.

Downward flow (percolation)

The MIKE SHE model consists of a number of compartments; overland, unsaturated zone and saturated zone. The parameter "Downward flow (percolation)" represents the annual water flow from the unsaturated zone to the saturated zone.

Upward flow deep soil to top soil (Fdsts)

The MIKE SHE model consists of a number of compartments; overland, unsaturated zone and saturated zone. The parameter "Upward flow deepsoil to topsoil (Fdsts)" represents the annual water flow from the saturated zone to the overland compartment, i e the water flow from the groundwater to wetter areas on the ground.

Upward flow (Fsads)

The value for the transpiration given in this report is the annual mean transpiration from the model area, i e a mean value both in time and space. The area is dominated by coniferous trees, but the value of the transpiration represents a mean for all the different types of vegetation within the model area.

Biota

Productivity of primary producers weighted over the area of the object (productivity_ plants)

Productivity of crops was estimated using information of the three most commonly grown crops (barley, rye, potatoes) in Forsmark parish during 1990, 1995 and 1999, and taking the area weighted average yield for these crops during this period using information in Tables 4-24 and 4-25 in /Miliander et al. 2004*/. Carbon content was assumed to be 46.1% of the dry weight /Fridriksson and Öhr 2003*/, which was 0.85 of the fresh weight /Miliander et al. 2004*/.

Productivity of secondary producers (productivity_animal)

Secondary producers comprise cattle, hare, voles, mice and roe deer. Productivity of cattle (including both meat and milk production) is from /Lindborg 2005*/ (Table 3-50, 3-70) and is averaged over the arable land and seminatural grasslands. The number of cattle is calculated based on a number of assumptions presented in /Miliander et al. 2004*/. Productivity for the other animals are from /Lindborg 2005*/, where the productivity for roe deer also have been adjusted according to the hunting pressure in the area /Lindborg 2005*/.

Productivity of food normally consumed (productivity_food)

This parameter includes productivity of crops (above) and cattle and wild game. These figures are extracted from the two parameters above. Cattle and wild game contribute less than 5% of the total productivity and statistics, describing minimum, maximum and standard deviation, are therefore based upon the statistics describing crop production.

Productivity of edible products (productivity_edible)

This parameter comprises the parameter above and potential food not consumed today, e.g. worms in contrast to tree trunks. Earthworms are therefore included and production is estimated assuming a yearly biomass turnover. Biomass estimates are from a grassland in Uppland /Lindborg 2005*/. Cattle, wild game and earthworms contribute less than 9% of the total productivity, and statistics, describing minimum, maximum and standard deviation, are therefore based upon the statistics describing crop production.

Transport of soil by earthworms (bioturbation)

This is an estimate of how much soil that is transported by soil organisms in the soil /Karlsson et al. 2001*/.

5.6 Forest

The forests are dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) situated mainly on wave washed till. The spruce becomes more abundant where a deeper soil cover is found along with more mesic-moist conditions. Outcrop is not a prevalent substrate in the Forsmark area, making pine forest on acid rocks quite scarce. The calcareous soil material provides nutrient-rich conditions, which can be seen in the predominant humus forms of mull type and of the intermediate moder type /Lundin et al. 2004/, indicating a rich soil fauna. Because of the young age of the soils, the Forsmark area exhibits less soil of Podsol type than most similar areas in Sweden. Instead, the typical soil types are the less developed Regosol soils, together with Gleysols and Histosols, which are formed under moist conditions. The field layer is heavily influenced by the calcareous content and is characterised by herbs and broad-leaved grasses along with a number of orchid species. The deciduous tree species are dominated by *Betula pendula*, *Alnus glutinosa* and *Sorbus acuparia*, but also *Acer platanoides* and *Fraxinus excelsior* are fairly common. Especially *F. excelsior* may be abundant along sheltered seashores. *Quercus robur* and *Ulmus glabra* are close to their northern limit and are very scarce.

The Forsmark area has a long history of forestry, which is seen today as a fairly high percentage of younger and older clear-cuts in different successional stages in the landscape. *Betula pendula* is the dominate species in many of the earlier successional stages until it is replaced by young *Norway spruce* or *Scots pine* depending on soil type and/or management.

5.6.1 Major flows and processes

The soil carbon pool is the largest carbon pool in the terrestrial environments of Forsmark /Lindborg 2005/. The primary producers are also a large carbon pool, whereas the total biomass of herbivores and carnivores is small. The latter may, however, be important due to the relative high carbon flow (in relation to weight) through herbivores. This pool also includes several species, which are regularly hunted by humans. The largest flux of carbon leaving forests (except for autotrophic respiration) is the heterotrophic soil respiration /Lindborg 2005/.

Boreal forests are generally assumed to be a sink for carbon /Schlesinger 1997/. This sink can be attributed to the building up of biomass in the vegetation and carbon accumulation in the soil. A downward flow of carbon from the leaching of DOC from the litter layer, may be as high as 10% of the litter fall /Persson and Nilsson 2001/. The DOC becomes less mobile in lower soil horizons /Neff and Ashner 2001, Berggren et al. 2003/. This fraction is probably a substantial part of the carbon that is retained over time in woodland soils.

The main transport from the terrestrial ecosystem is that of dissolved organic carbon (DOC) via more or less diffusive discharge, which is related to the precipitation. This carbon flux is, however, comparably low in comparison to other carbon fluxes within the ecosystem /Algesten et al. 2004, Humborg et al. 2004, Canhem et al. 2004/.

5.6.2 Development over time

The uplift of land continuously create new terrestrial areas. The most important abiotic conditions, affecting the vegetation community on the sea shore, are the soil type, the degree of exposure and the salinity /Jerling 1999/. The soil type is strongly connected to the degree of exposure, where more wave exposed areas contain larger stone fractions than areas with low exposure. Studies of the vegetation on the Baltic sea shores show that emerging areas are rapidly colonised by vegetation /Ericson and Wallentinus 1979/. Because of the flooding frequency and salt spray intensity, the vegetation composition does not change independently from the land uplift rate until many years after emergence of sites from the sea /Cramer 1986/. The Baltic sea shore can be divided into four different types: rocky shores, shores with wave-washed till, sandy shores and shores with fine sediments. In the Forsmark area, shores with wave-washed till are the most common; rocky shores and shores with fine sediments do occur. The flat emerging till shores outside Forsmark have a sea shore vegetation zonation that is defined from their tolerance to water inundation and salt sprays /Jerling et al. 2001, Jerling 1999/. The first pioneer woody species is Hawthorn (*Hippophaë rhamnoides*) closely followed by the tree Alder (*Alnus glutinosa*). Both these species have a litter that is rich in nitrogen and this facilitates the establishment of many species. From bushes and trees a varied light environment and new habitats are created. In this way, the flora and vegetation is steadily changing but with a relatively high degree of determinism /e.g. Svensson and Jeglum 2000/. In most areas with a thicker soil layer, the Norway spruce forest has to be regarded as the climax vegetation type in this area. Although Scots pine is abundant too, it would probably be more restricted to areas with a shallower, more nutrient poor soil layer, if forestry management were to decrease and fire, again, was to become a natural disturbance in the landscape /Sjörs 1967, Engelmark and Hytteborn 1999/.

5.6.3 Simplified radionuclide model

A schematic view of the numerical model that describes the transport and accumulation of radionuclides in forests is presented in Figure 5-10. The figure shows the different parameters and how these are related in order to describe fluxes of radionuclides. The site-generic parameters are presented in further detail below whereas object-specific parameters are treated in Chapter 6

5.6.4 Radionuclide model parameterisation

This section describes assumptions and data behind the parameterisation of the site-generic parameters in the conceptual radionuclide model (described above). The parameter name within brackets is the name in the radionuclide model. The parameter values are presented in Appendix 1.

Regolith

Depth of top regolith (z_uppers)

This depth is defined as the fine root zone depth. /Lundin et al. 2005*/ investigated the fine root depth in a large trench in Forsmark, characterised by fresh mosses in the bottom layer, low herbs or bilberry type in the field layer and trees comprising pine, spruce and birch. The fine root depth in the mineral soil and the thickness of the humus layer were determined independently. So the mean humus layer thickness was added to the mean fine root depth in the mineral soil and the median added to the median etc. Total standard deviation was calculated according to the formula:

$sd_{tot} = sqrt(sd_1^2+sd_2^2)$.

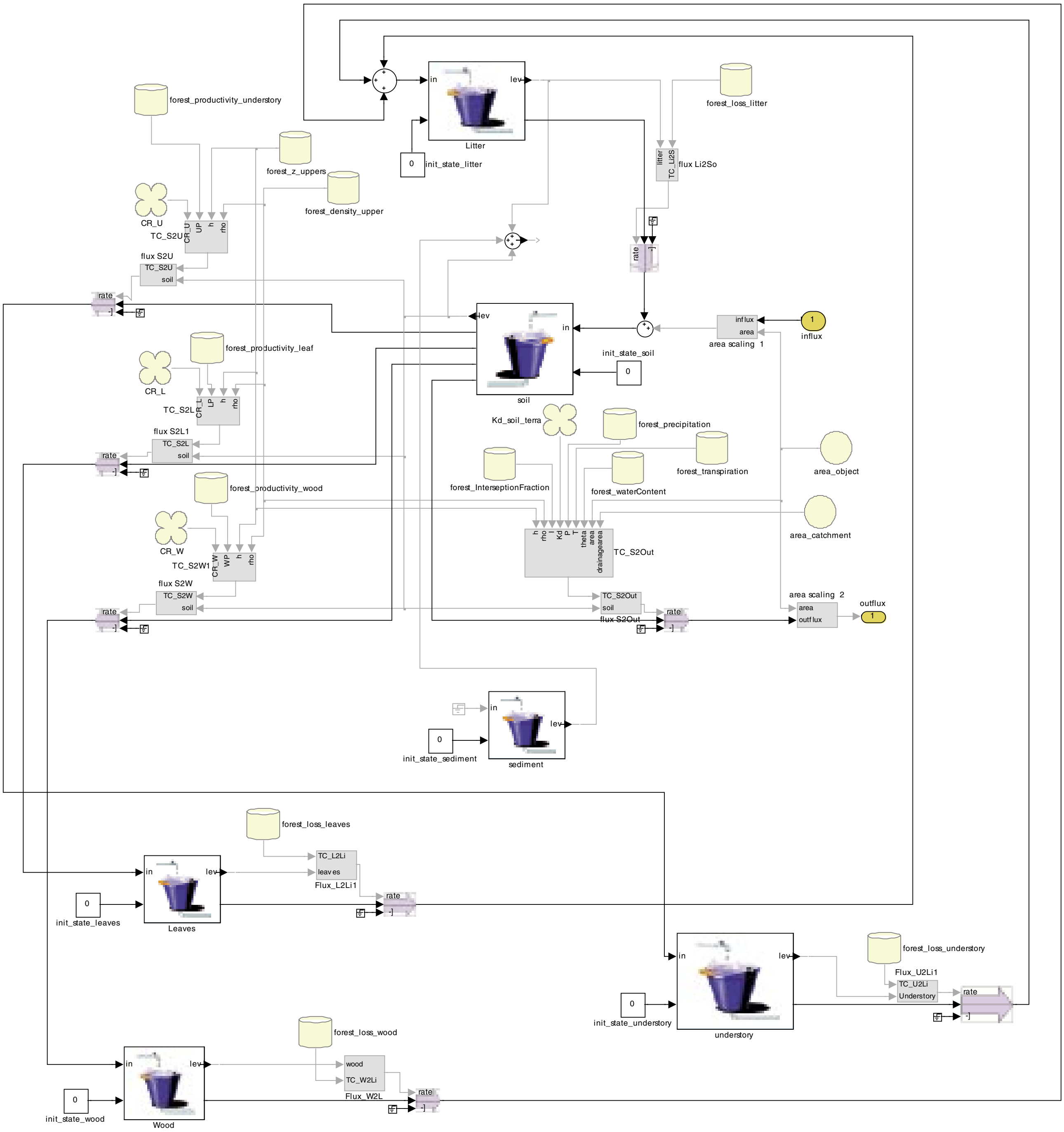


Figure 5-10. *The model that describes the transport and accumulation of radionuclides for a forest. Orange symbols are radionuclide fluxes into and out of the system. Large boxes denote the amount of radionuclides within the system, distinguished into soluble and particulate phases, whereas the smaller grey boxes are transfer coefficients used to calculate fluxes. Yellow circles show object-specific parameters, whereas yellow cylinders are site-generic parameters (but the Tk-cylinder is half-time to sorption equilibrium and is further treated in /Avila 2006/). Yellow propellers show radionuclide-specific parameters. Large arrows show fluxes of radionuclides between compartments, whereas small arrows show how functions and parameters are connected within the model. From /Avila 2006/.*

Density of top regolith (density_upper)

/Lundin et al. 2004*/ have measured the dry bulk density in five horizons of the upper 0.6 m of the mineral soil from four sites located in Regosol/Gleysol in spruce forest at Forsmark. The value for the density (i e the mean value and the standard deviation) is based on 17 measurements.

Volumetric water content in soil (waterContent)

The value is the mean of measurements on 16 samples from the upper metre in a large trench in Forsmark /Lundin et al. 2005*/.

Hydrology

The water balance data presented in this report are calculated values from the near-surface hydrological model for Forsmark /Bosson and Berglund 2006*/ The physically based and spatially distributed modelling tool MIKE SHE was used for the near-surface hydrological modelling. The model is driven by local meteorological data from the Forsmark area for 2003–2004. Meteorological input data to the model is temperature, potential evapotranspiration and precipitation. The actual evapotranspiration and its different components (transpiration, evaporation from soil, interception) was calculated in timesteps less than periods of twenty-four hours during the simulation.

Precipitation (precipitation)

The precipitation is based on local meteorological data from the Forsmark area from 2003–2004 /Bosson and Berglund 2006*/.

Evaporation (evaporation)

The value for the evaporation given in this report is the annual mean evaporation from the model area, i e a mean value both in time and space.

Transpiration (transpiration)

The value for the transpiration given in this report is the annual mean transpiration from the model area, i.e. a mean value both in time and space. The area is dominated by coniferous trees, but the value of the transpiration represents a mean for all the different types of vegetation within the model area.

Interception fraction (InterceptionFraction)

The value for the interception fraction given in this report is the annual mean interception fraction for the model area, i e a mean value both in time and space. The area is dominated by coniferous trees, but the value of the interception fraction represents a mean for all the different types of vegetation within the model area.

Biota

Norway spruce and Scots pine of mesic types with some intermixed deciduous trees are the most commonly found forest type in the area and most estimates concerning the vegetation are therefore representing this vegetation type, if not otherwise stated.

Understorey biomass (biomass_understorey)

/Löfgren 2005*/ investigated biomass of the field and bottom layer on six site types with different soils. Here the estimate used from the Regosol/Gleysol soil site type /Lundin et al. 2004/ from a coniferous forest with tall herbs without shrubs in the field layer and mesic mosses in the bottom layer. A mean of 0.45 from /Fridriksson and Öhr 2003*/ was used to convert dry weight to the carbon content.

Tree leaves biomass (biomass_leaves)

Data from 368 plots within the Swedish National Forest Inventory /Anonymous 2002/ classified as coniferous forest (Norway spruce dominates) older than 30 years was used to estimate the biomass of needles. This fraction also includes the smallest fraction of branches. The plots are located within and in the immediate neighbourhood of the regional model area. Carbon content is assumed to be 0.49 of the dry weight /Alriksson and Eriksson 1998/.

Tree wood biomass (biomass_tree)

Data from 368 plots within the Swedish National Forest Inventory /Anonymous 2002/ classified as coniferous forest (Norway spruce dominates) older than 30 years was used to estimate the biomass of wood. The plots are located within and in the immediate neighbourhood of the regional model area. Wood from the stem (without bark) and the branches are included. Carbon content is assumed to be 0.49 of the dry weight /Alriksson and Eriksson 1998/.

Productivity of food normally consumed (productivity_food)

Products normally consumed from the forest comprise fungi, berries, roe deer, moose and mountain hare. The estimate of edible fungi production (40 kg/ha) is based on a three year field study between 1974 and 1977 /Eriksson and Kardell 1987/, while berry production is based on production estimates from forests of lingonberry, bilberry and raspberry between 1975 and 1977 ($429 \cdot 10^6$ kg y^{-1}) /SCB 1999/. Berry production was divided by the total forest area in Sweden /Statistics Sweden 1998/. The carbon content is assumed to be 1.2% in fresh fungi and 10% in fresh berries /Lindborg and Kautsky 2004*/. Production estimates of the most hunted mammals are based on densities in the area /Truvé and Cederlund 2005*/.

Yearly production of understorey plants (productivity_understorey)

/Löfgren 2005*/ investigated the production of field and bottom layer on six different soil types. The field layer was harvested at the time of peak biomass and all biomass produced during the year was taken as an estimate of the production. Bryophyte production was estimated from shoot elongation. Here, the estimate used is from the regosol/gleysol soil type /Lundin et al. 2004*/ from a coniferous forest with tall herbs without shrubs in the field layer and mesic mosses in the bottom layer. A mean of 0.45 from /Fridriksson and Öhr 2003*/ was used to convert dry weight production to the carbon content.

Yearly production of tree leaves (productivity_leaf)

Data from 368 plots within the Swedish National Forest Inventory /Anonymous 2002/ classified as coniferous forest (Norway spruce dominates) older than 30 years was used to get an estimate of the production of needles. The plots are located within and in the immediate neighbourhood of the regional model area. The net annual increase of needles was calculated as a function of the stem biomass increase using values from a nearby study area (0.13 of the annual stem biomass increase is the annual needle biomass increase, Knottåsen, /Berggren et al. 2004/). To that figure the litter fall was added, using the assumption of a steady state between litter fall and production. The litter fall was estimated using a figure from a moist Norway spruce forest in same study area (0.22 of the needle biomass was shed each year, /Berggren et al. 2004/). Carbon content is assumed to be 0.48 of the dry weight /Alriksson and Eriksson 1998/.

Yearly production of tree wood (productivity_wood)

Data from 368 plots within the Swedish National Forest Inventory /Anonymous 2002/ classified as coniferous forest (Norway spruce dominates) older than 30 years was used to estimate the yearly production of wood. The plots are located within and in the immediate neighbourhood of the regional model area. The variable "AVSTILLV" in the Swedish National Forest Inventory was converted from volume to dry weight using a conversion factor from /Fink et al. 2003, 0.404/. Carbon content is assumed to be 0.48 of the dry weight /Alriksson and Eriksson 1998/.

Yearly fractional loss of understorey plants biomass (loss_understorey)

Figures from /Löfgren 2005*/ was used to describe the fraction that was lost from the aboveground component of grasses, herbs and dwarf shrubs from a regosol/gleysol soil type /Lundin et al. 2004*/ in a coniferous forest with tall herbs and few shrubs in the field layer, and mesic mosses in the bottom layer. All non-woody tissue (except for *Vaccinium vitis-idaea* that is evergreen) was assumed to be lost, while woody tissue was retained. No bryophyte loss is included in this estimate.

Yearly fractional loss of litter biomass (loss_litter)

An estimate was taken from /Chapin et al. 2002/ concerning a mixed forest.

Yearly fractional loss of tree leaf biomass (loss_leaves)

The mean fraction lost by litter fall was estimated using a figure from a moist Norway spruce forest in a nearby study area (0.22, /Berggren et al. 2003/). Minimum and maximum values were taken from the dry and mesic plots, respectively.

Yearly fractional loss of tree wood biomass (loss_wood)

The figure was taken from /Garten 1999/.

Tree life time (lifelength_tree)

A mean tree life length of 300 years was assumed for Norway spruce (not taking consequences of forestry into account), whereas the minimum was defined by when a tree becomes a tree, passing a height of 1.3 m.

Fraction of tree leaves in the diet of moose (food_leaves_moose)

Based on a literature survey presented in /Truvé and Cederlund 2005*/.

Fraction of mushrooms in the diet of moose (food_mush_moose)

Based on a literature survey presented in /Truvé and Cederlund 2005*/.

Fraction of understorey plants in the diet of moose (food_plants_moose)

Based on a literature survey presented in /Truvé and Cederlund 2005*/.

Fraction of tree wood in the diet of moose (food_wood_moose)

Figures from /Cederlund et al. 1980/.

Fraction of tree leaves in the diet of roe deer (food_leaves_deer)

Based on a literature survey presented in /Truvé and Cederlund 2005*/.

Fraction of mushrooms in the diet of roe deer (food_mush_deer)

Based on a literature survey presented in /Truvé and Cederlund 2005*/.

Fraction of understorey plants in the diet of roe deer (food_plants_deer)

Based on a literature survey presented in /Truvé and Cederlund 2005*/.

Fraction of tree wood in the diet of roe deer (food_wood_deer)

Figures from /Cederlund et al. 1980/.

Body weight of a roe deer (weight_deer)

The body weight of carbon is 22.9% of the fresh weight. Body weight presented in /Truvé and Cederlund 2005, Appendix 1*/.

Body weight of a moose (weight_moose)

The body weight of carbon is 22.9% of the fresh weight. Body weight resented in /Truvé and Cederlund 2005, Appendix 1*/.

5.7 Well

In the Forsmark area, the groundwater table is generally very shallow. Groundwater monitoring at the site /Johansson et al. 2005/ shows that the groundwater level in the majority of the groundwater wells is located between the ground surface and a depth of one metre. However, it is not only the groundwater level that is important for the location of a well. The geology has large influence on the capacity of the well. The transmissivity of the bedrock or the Quaternary deposits has to be high enough for the water to flow to the well /Grip and Rodhe 1985/.

The well capacity can be good both in discharge and recharge areas. The topography in Forsmark is very flat, which makes it possible to locate a well even in local high areas. The well creates a local discharge area if it is in use /Grip and Rodhe 1985/. Although the capacity of the well depends more on the geology than of the topography, often the preferred geological and topographic conditions coincide; valleys between high altitude areas are often filled with thick layers of Quaternary deposits.

The overburden in Forsmark is dominated by sandy till. The transmissivity of this fine grain till can be limiting for the water flow to the well and it is necessary to find highly conductive layers of sand or gravel of sufficient extent to ensure the water supply in the well /Grip and Rodhe 1985/. For drilled wells in the bedrock, it is the fracture zones that play an important role for the water supply. The well capacity is limited by the hydraulic conductivity of the fractures close to the well.

5.7.1 Major flows and processes

The well creates a local discharge area for the water if it is in use /Grip and Rodhe 1985/ and the transport of organic material is generally low, due to percolation through Quaternary deposits.

5.7.2 Development over time

The well capacity and the quality of the water in the well can deteriorate. Meteorological conditions can affect the water supply of the well (a drier climate will cause a lowering of the water levels in the area) but also human activities can cause a decreased water supply in a well. Excavations, ditching or large water outtake in the surroundings can cause a lowering of the water table and the capacity of the well will decrease /Grip and Rodhe 1985/. The impact on a well from excavations or water outtake is largest in coarse soils.

The quality of the water can be affected by different kind of pollution in the area. Dry or wet deposits of chemicals in the drainage area of the well will be dissolved by the water and transported to the well.

5.7.3 Simplified radionuclide model

The concentration of the radionuclide in the well water was calculated by dividing the release rate by the well capacity /Avila 2006/.

5.7.4 Radionuclide model parameterisation

This section describes assumptions and data behind the parameterisation of the site-generic parameters in the conceptual radionuclide model (described above). The parameter name within brackets is the name in the radionuclide model. The parameter values are presented in Appendix 1.

Hydrology

Capacity of the well to deliver water (wellcapacity)

The capacity of wells in Forsmark is taken from /Gentzschein et al. 2006*/. A list of the wells in the Forsmark area is presented in that report, the value used is the mean well capacity of the listed wells.

5.8 Uncertainties in the site-generic parameterisation

The site-generic parameterisation is in most cases derived from investigations made at the site. This ensures that local conditions are used to constrain the possible output from the biosphere radionuclide modelling. However, some aspects of uncertainty associated to spatial and temporal variation, and to the extrapolation of today's site properties to the future, are discussed below.

5.8.1 Spatial and temporal variation

In the present work we have, for most of the parameters, beside an estimate of the central value, also estimates of standard deviation and min and max values, in order to describe the potential variation under present conditions. These estimates are a basis for sensitivity analysis that pin-point the relative importance of different parameters under present conditions (see Section 8.1.5 and /Avila et al. 2006/. However, some of the field estimates do not have neither the spatial, nor, and perhaps more important, the temporal extension that would be desirable in a short-term perspective (e.g. 100 years). This implicates that the described variation for some parameters at the site does not comprise the potential variation range, even though the estimated mean may be close to the true mean even for a longer time period. E.g. the modelling of climate parameters, such as precipitation and run-off lacks a variation range in this version (see Appendix 1). In the case of run-off the variation range has been shown to be rather low, approximating 10%

/Larsson-McCann et al. 2002/. Similarly, most of the parameters describing the regolith have a rather low range, which further emphasize the use of, so called, site-generic parameters in comparison to parameters describing a specific Biosphere Object, e.g. areas or volumes (described in Chapter 6). However, in future versions some of the site-generic descriptions with a large variation range will be replaced by a Biosphere Object specific description. Generally, the variation range or range of the site-generic parameter statistics have to be regarded as low in comparison to the uncertainties associated with the radionuclide specific parameterisation that is presented in /Avila 2006/.

5.8.2 Future conditions

The parameterisation of the situation today is used for the modelling of future conditions as far as to 50,000 AD. This modelling includes both permafrost conditions and a greenhouse variant, both of which will have profound effects on e.g. production and the hydrological cycle. In some cases, the estimated parameters together with their measures of variation will, most certainly, be valid even under permafrost conditions, e.g. the porosity of peat in a mire or the density of soil used for agriculture purposes. In other cases the estimates will be overestimates for permafrost conditions, such as tree net primary production or bioturbation. Still, as pointed out above, the variation generated by a changing climate, will probably be subordinate to the large range found in radionuclide specific parameterisation. However, these issues will be further penetrated in later versions as a result of the feedback from the sensitivity analyses, described in Section 8.1.5 and /Avila et al. 2006/.

6 Landscape model

The landscape, into which radionuclides may be released, is comprised of a number of different terrestrial and aquatic ecosystems (see Chapter 5). In order to model the fate of a potential radionuclide release into the biosphere, the specific ecosystems subjected to such an release, here called Biosphere Objects, are interconnected by the major water flows. The potential discharge points i.e. the exit points from the deep ground water modelling /Hartley et al. 2006/, are in this chapter used as input to define the spatial configuration of the landscape model. The main objective in this chapter is to describe the methods and input data used to define the spatial and temporal extent of the Biosphere Objects and their interconnections in the landscape model. In Chapter 5, the different ecosystems and their corresponding dose models are presented along with their site-generic parameterisation, and in Chapter 8 a dose model, based on the landscape model, is presented.

The time span for the landscape development concerns the period 8,000 BC to 9,000 AD, evaluated in time steps of 1,000 years. The duration is considered to be typical of a temperate interglacial during which it is anticipated that substantial changes in the landscape will occur (cf Chapter 4). It should be noted that the modelling was based on the assumption that the current climate condition is valid for the whole period modelled. In contrast, the time span for the radionuclide modelling stretches over a temperate period (an interglacial period) and a permafrost period (a glacial period) beyond 10,000 AD until 50,000 AD, see Figure 2-4 and Chapter 8. In addition, a greenhouse variant, in which temperate conditions prevailed was modelled.

In this section, we describe the different steps involved in building the landscape model from site data, presenting the methodology, the delimitation of Biosphere Objects, and how to link them into a landscape model. Finally, we describe the methodology for landscape development over time. The different steps in the development and parameterization of a landscape model can be described as:

1. visualisation of the potential Discharge Points (DP) on a land use map,
2. identification of Biosphere Objects by identifying clusters of DP's on the map, assigning each cluster to a specific ecosystem and delimiting the Biosphere Object. Areas situated downstream identified objects, and identified by the future lake model as future lakes, were also identified as Objects,
3. construction of the Landscape model by linking the Biosphere Objects based on current and future drainage patterns,
4. description of the development over time for each Biosphere Object,
5. compiling a database describing each Biosphere Object, through object-specific parameters, at each time step.

The database with the object-specific parameters may be retrieved, upon request, from SKB.

6.1 Input data

A large part of the information in the analysed Geographical Information System (GIS) layers was based on other models, see for example /Brydsten 2006b/ (elevation); /Johansson et al. 2005/ (hydrology) and /Lindborg 2005/ (terrestrial) for site-specific data. In Table 6-1, various input datasets and models are identified. The interrelationship between the input models and the landscape model is shown in Figure 6-1.

Table 6-1. The descriptive data that was used during the GIS modelling along with the data location, the dates and the references where data is presented.

GIS data	Name in /SKB GIS database 2006/	Date	Report reference
DEM	SDEADM.UMEU_FM_HOJ_3085	2005-06-28	/Lindborg 2005/
Shoreline displacement	Equation from /Påsse 1997/ applied in the DEM	–	/Brydsten 2006b/
Regolith (land)	SDEADM.SGU_FM_GEO_1935	2004-01-21	/Sohlenius et al. 2004/
Boulderness (land)	SDEADM. SGU_FM_GEO_1936	2004-01-21	/Sohlenius et al. 2004/
Regolith (sea)	SDEADM.SGU_FM_GEO_2630, SDEADM.SGU_FM_GEO_2632	2003-06-03	/Elhammer and Sandkvist 2005/
Soil	SDEADM.SLU_FM_GEO_1901	2002	/Lundin et al. 2004/
Hydrological model	Not stored in the database. Created from the DEM, with the Hydrology Modelling Tool in ArcGIS 9.0.	–	/Löfgren and Lindborg 2003, Appendix 1, Bosson and Berggren 2006/
Vegetation map (land)	SDEADM.SWP_OST_BIO_1256	2002-08-29	/Boresjö Bronge and Wester 2003/
Vegetation map (sea)	SDEADM.HSK_FM_BIO_2636	2005-05-25	
Historic map	http://www.humangeo.su.se/kartburken/	2005-03-29	/Jansson et al. 2004/
Lake characterization	SDEADM.UMEU_FM_VTN_1972	2004-01-29	/Brunberg et al. 2004/
Catchment	SDEADM.UMEU_FM_VTN_1938–1970 and SDEADM.UMEU_FM_VTN_1973–1980	2004-01-29	/Brunberg et al. 2004/
Future lakes and water courses	Not yet stored in the database.	–	/Brydsten 2006b/
Future catchment	Not yet stored in the database.	–	/Brydsten 2006b/
Lake sedimentation	Not yet stored in the database.	–	/Brydsten 2006b/
Basin table	Not yet stored in the database.	–	/Brydsten 2006b/
Accumulation bottom	Not yet stored in the database.	–	/Brydsten 2006b/
Land use	SDEADM.LMV_FM_FK_MY_324	2003-09-25	/Lindborg 2005, Miliander et al. 2004/

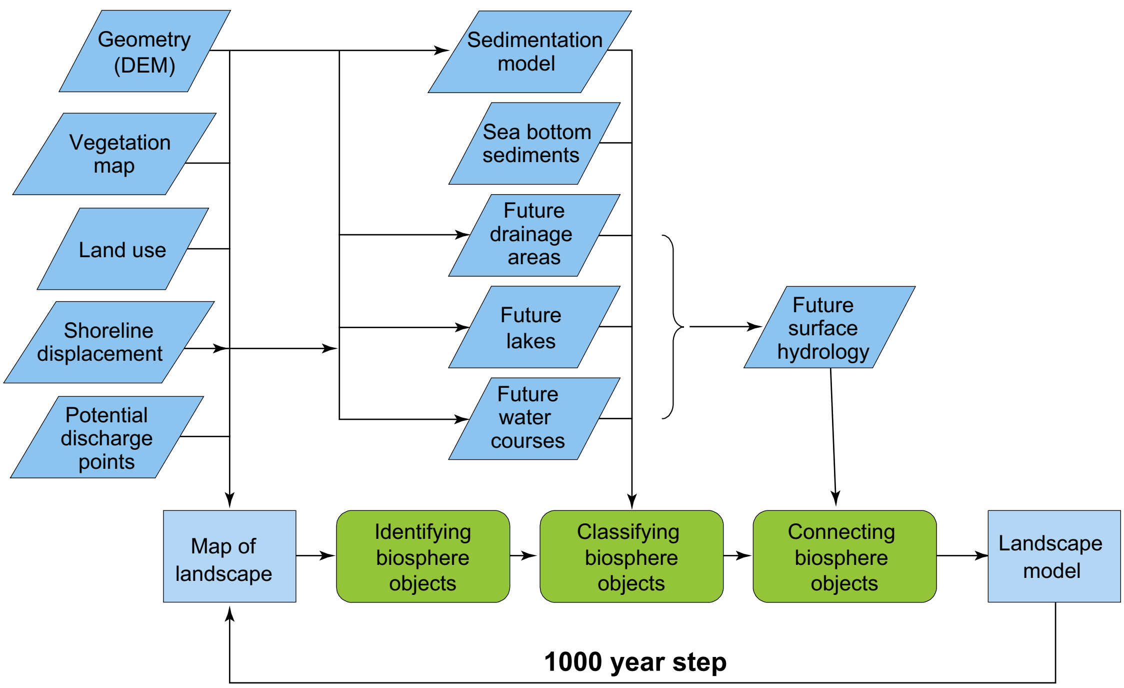


Figure 6-1. *Flow chart describing the iterative process of constructing a landscape model. The blue boxes show different input models, green boxes represents actions described in this chapter. This process generates a landscape model for time steps of 1,000 years, describing the configuration and succession of Biosphere Objects in the landscape.*

6.2 Visualisation of Discharge Points and identification of Biosphere Objects

Based on the radionuclide transport modelling of the rock /Hartley et al. 2006/, potential Discharge Points (DP) from a hypothetical repository were presented in a GIS. In this report, we have used the DP results from Realisation 3 of the reference case SC_HCD3_AC_HRD3EC3 in the transport modelling. The transport modelling of the rock uses both continuum and discrete fracture network models on many scales, to investigate the radionuclide transport from each canister position in the potential disposal facility, up to the biosphere, and a discussion on the uncertainties associated with the different models is provided in Section 6.8. In Figure 6-2, the DP's are plotted in the landscape according to the time of particle release from the repository, which started 2,020 AD and continued in steps of 1,000 years until 9,000 AD. The results from

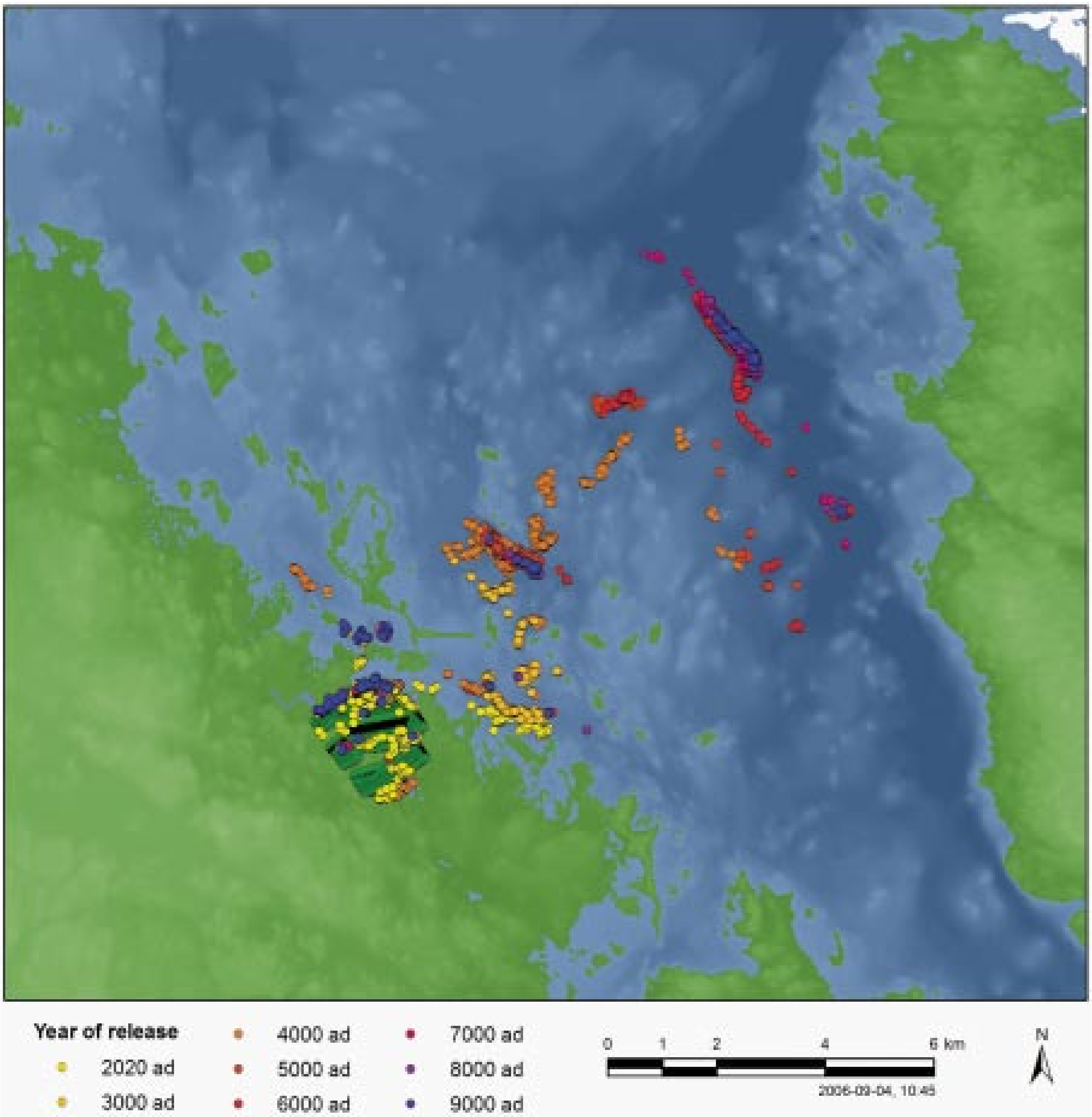


Figure 6-2. *Forsmark site with the potential location of the repository (green dots) and the potential discharge points over time from realisation 3 of the reference case SC_HCD3_AC_HRD3EC3 in the transport modelling /Hartley et al. 2006/. The different colours of potential discharge points show from which 1,000 year period of release from the repository (2,020 AD – 9,000 AD) the potential discharge point is derived.*

this exercise show that discharge points are attracted to nearby low elevation points in the landscape, e.g. shorelines, lakes and mires. This was further confirmed by a study of surface and near surface hydrology with the MIKE-SHE model, that has a higher resolution of the surface and near surface regime /Bosson and Berglund 2006/. Moreover, the future DP's are for the most part located in areas which are covered by the sea today. The potential DP's, with the time for advective transport added to the release time, were also plotted over time, but this did not differ much from the pattern in Figure 6-2. The location of the DP's may be affected by future hydraulic changes, however, such hydraulic changes were not included in the transport model /Hartley et al. 2006/.

Together with maps of land use and vegetation, the DP's were visualised and clusters of DP's were identified. Generally, each identified cluster fell within a specific ecosystem (see Chapter 5 for a description of ecosystems). Accordingly, each cluster was assigned to the specific ecosystem and a Biosphere Object was delimited based on the spatial extent of the ecosystem, as described below. Very few DP's were isolated from the identified clusters, and the isolated points found were transferred to the closest object downstream. This procedure was repeated until all of the DP's had been included in a Biosphere Object. To identify all possible Biosphere Objects (historical, current and future), the DP's were plotted on the map of historical and future identified sub-catchment areas, lakes and running waters. Thus, clusters of DP's were used to identify Biosphere Objects relevant both at the present day and in the future.

6.2.1 Delimitation of Biosphere Objects

For lakes as well as for terrestrial ecosystems, the borders of the Biosphere Objects were defined from the existing or projected geometry of the ecosystem, e.g. a defined shoreline of a lake, firm ground for wetlands, or borders of agriculture land. For marine Biosphere Objects, the shoreline and the future sub-catchments (called basins) of the area were used as limits for the objects. Thus, some Biosphere Objects were aggregated when they were in their sea period and shared the same drainage area.

Sea objects were created for every step of 1,000 years (8,000 BC to 9,000 AD) from existing or future catchments. If some parts of the catchment were situated on land, the land areas were excluded.

The forest objects were delimited by using the hydrological model and the Hydrology Modelling Tool in ArcGIS by defining the catchment areas upstream of the most downstream Discharge Point in a defined cluster. The geometry of these objects did not change over time.

The running water objects were delimited based on the layer with future water courses, and their lengths were defined by the shoreline at the time. Accordingly, the geometry for these objects changes over time, due to shoreline displacement.

In Forsmark, 25 Biosphere Objects were identified (Figure 6-3). Object 1 is the Baltic Sea and is assumed to be outside the boundary of Öregrundsgrepen (Object 3). Object 17 is in the drainage area situated above the potential repository. These three objects were used during the entire period from 8,000 BP to 9,000 AD, but, with changing geometry depending on the shoreline displacement (except for the Baltic Sea (1)). Running water was described with the two objects; 20 and 25. Object 20 is the entire water course from the uppermost object (24), through multiple objects, to the sea, and in the future also to the junction with object 25. Object 25 is a future large river from the northern part of Uppland (today Forsmarksån and Olandsån). The length of object 25 is estimated from the location of the junctions with object 20 and the sea.

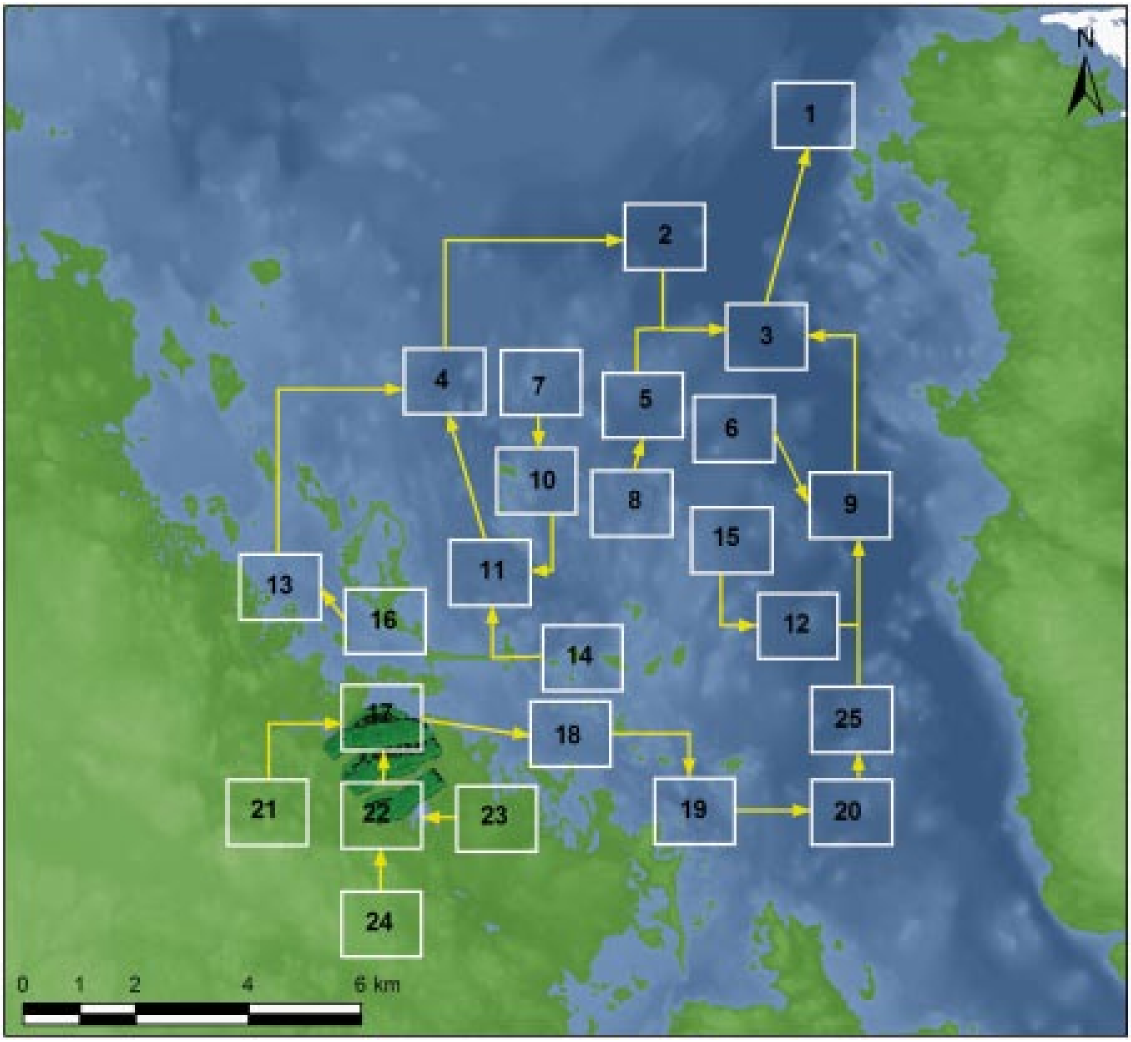


Figure 6-3. *The identified Biosphere Objects (squares) in the Forsmark area for all time steps between 8,000 BC to 9,000 AD, interconnected according to the description in Section 6.3 (arrows). The green dots below Biosphere Objects 17 and 22 show the hypothetical repository with the individual canister locations.*

6.3 Linking Biosphere Objects and their successional development

6.3.1 Linking Biosphere Objects

The defined and delimited Biosphere Objects were linked together in chains based on current and future drainage patterns, determined from the Digital Elevation Model (DEM). This procedure was reiterated for all time periods during the construction of the landscape model. The classification of the present-day Biosphere Objects into different ecosystems was done from site investigation data /Lindborg 2005/. For future and past Biosphere Objects, the classification of ecosystem type was done by a procedure described in the following section.

6.3.2 Successional development of Biosphere Objects

After construction of the current landscape model, including all the potential Discharge Points and Biosphere Objects, the landscape development over time was described. The work was performed by describing each Biosphere Object in the landscape model over time, in time steps of 1,000 years, from 8,000 BC to 9,000 AD. To create the past and future landscape, a land/sea grid for every thousand year step, from 2,000 BC when the whole area was covered by sea, to 9,000 AD, was constructed by using the DEM /Lindborg 2005/ and the shoreline displacement equation /Påsse 1997/. A generic flow chart of the work process is illustrated in Figure 6-4, and the work is further described below.

Successional development of aquatic Biosphere Objects

For each object, the location in relation to the sea level was examined by using the land /sea-grid. If the Biosphere Object was below sea level, it was classified as a sea object during the time period. The sedimentation model /Brydsten 2006b/ was run for defined time steps of 1,000 years, and thereafter the same procedure was repeated until the Biosphere Object was above sea level. The Biosphere Object was then compared with the "future lake map", created by the Future lake model /Brydsten 2006b, Påsse 1997/ (see Figure 6-5). The majority of the Biosphere Objects were defined as future lakes and the fate of these was determined by the sedimentation model /Brydsten 2006b/. The sedimentation model uses the DEM /Lindborg 2005/, the future lake model and the marine geology map /Elhammer and Sandkvist 2005/ as input when calculating sediment growth and lake infilling. One output from the sedimentation model is the proportion of lake and mire for an object at the specific time (depending on e.g. water depth). The sedimentation accumulation model was run until the whole lake basin was defined as mire. However, if less than 50% of the surface area was open water and the bathymetry of the lake basin was flat the lake was defined as a mire. For lake objects with steep bathymetry, e.g. the blasted inlet channel to the nuclear power plant, the lake stage continued until it was filled up. The steepness was not calculated and the classification was made on the basis of expert judgement.

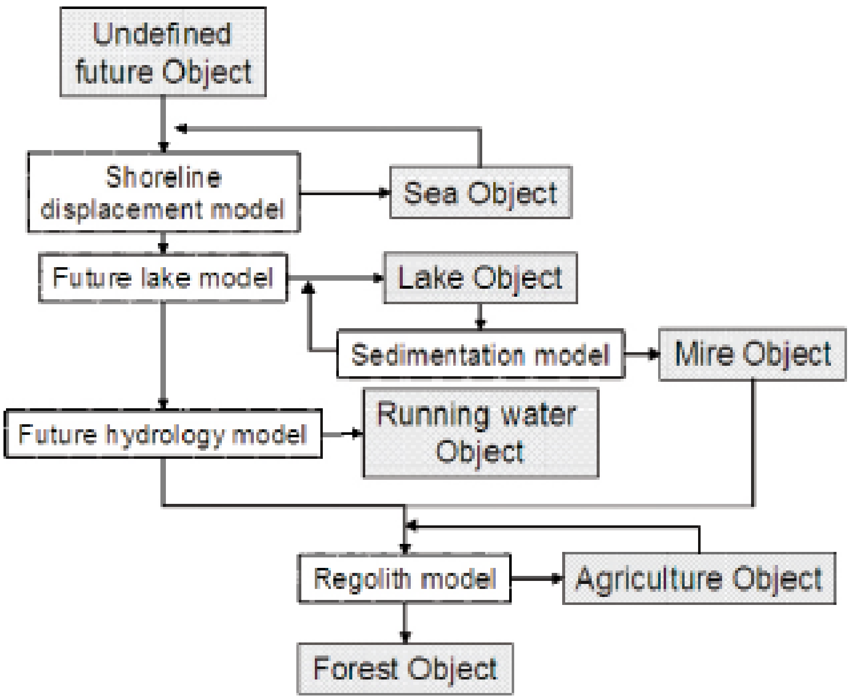


Figure 6-4. *Flow chart describing the process of assigning the successional stages of future Biosphere Objects. Each model will answer the question if an Object will be transformed to a new type of object in the next successional stage by Yes/No. If Yes, the next model in the chain is applied.*

Figure 6-5. Existing and predicted future lakes in the Forsmark area, based on the Future lake model /Brydsten 2006b/.

Successional development of terrestrial Biosphere Objects

An important factor for the fate of a mire object is the hydrology. Mire objects were assumed to be drained and used for agriculture after the first time step if five criteria were met.

- The boulder frequency of the underlying regolith should be low (< 1 boulder/100 m^2 /Sohlenius et al. 2004/). Unfortunately, the current marine geology map does not include this kind of detailed information. If boulders were present they were represented as till on the map. When information from this map was used, it was assumed that areas defined as clay may be used for agricultural purposes in the future.
- A suitable soil type with appropriate clay content. In Forsmark, agricultural activities today are performed on till, where the clay content is higher than 6% /Sohlenius et al. 2004/. We assume that this is valid also for the future.
- The object should be larger than a minimum size. The smallest area used for cultivation at either of the two site investigation areas (Forsmark and Simpevarp/Laxemar) is about 750 m^2 /SKB GIS database 2006/. If the area of an object was smaller, it was assumed to be too small to be worth cultivating. If a mire object did not meet these three criteria, it continued the mire stage or was assumed to slowly transform into a forest object.

- If an object had a topographical wetness index (TWI) higher than 6.1 (which is the lowest TWI value found for a wetland in the Forsmark area today /Lundin et al. 2004/), it was classified as a mire object, otherwise it was classified as a forest object.
- The object had to be at least one metre above sea level. No present agricultural area in Forsmark or Simpevarp/Laxemar site investigation areas is situated below this height.

It was assumed that future agricultural activities in Forsmark will be performed on previous mires. Whether cultivation is possible depends on the thickness of the organic layer, accumulated during earlier stages, and the deposits underlying the peat. When cultivating peat areas, oxidation processes will increase the weathering of the organic layer. It could be assumed that the thickness of the organic soil layer would decrease by 1 cm per year during the cultivation period /Osvald 1937, Kasimir-Klemedtsson et al. 1997/. In the approach used here, after a certain period, the agricultural object would turn into a forest object due to this oxidation process. The time-scale for that transition would be governed by the thickness of the regolith, assuming that the cultivation of an area would end when the thickness is below 1 m. However, this assumption can be disputed, as the cultivated areas in Sweden have the potential, if fertilised, to stay arable for long time periods. Therefore, the transition from agriculture to forest was not necessarily determined by this criterion in the landscape model. In the final landscape model only one object, object 21, was set to forest after a period of agriculture, and this, due to the shallow soil depth and unfavourable underlying mother material.

If a future object, situated above sea level, was not classified as a future lake according to the Future lake model, four different object classifications were available depending mainly on hydrological criteria;

1. it was classified as a mire object if the Geomorphic model indicated likelihood for water discharge /Brydsten 2006a/ and TWI > 6.1, and if the Hydrology model /Bosson and Berggren 2006/ showed that the characteristics for running water were not fulfilled, else,
2. if the characteristics for running water according to the Hydrology model were fulfilled, it was classified as a running water object, else
3. it was classified as one of the other terrestrial objects, forest or agriculture.

6.4 The resulting landscape development

Creating the landscape model was an iterative procedure. After a Biosphere Object had been identified and delimited, the procedure was rerun to identify neighbouring objects in the same sub-catchments. Sub-catchment objects were displayed on maps in 1,000 year steps and combined to one object if they were in the same stage of development. Some sub-catchments, with Biosphere Objects not synchronised in time, were instead distinguished into several Biosphere Objects. During this process, the difference in height above sea level for the objects was also compared to evaluate if a further subdivision was relevant.

The modelled development of the landscape over time was plotted in a series of maps at 1,000 years interval. Examples of different time periods are shown in Figure 6-6. In Table 6-2 the Biosphere Objects are listed for all time periods.

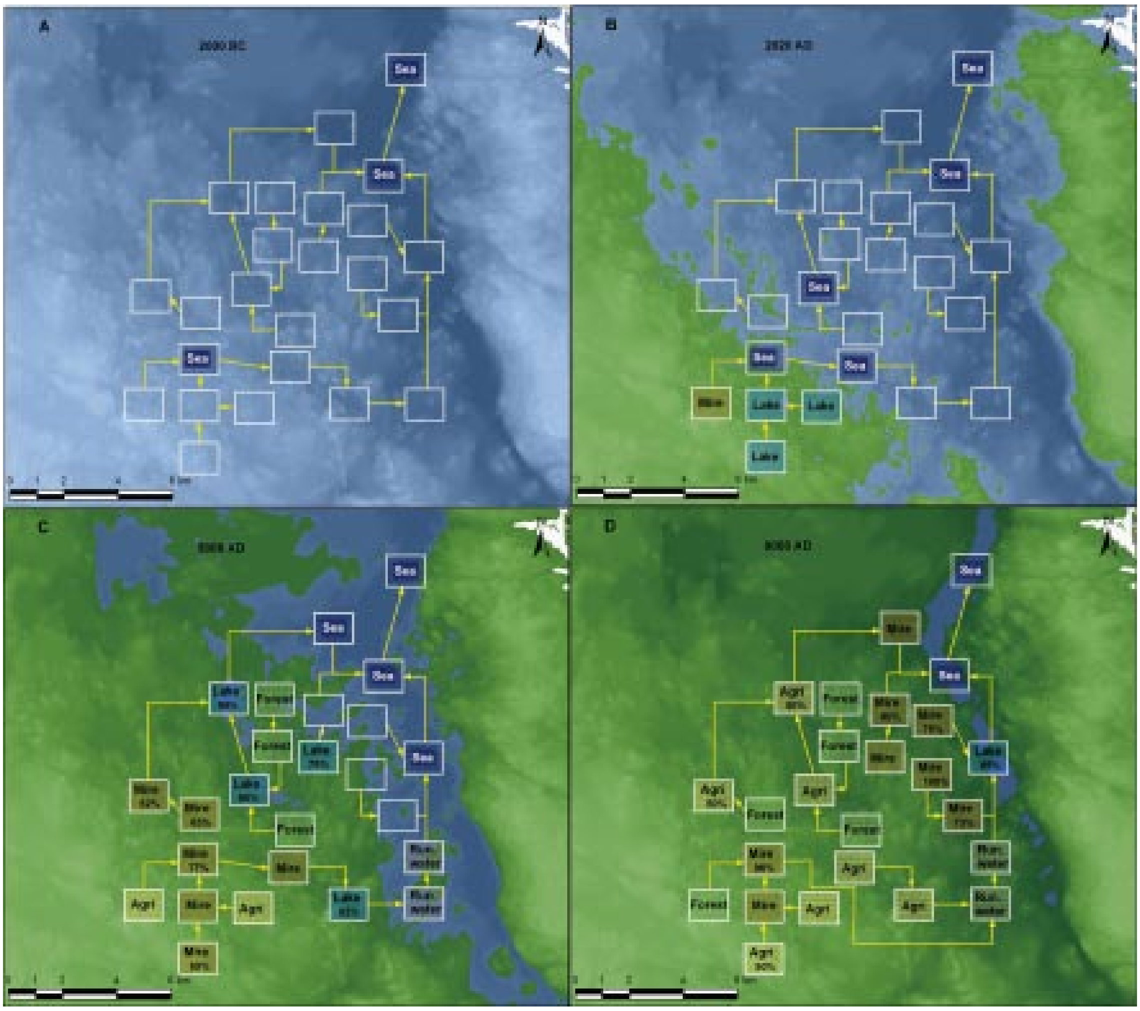


Figure 6-6. *The landscape at four different time periods in Forsmark. Marine stage from 8,000 BC to 1,000 AD (A), the coastal stage today (B) and at 5,000 AD (C) and the terrestrial stage from 7,000 AD and onwards (D). The ecosystems of the objects change gradually according to Table 6-2.*

Three main periods with different conditions were identified; the sea period from 8,000 BC to about 1,000 AD, a coastal period from 1,000 AD to about 5,000 AD and a terrestrial period from 5,000 AD onwards. For the first 10,000 years after deglaciation (see Chapter 4) the site is submerged under the sea. During this period, the water volume of the marine Biosphere Objects decreases and only three objects are modelled, the basin above the repository (17), the entire Öregrundsgrepen (3) and the rest of the Baltic Sea (1). The coastal period starts at the present time, with 4 objects on land; a mire (21) and three lakes (22, 23, 24). There are two future objects situated in the sea today (11 and 18), both with a modelled discharge of radionuclides during this time period. The shoreline displacement gradually reveals more objects and a continued succession of existing Biosphere Objects make the landscape heterogeneous. During the coastal period, the largest representation of different Biosphere Object types occurred. From 7,000 AD and onwards there were only few sea objects (1, 3) and one lake (9), the other Biosphere Objects having turned into forests and mires, and some transformed to agricultural land.

Table 6-2. Succession of the 25 identified Biosphere Objects in the Forsmark area. The object numbers correspond to those in Figure 6-3. The colours denotes the different Biosphere Object types; dark blue-sea, blue-lake, grey-running water, brown-mire, yellow-agriculture land, green-forest.

Object no.	8000BC-1000AD	2020AD	3000AD	4000AD	5000AD	6000AD	7000AD	8000AD	9000AD
1	Sea -constant Baltic Sea as today	Sea -constant Baltic Sea as today	Sea -constant Baltic Sea as today	Sea -constant Baltic Sea as today	Sea -constant Baltic Sea as today	Sea -constant Baltic Sea as today	Sea -constant Baltic Sea as today	Sea -constant Baltic Sea as today	Sea -constant Baltic Sea as today
2	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Mire- Sed model	Mire- Sed model
3	Sea -below sea level. Decreasing size	Sea- present status	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size
4	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Lake- 95% 0pen water. Sed model	Lake- 70% 0pen water. Sed model	Mire- 44% open water. sed model	Mire- 19% open water. sed model	Agriculture- 50% of area utilized, TWI model, Regolith model
5	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Lake- 92% 0pen water. Sed model	Lake- 65% 0pen water. Sed model	Mire- 37% open water. sed model	Mire- 10% open water. sed model
6	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Lake- 87% 0pen water. Sed model	Lake- 56% 0pen water. Sed model	Mire- 25% open water. sed model
7	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Forest- Regolith model, TWI model	Forest- Regolith model,	Forest- Regolith model,	Forest- Regolith model,	Forest- Regolith model,
8	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Lake- 75% 0pen water. Sed model	Mire- 44% open water. sed model	Mire- 13% open water. sed model	Mire- Sed model	Mire- Sed model
9	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Lake- 65% 0pen water. Sed model
10	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Forest- Regolith model, TWI model	Forest- Regolith model,	Forest- Regolith model,	Forest- Regolith model,	Forest- Regolith model,
11	Sea - No release directly to this object	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Sea -below sea level. Decreasing size	Lake- 90% 0pen water. Sed model	Lake- 65% 0pen water. Sed model	Mire- 40% open water. sed model	Mire- 14% open water. sed model	Agriculture- TWI model, Regolith model
12	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Lake- 81% 0pen water. Sed model	Lake- 54% 0pen water. Sed model	Mire- 27% open water. sed model
13	Sea - No release directly to this object	Sea - No release directly to this object	Lake- 98% 0pen water. Sed model	Lake- 73% 0pen water. Sed model	Mire- 37% open water. sed model	Mire- 23% open water. sed model	Mire- Sed model	Agriculture- 50% of area utilized, TWI model, Regolith model	Agriculture- 50% of area utilized, TWI model, Regolith model
14	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Forest- Regolith model, TWI model	Forest- Regolith model,	Forest- Regolith model,	Forest- Regolith model,	Forest- Regolith model,	Forest- Regolith model,
15	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Lake- 77% 0pen water. Sed model	Mire- 47% open water. sed model	Mire- 18% open water. sed model	Mire-. Sed model
16	Sea - No release directly to this object	Sea - No release directly to this object	Lake- 94% 0pen water. Sed model	Lake- 66% 0pen water. Sed model	Mire- 37% open water. sed model	Mire- 8% open water. sed model	Forest- Regolith model, TWI model	Forest- Regolith model, TWI model	Forest- Regolith model, TWI model
17	Sea -below sea level in shoreline displacement model	Sea- present status	Lake- 82% 0pen water. Sed model	Lake- 53% 0pen water. Sed model	Mire- 23% open water. Sed model	Mire- 9% open water. Sed model	Mire- 7% open water. Sed model	Mire- 5% open water. Sed model	Mire- 4% open water. Sed model
18	Sea - No release directly to this object	Sea- present status	Sea -below sea level. Decreasing size	Mire- sed model	Mire- sed model	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model
19	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea -below sea level. Decreasing size	Lake- 82% 0pen water. Sed model	Lake- 52% 0pen water. Sed model	Mire- 22% open water. sed model	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model
20	Sea - No release directly to this object	Sea - No release directly to this object	Running Water	Running Water	Running Water	Running Water	Running Water	Running Water	Running Water
21	Sea - No release directly to this object	Mire- Present status	Mire- Sed model, Regolith to shallow to utilize	Mire- Sed model, Regolith to shallow to utilize	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model	Forest- Regolith to thin for agriculture	Forest- Regolith to thin for agriculture	Forest- Regolith to thin for agriculture
22	Sea - No release directly to this object	Lake- Present status	Mire- 24% open water. Sed model	Mire- Sed model, running water prevent succession	Mire- Sed model, running water prevent succession	Mire- Sed model, running water prevent succession	Mire- Sed model, running water prevent succession	Mire- Sed model, running water prevent succession	Mire- Sed model, running water prevent succession
23	Sea - No release directly to this object	Lake- Present status	Mire- 13% open water. Sed model	Mire- Sed model	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model	Agriculture- TWI model, Regolith model
24	Sea - No release directly to this object	Lake- Present status	Lake- 72% 0pen water. Sed model	Mire- 44% open water. Sed model	Mire- 15% open water. Sed model	Agriculture- 50% of area utilized, TWI model, Regolith model	Agriculture- 50% of area utilized, TWI model, Regolith model	Agriculture- 50% of area utilized, TWI model, Regolith model	Agriculture- 50% of area utilized, TWI model, Regolith model
25	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Sea - No release directly to this object	Running Water	Running Water	Running Water	Running Water

6.5 Object-specific parameterisation

The Biosphere Objects are characterised both in regard to ecosystem properties, so called site generic-parameters, that are described in Chapter 5, and in regard to parameters that are taken as unique for each identified Biosphere Object, so called object-specific parameters, such as area and water volume. Below follows a description of how these object-specific parameters were estimated. The object-specific parameters are available upon request from SKB.

6.5.1 Sea, lake, mire and forest objects (polygon objects)

Objects that were created out of existing or future lakes already had their area, volume, surface elevation, mean depth and maximum depth assigned /Brunberg et al. 2004, Brydsten 2006b/. The lake objects also have information about when they are cut off from the sea (time of initiation) and time when they are overgrown (time of extinction).

Areas of the other object types (sea, mire and forest) were calculated by using the tool XTools in ArcGIS 9. The surface elevation for every time-step was calculated with the shoreline displacement equation /Påsse 1997/. With the tool Zonal Statistics, minimum, maximum and mean elevation today was computed from the DEM. The mean depth (sea objects) for each time step was calculated as the difference between the surface elevation of the time step and the mean elevation of today. The volumes for sea-, mire- and forest objects were calculated as mean depth multiplied by area. Catchment, slope and basin areas were assigned to the objects using the DEM model. The mean slope was assigned to the objects by using the ArcGIS tool Zonal Statistics.

The properties of the dominant regolith type for each object were obtained by a union of the regolith map and the object polygon. Regolith data were not available for some objects outside the regional site investigation area. For those objects, generic regolith data were applied and this is noted in the attribute list.

The proportion of accumulation bottom within each sea object was calculated from the accumulation bottom map /Brydsten 2006b/. The proportion of accumulation bottom was calculated as the area of accumulation bottoms divided by total object area. Table 6-3 shows examples of Biosphere Objects changing over time and their assigned object specific parameters, such as area and elevation.

Table 6-3. Example of Biosphere Objects (rows) and their transitions over time (column 4–17), and some of their characteristic parameters (column 18–21).

Attributes of all_objects_except_runwater

FID	Shape*	ID	_4000BC	_3000B	_200	_100	_0B	_10	_2020	_3000	_4000AD	_500	_6000	_7000	_800	_9000	AREA	ELEVATION	MEAN_DEPTH	MAX_DEP
52	Polygon	12:1													Mire	Mire	336500	-25,8	0,66	
32	Polygon	12												Sea			1120812	-23,52	1,66	
29	Polygon	12											Sea				4167576	-19,74	2,58	
53	Polygon	21:1											Lake	Lake	Mire	Mire	547600	-18,7	0,64	
41	Polygon	32:1									Mire	Mire	Agricult	Agricult	Agricul	Agricult	238300	-10,59	0,66	
42	Polygon	31:2							Mire	Mire	Mire	Agricul	Agricult	Forest	Forest	Forest	41763	0	0	
22	Polygon	12										Sea					8343815	-15,57	4,47	
30	Polygon	Grepen											Sea				8405670	-19,74	9,64	
44	Polygon	2:3							Lake	Lake	Mire	Mire	Agricult	Agricult	Agricul	Agricult	611311	0,64	0,61	
56	Polygon	53:1											Lake	Mire	Mire	Mire	314000	-16,78	1,3	
24	Polygon	33										Sea					2729556	-15,57	3,05	
57	Polygon	54:1												Lake	Lake	Mire	568400	-21,12	1,83	
46	Polygon	2:11							Lake	Mire	Mire	Agricul	Agricult	Agricult	Agricul	Agricult	82741	0,63	0,37	
48	Polygon	25:1										Lake	Mire	Mire	Mire	Mire	242800	-12,04	0,61	
17	Polygon	32								Sea							1818210	-5,77	2,92	
43	Polygon	30:1								Lake	Lake	Mire	Mire	Forest	Forest	Forest	359800	-4,86	1,12	
45	Polygon	2:1							Lake	Mire	Mire	Mire	Mire	Mire	Mire	Mire	76070	0,56	0,31	
58	Polygon	28:1										Lake	Lake	Mire	Mire	Agricult	1601900	-14,04	1,37	
47	Polygon	29:1								Lake	Lake	Mire	Mire	Mire	Agricul	Agricult	1866600	-5,64	1,04	
21	Polygon	Grepen									Sea						1214026	-10,93	8,2	
55	Polygon	22:1										Lake	Lake	Mire	Mire	Agricult	1925400	-15	1,7	
40	Polygon	35/36:1										Lake	Lake	Mire	Agricul	Agricult	801600	-13,09	1,17	
27	Polygon	55											Sea				6980247	-19,74	7,09	
25	Polygon	55										Sea					1364285	-15,57	7,39	
20	Polygon	28									Sea						5824149	-10,93	2,53	

Record: 47 Show: All Selected Records: (0 out of 67 Selected.) Options

6.5.2 Running water objects (line objects)

For the running water objects, the length was calculated and assigned to the objects. The modelling resulted in a GIS project file (an mxd file created in ArcGIS 9.1), that comprises two shape files relating to the Biosphere Objects (a polygon and a line file).

6.6 Permafrost conditions and the landscape model

Permafrost conditions occur in several episodes during the Weichselian glacial cycle that is used as a model for future glacial cycles. At the Forsmark site, the next permafrost episode is assumed to start about 10,000 AD, following the present interglacial (see Chapter 4). At that time, the coastline is located at some distance from the repository and major discharge areas are not located offshore. The situation is similar at the end of any future interglacial when global sea levels are falling. To simulate the permafrost conditions, it was assumed that the spatial distribution of landscape objects is similar to that at the end of the temperate interglacial period (Figure 2-4), except that agricultural land is replaced by forests or mires, reflecting the consideration that a significant degree of agriculture would not be tenable in such a context.

6.7 Greenhouse variant and the landscape model

In the dose modelling of the greenhouse variant, in which the temperate conditions are prolonged until 50,000 AD, the landscape model at 9,000 AD was used throughout the period until 50,000 AD (see also Figure 2-4).

6.8 Uncertainities of the landscape model

In the development of a landscape model, a number of assumptions and simplifications have had to be made. From one step to another, uncertainties associated with these assumptions are accumulated. For this reason, the major underlying models that affect the properties of the overall model (e.g. classification of ecosystems, ecosystem changes over time (both natural succession and changes caused by humans) and location of Biosphere Objects have to be simple and robust. The strategy to use the sites as they appear today as basic input, and to use simple geometrical models to further describe the history and the future, is a way to decrease uncertainties. This argument, of course, depend on the reliability of the underlying models used, e.g. geometry, shoreline displacement, hydrogeological transport models and surface hydrology.

Our approach to evaluate the uncertainties in the landscape model is firstly to assess the uncertainties in the underlying models upon which the landscape model is built, and secondly to evaluate the assumptions made within the landscape model. Below are the main models described in terms of uncertainty, followed by an evaluation of the uncertainties of the overall landscape model.

Digital elevation model (DEM)

The DEM is constructed by interpolation from irregularly spaced elevation data using a Kriging interpolation method. Kriging weights the surrounding measured values to derive a prediction for unmeasured locations. Weights are based on the distance between the measured points, the prediction locations, and the overall spatial distribution of the measured points. A validation procedure is then used in order to change the Kriging parameters to minimise the prediction errors. An indisputable best combination of Kriging parameters is impossible to find, but in the development of the DEM the validation procedure was performed until only minor changes was noted in the prediction errors. The final choice of parameters is presented in /Brydsten and Strömgren 2004b/.

The DEM has a high resolution and the uncertainties in the model must be considered as generally small. However, due to the relatively flat terrain in the Forsmark area and to human encroachment in the area (mainly ditching), the DEM has some small errors. These errors, which may affect the modelled flow paths in the GIS model, are possible to evaluate by estimating the deviation between the modelled flow paths and the actual water courses that exist today. This type of evaluation has been done /Brydsten 2006a/, and the results show that the major part of the GIS model deviates only marginally from the actual water courses, and that the Biosphere Objects on present land are connected in the same way when using the GIS model. It is, however, difficult to evaluate errors in the DEM model for areas that are submerged today.

Shoreline displacement

The start of the shoreline displacement curve (10,800 years ago/151 m above sea level) represents the deglaciation of Forsmark, according to the regional compilation in /Fredén 2002/. The time for the deglaciation is based on clay varve chronology that has an uncertainty of *at least* ± 200 years. The estimation of the Highest Coastline (HC) presented in /Fredén 2002/ implies an elevation of 190 m above sea level for northern Uppland. This altitude is based on a long-distance interpolation between the Kilsbergen area (Närke) and Borlänge (Dalarna). The uncertainty in the time of deglaciation is thus inherited in the altitude of HC. It should be noted, however, that there were no land areas in the Forsmark area at this time. What the new curve shows is that the water depth during deglaciation was between c 130 and 150 m in the areas presently above the sea level.

It is also notable that the oldest empirical data in the curve (dated samples from isolated basins) is c 6,500 years old, representing the isolation age of Lake Bången. The ages are initially based on radiocarbon dates of various types of material, i.e. both terrestrial macrofossils and samples of gyttja clay and other sediment. The isolation age of each basin can not be stated with less than ± 150 year uncertainty, often more. The uncertainty in the altitude is based on the geological conditions at the isolation threshold and is specific for each site. The altitude of the isolation thresholds included in the curve is stated with ± 0.5 m. This implies that the chronology is affected by a larger degree of uncertainty than the altitude /Lindborg et al. 2005/.

Surface hydrology

The evaluation of time series of local meteorological data and surface water and groundwater levels, enabling comparisons between different processes and hydrological sub-systems, has lead to an improved understanding of the site that supports some of the fundamental aspects of the descriptive model. The locations of recharge and discharge areas at different scales are crucial for the understanding of the groundwater system. Ongoing work is evaluating the modelled recharge and discharge areas using independent data, such as hydrological measurements, Quaternary deposits and vegetation. The present overall descriptive model of the surface-hydrological and near-surface hydrogeological system is considered to be acceptable in a qualitative sense, which means that the general description of the hydrological and hydrogeological driving forces and the overall flow pattern is not thought likely to change substantially in future models. Furthermore, there exists a relatively large amount of quantitative information on, primarily, the hydraulic properties of the Quaternary deposits /Johansson et al. 2005/.

Potential discharge points

Different conceptual models of the bedrock provide different discharge points. Specifically, in a continuum representation discharge points tend to follow the displacing shoreline, whereas in a Discrete Fracture Network (DFN) representation the discharge points are primarily governed by vertical deformation zones and larger vertical fractures. Thus, discharge points do not move in time to the same extent as in a continuum models. However, in both model types discharge takes place in low altitude areas such as lakes, sea, wetlands and agricultural areas. Furthermore, a correlation exists between these low points in the landscape and the occurrence of major vertical deformation zones. Discharge thus predominantly takes place at these low points irrespective of whether an DFN or continuum representation is used.

In the models, particle tracking identifying the discharge points has been performed in steady-state velocity fields. In reality, migrating solutes are subject to changes in the velocity field implied by e.g. the receding shore line. In a numerical study relevant for deep repository conditions, /Moreno et al. 2006/ investigated the effect of transient flow fields on solute transport subject to both matrix diffusion and sorption. It was shown that non-interacting solutes pre-dominantly are governed by the flow field at the release time, whereas strongly sorbing solutes are governed by the late time flow field. Intermediately sorbing solutes, however, experience the evolving flow field to a greater extent. The discharge locations calculated with the models in SR-Can for different times may consequently be seen to represent the span of possible discharge locations for a solute release consisting of nuclides with different sorption properties. It should be kept in mind, however, that some nuclides will have travel times of hundreds of thousands of years. Over such time periods, permafrost and glacial conditions will occur for extended intervals. The effect of such climatic conditions on the final discharge points of a solute affected by retention processes in the geosphere has not been evaluated.

The Landscape model

In the first two steps of the construction of the Landscape model, potential discharge points are displayed and the Biosphere Objects are delimited. The main uncertainty related to these tasks is the combination of many and sometimes scattered, discharge points to define a single Biosphere Object. As mentioned above, the potential discharge points are most often found in low altitude areas, which was also confirmed by /Werner et al. 2006/. These low altitude areas most often coincide with a specific ecosystem, which also by it's low altitude will constitute the recipient for discharge points within the catchment of that ecosystem.

In the next step, the identified Biosphere Objects are connected to each other. The technique uses the hydrological GIS models of the surface flow paths and is fairly straightforward and simple. The main uncertainty related to this step is the accuracy in the terrain model (DEM), which is treated above.

Finally, the development of the landscape model over time, including successional development of the different Biosphere Objects, has to be described during the whole time period between 8,000 BC and 9,000 AD. This task is dependent on a number of assumptions and sub-models (see Section 6.1). The major uncertainties recognised are:

- In the successional development of Biosphere Objects, and the timing of these changes;
- In the climate conditions adopted.

Due to the complexity of processes involved in the natural development of the landscape and the ecosystems there within, coupled with anthropogenic influences on the landscape, the description of the succession is built on just a few "master-parameters". For example, from parameters describing the geometry and the shoreline displacement model, we can predict when a sea object turns into a lake object, and by modelling the sedimentation rate we can tell when the lake turns into mire. We will not know the biotic properties of these future objects, but from the present situation we can predict the upper limits of their production capabilities.

All this is, of course, dependent on how the climate develops. In this work with the landscape model we used the present climate conditions for the whole time period. For example, no greenhouse effects were taken into account in the shoreline displacement model. The effect of this assumption of no change in climate in terms of uncertainties has not been evaluated. However, we are modelling the Forsmark site for the whole temperate interglacial, so we can, for example, use the time periods with a higher sea level to simulate site conditions for a rising sea level or vice versa.

In conclusion, we believe that this methodology that uses few and physically driven parameters to build the landscape model, not only minimises the uncertainties and limits the potential for error, but shows a clear and precise methodology that limits the speculations of possible future landscape changes.

7 Humans

When modelling doses to humans from exposures to radionuclides, site-specific data have an important influence on the result obtained, but, in addition, a number of assumptions concerning human behaviour have to be made. This section describes the methodology and the assumptions behind the calculations of doses to humans from exposures to radionuclides.

7.1 Food intake, production and population size

In previous assessments of doses to humans, a standardised diet was used /e.g. Bergström et al. 1999, Karlsson et al. 2001/. An important task in order to improve the assessment is to populate the models with food data from the site. Previously, the food production has been generalised from national food statistics, without any reference to the productivity of that particular food item at the site. The problem is that in a specific ecosystem, only a subset of all food items is available or possible to produce. For some food items this is obvious, e.g. it is impossible to get fish from agricultural land. However, for other food items, for which production may occur, but may not be sufficient to feed one person, the question is more difficult to address. The other problem is to weight the importance of different food items, according to their varying nutritional value and to human preferences. For long-term assessments, it is difficult to postulate a particular dietary composition, as human habits and choices may change over time.

To avoid speculations in SR-Can about future food habits and exploitation of the landscape, the nutritional demand corresponding to 110 $kgC \cdot y^{-1}$ was used as the intake of food by an adult /Avila and Bergström 2006/. Organic carbon was used as a unit of caloric intake to weight different food items proportionally to their nutritional value, as is commonly done in ecosystem studies /Odum 1983/. It was assumed that nutritional demand will be fairly constant even for future humans. The intake of water, food and air adopted is tabulated in Table 7-1, which is taken from /Avila and Bergström 2006/.

Another important assumption is that humans will exploit the contaminated landscape maximally, thus eating all potentially edible food produced within the Biosphere Objects. Thus the number of persons that can live of the production from a specific Biosphere Object is constrained by the annual area-specific productivity of edible products and the size of the object. The production of naturally occurring food items is constrained by the primary production of the object and can be assessed separately (cf Chapter 4).

Table 7-1. Values for human intake of food, water and air used in calculation of doses to humans via water ingestion, food ingestion, inhalation and external exposure. All values are chosen at the high end of the range of values in, or estimated from, ICRP recommendations (see further /Avila and Bergström 2006/).

Parameter	Units	Value	Comments
Intake rate of water by an individual	$m^3\ y^{-1}$	0.6	Intake rate of water by adults, excluding water consumed as a component of food. /ICRP 1975, 2004/
Intake rate of carbon by an individual	$kg\ C\ y^{-1}$	110	Estimated from the intake of protein, carbohydrates and fats by adult males given in /ICRP 1975/.
Inhalation rate	$m^3\ h^{-1}$	1	Based on values of total ventilation during a day for adult males given in /ICRP 1975, 2004/.

In principle, individuals can consume, occupy or otherwise utilise environmental media (e.g. food, water for consumption or irrigation, construction materials) from several different Biosphere Objects, and it is this overall pattern of utilisation that determines the time-averaged effective dose rate that they receive. However, the regulatory requirements place emphasis on the most highly exposed subgroup of individuals in the population. Consequences should be calculated for a representative individual in the group exposed to the greatest risk (the most exposed group). SSI's general guidance indicates that the group should be defined to include "the individuals that receive a risk in the interval from the highest risk down to a tenth of this risk" /SSI 2005/.

In order to ensure that the effective dose rate to the most exposed subgroup is identified, calculations of effective dose rate are made for population groups that are taken to occupy a single Biosphere Object and obtain all their resources from that object. This ensures that individuals make maximum reasonable use of local resources and that the effective dose rate arising from utilising the most contaminated part of the landscape is not diluted by utilisation of less contaminated parts of the landscape.

Having adopted this approach, it is possible to estimate not only the effective dose rate to individuals utilising a particular Biosphere Object, but also the number of individuals that object can fully support. For the Biosphere Object giving the highest effective dose rate, this is the maximum number of people that could be associated with that effective dose rate. In practice, most individuals would utilise resources also from other parts of the landscape, so the effective dose rate that they receive will be lower.

The number of individuals that the identified Biosphere Objects in the Forsmark area can support varies from less than one (0.0001) for some terrestrial objects, to many thousands in the case of some marine objects /cf Avila et al. 2006/. Clearly, where the Biosphere Object that gives the highest effective dose rate based on sole utilisation can support less than one person, that effective dose rate is too high to be applicable to the most exposed individual, since an individual utilising that Object would also have to utilise resources from other Objects. Conversely, where the Biosphere Object that gives the highest effective dose rate based on sole utilisation can support a large number of people, heterogeneities in environmental concentrations would mean that, in practice, some individuals would receive higher effective dose rates than that calculated, whereas others would receive lower effective dose rates.

In reality, the utilisation of natural food production is overestimated for some of the ecosystems (e.g. mire and forest) since only minor fractions of the produced berries or mushrooms are utilised.

7.2 Dose conversion factors

A revised methodology for the calculation of doses from exposures to radionuclides in the environment, starting from radionuclide concentrations in environmental media (i.e. air, water, food and soil) is presented in /Avila and Bergström 2006/. The methodology considers the main exposure pathways that may arise from a continuous input of radionuclides into the biosphere with contaminated groundwater, which is the release scenario of most relevance for the safety assessment of geologic repositories. The report also describes the methodology implementation in Pandora /Åstrand et al. 2005/, which is the tool currently used by SKB and POSIVA (The Finnish equivalent to SKB) for biosphere dose modelling. The dose estimations obtained from this modelling can be considered pessimistic, but still realistic, life-time dose estimates in most relevant exposure situations /Avila and Bergström, 2006/.

Humans can be exposed both externally and internally to radionuclides occurring in the environment. The external exposure comes from radiation emitted by the radionuclides in surrounding environmental media; air, water and soils. Previous safety assessments of planned geologic repositories in Sweden and Finland /Bergström et al. 1999, Karlsson and Bergström 2000/ have shown that for most radionuclides of concern, external exposure gives a minor contribution to the total dose. External exposure from air and water is negligible for all radionuclides of interest, but for radionuclides with high gamma-energy and low bioavailability, such as Nb-94, external exposure to radionuclides accumulated in the ground (soil) may give an important contribution to total dose. Hence, exposure from radionuclides accumulated in the ground is the only external exposure pathway included in this methodology /Avila and Bergström 2006/.

Internal exposure is always preceded by incorporation of radionuclides into the human body. This can occur mainly by inhalation of contaminated air, or by ingestion of contaminated water, soil and food. For inhalation (and external exposure), the applied methodology considers outdoor exposure for hundred percent of time, which in most cases gives a cautious estimate for inhalation, as the radionuclide contamination of the air comes from resuspension of soil particles.

The methodology also considers the internal exposure due to oral intake of radionuclides. This exposure will, among other things, depend on the fraction of contaminated food, soil and water consumed, and on the level of activity in the foodstuffs, soil and water. In this methodology it is assumed that the annual demand of water and food is contaminated. Hence, no assumptions have been made regarding food preferences (see Section 7.1) and instead the calculations are based on values of food energy intake given by the ICRP for the reference human /ICRP 1975, 2004/.

The dose coefficients used in SR-Can are tabulated in Table 7-2 and described further in /Avila and Bergström 2006/. All recommended values, with the exception of the values for Rn-222, are taken from the European Union recommendations /EUR 1996/. Values for radon, Rn-222, are missing in the European Union recommendations and were taken from /NRC 1999/.

Table 7-2. Dose coefficients used in SR-Can modelling for ingestion and inhalation (Sv/Bq), and for external exposure (DCC, Sv/h per Bq/m^3), for human adults. The values are based on /EUR 1996/ and, for ingestion of Rn-222, on /NRC 1999/. The dose coefficients for external exposure are taken from /Eckerman and Leggett 1996/. See further /Avila and Bergström 2006/.

Nuclide	Ingestion (Sv/Bq)	Inhalation (Sv/Bq)	DCC (Sv/h per Bq/m^3)
H-3	1.8E–11	2.6E–10	–0.0E+00
Be-10	1.1E–09	3.5E–08	1.9E–17
C-14	5.8E–10	5.8E–09	2.1E–19
Cl-36	9.3E–10	7.3E–09	4.8E–17
Ca-41	1.9E–10	1.8E–10	0.0E+00
Co-60	3.4E–09	3.1E–08	3.0E–13
Ni-59	6.3E–11	4.4E–10	0.0E+00
Ni-63	1.5E–10	1.3E–09	0.0E+00
Se-79	2.9E–09	6.8E–09	3.0E–19
Sr-90	2.8E–08	1.6E–07	1.2E–17
Zr-93	1.1E–09	2.5E–08	0.0E+00
Nb-94	1.7E–09	4.9E–08	1.8E–13
Mo-93	3.1E–09	2.3E–09	8.0E–18
Tc-99	6.4E–10	1.3E–08	2.1E–18
Pd-107	3.7E–11	5.9E–10	0.0E+00
Ag-108m	2.3E–09	3.7E–08	1.7E–13
I-129	1.1E–07	9.8E–09	1.8E–16
Cs-134	1.9E–08	2.0E–08	1.7E–13
Cs-135	2.0E–09	8.6E–09	6.2E–19

Nuclide	**Ingestion (Sv/Bq)**	**Inhalation (Sv/Bq)**	**DCC (Sv/h per Bq/m³)**
Cs-137	1.3E–08	3.9E–08	6.5E–14
Sm-151	9.8E–11	4.0E–09	1.3E–20
Eu-152	1.4E–09	4.2E–08	1.3E–13
Eu-154	2.0E–09	5.3E–08	1.4E–13
Eu-155	3.2E–10	6.9E–09	3.1E–15
Ho-166m	2.0E–09	1.2E–07	1.9E–13
Pb-210	6.9E–07	5.6E–06	3.8E–17
Po-210	1.2E–06	4.3E–06	9.5E–19
Rn-222	0.0E+00	3.5E–09	4.2E–17
Ra-226	2.8E–07	9.5E–06	5.6E–16
Ac-227	1.1E–06	5.5E–04	8.6E–18
Th-229	4.9E–07	2.4E–04	5.6E–15
Th-230	2.1E–07	1.0E–04	2.1E–17
Th-232	2.3E–07	1.1E–04	8.8E–18
Pa-231	7.1E–07	1.4E–04	3.4E–15
U-233	5.1E–08	9.6E–06	2.4E–17
U-234	4.9E–08	9.4E–06	6.6E–18
U-235	4.7E–08	8.5E–06	1.3E–14
U-236	4.7E–08	8.7E–06	3.4E–18
U-238	4.5E–08	8.0E–06	1.5E–18
Np-237	1.1E–07	5.0E–05	1.3E–15
Pu-238	2.3E–07	1.1E–04	2.2E–18
Pu-239	2.5E–07	1.2E–04	5.1E–18
Pu-240	2.5E–07	1.2E–04	2.2E–18
Pu-241	4.8E–09	2.3E–06	1.0E–19
Pu-242	2.4E–07	1.1E–04	1.9E–18
Am-241	2.0E–07	9.6E–05	7.2E–16
Am-242m	1.9E–07	9.2E–05	2.8E–17
Am-243	2.0E–07	9.6E–05	2.4E–15
Cm-244	1.2E–07	5.7E–05	1.7E–18
Cm-245	2.1E–07	9.9E–05	5.9E–15
Cm-246	2.1E–07	9.8E–05	1.6E–18

8 Landscape dose factors and doses to humans and biota

The Landscape Model with the interconnected Biosphere Objects, described in Chapter 6, was, together with the ecosystem-specific radionuclide models (Chapter 5), used to construct a radionuclide exposure model. This model was populated with site-generic parameter values (Chapter 5) and object specific parameters values (Chapter 6) for the different time periods listed in Table 6-2. The number of potential discharge points in each Biosphere Object and time period was used to weight the importance of the different objects. This chapter describes how the exposure model was run in the Pandora tool, to obtain the Landscape Dose Factor (LDF) values used in SR-Can.

8.1 Modelling of long-term distribution of radionuclides in the landscape during an interglacial

All ecosystem models applied are briefly outlined in Chapter 5. A more detailed description can be found in /Avila 2006/. The models are in principle the same that were used in the assessments performed for SR-Can Interim /SKB 2004/, with the exception of the forest model, which was not available at that moment. The radionuclides included in the simulations are presented in Table 7-2. For radionuclides with decay chains, the distribution of the daughter radionuclides in the landscape, resulting from unit releases of the parent, were also considered.

8.1.1 Data

The numerical modelling using the Landscape Model use three different types of model parameters 1) site generic parameters describing properties of the different ecosystems (Chapter 5), 2) radionuclide specific parameters describing the behaviour of specific radionuclides, such as distribution coefficients (Kd) and the transfer factors from soils and waters to biota /Avila 2006/, 3) object specific parameters describing properties of specific objects (Chapter 6).

The parameter databases were version controlled using Subversion (http://tortoisesvn.tigris.org/). The versions, used in the Pandora modelling, of the site-generic parameter database and the object-specific parameter database was number 473 and 343, respectively /SKB database 2006/.

8.1.2 Model implementation

The landscape models were implemented in the software package Pandora /Åstrand et al. 2005/. Pandora is a development of Tensit /Jones et al. 2004/ and an extension of the well known software Matlab© and Simulink© from Mathworks (see www.mathworks.com). Pandora simplifies the development of models resulting in large systems of differential equations and the handling of radionuclide decay chains. The Pandora tool comprises a library of Simulink© blocks that facilitates the creation of compartment models and a standalone Toolbox for management of parameter values and probabilistic simulations.

A library of ecosystem models was created in Pandora, which facilitates handling several instances of the ecosystem models in the landscape model. For each landscape object a Simulink© subsystem was created, which includes models of all ecosystem types that may exist in this object during the whole simulation period. The discrete transition between ecosystem models was implemented using switches available in Simulink©. The decay and in growth of radionuclides in a chain was handled with the help of the Pandora Radionuclide block. For integrating the model, the solver ode15s was used, which is an appropriate solver for stiff systems of equations with discrete events. The activity concentrations and doses were calculated from the amount of activity in different compartments predicted with the Pandora model by using a post-processing routine created in Matlab©.

8.1.3 Landscape change

The transformation between ecosystems (every thousand years) was modelled as discrete events, by substituting one model by another. The activity in different compartments of the "mother" ecosystem was transferred instantaneously to the appropriate compartments of the "daughter" ecosystem following specified rules that were set so as not to underestimate the potential doses (see Table 2-3 in /Avila et al. 2006/ for the rules). For example, if an ecosystem was transformed into a forest from e.g. a seabed or mire, then the total activity in the ecosystem, including the fraction in the deep sediment, was transferred to root zone of the forest soil. As the inventory is transferred this is equivalent to setting the initial conditions of the compartments in the daughter ecosystem to a value equal to the transferred inventory. In the Forsmark model, there are only three Biosphere Objects at the start of the simulation period (see Figure 6-6), i.e. objects 1, 3 and 17. All other future Biosphere Objects in the model emerge from Biosphere Object 3; although these Biosphere Objects do not cover all the land that emerges from Biosphere Object 3. To be on the conservative side, no activity was transferred to emerging lands that are not included in the model. This means that, over the whole simulation period, all activity accumulated in the sea is either transferred to terrestrial Biosphere Objects in the model or remains in Biosphere Object 3. The reason for not including some of the emerging lands in the model is that these lands are upstream from potential discharge points.

8.1.4 Results

This section presents briefly some results describing the radionuclide inventories obtained for Forsmark for the interglacial period that is presented in more detail in /Avila et al. 2006/.

The landscape

The total inventory in the Grepen of radionuclides with very long half-life (Cl-36, Ni-59, Se-79, Tc-99, I-129, Cs-135 and Pu-239) increases monotonically and reaches a maximum or a value close to the maximum at the end of the simulation period (10,000 AD). The non-monotonic time variation observed for Am-241 and Ra-226 can be explained by their shorter half-lives.

The retention in the Grepen of the released long-lived radionuclides is between 10 and 40% at the end of the simulation period. The remaining fraction of the releases ends up in the Baltic Sea.

All Biosphere Objects have some radionuclide inventory at the end of the simulation period, independently of whether or not they receive a release fraction (Figure 8-1).

Terrestrial Biosphere Objects

Overall, the retention of radionuclides in soils during the terrestrial period does not seem to have a substantial contribution to the overall accumulation in soil, taken over the whole simulation period. Pronounced differences in the activity concentrations in soil are observed between the different Biosphere Objects (Figure 8-1), with a few Biosphere Objects having concentrations more than 10 times higher than the rest of the Biosphere Objects. A pronounced variation of the doses from these Biosphere Objects can therefore be expected. Biosphere Objects with the highest release fractions often show the highest concentrations.

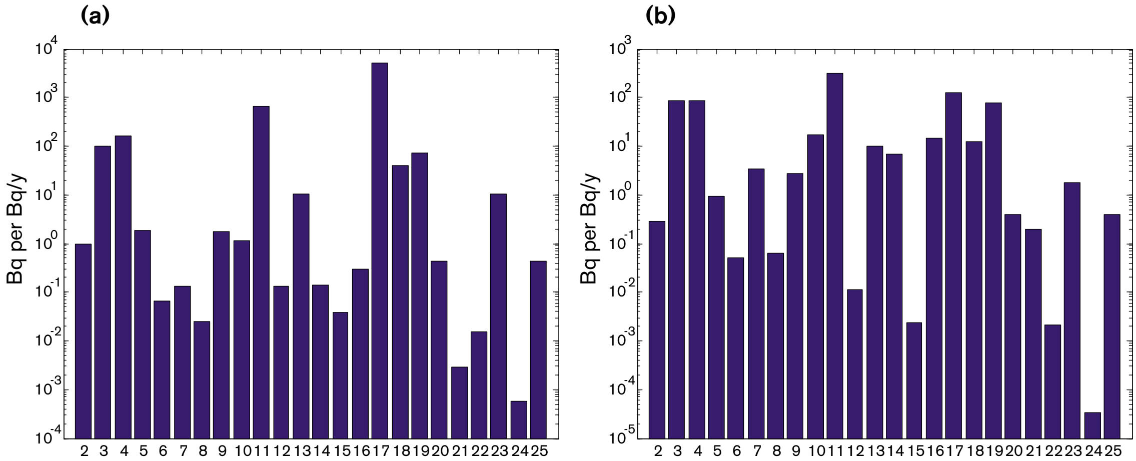


Figure 8-1. *Total inventory of I-129 (a) and Ra-226 (b) in different objects at the end of the simulation period (10,000 AD) (from /Avila et al. 2006/).*

Lake and running water Biosphere Objects

The maximum radionuclide concentrations in waters of lakes and rivers for all radionuclides, except for Am-241 because of its shorter half-life, stabilise at the same value starting from around 5,000 AD. The maximum concentration of the most mobile radionuclides (Tc-99, Cl-36 and I-129) starts from a higher value and decreases to the same level. The highest between-object difference in freshwater activity concentrations was observed at the end of the simulation period. At this time, there are three freshwater objects left in the Grepen, two lakes and one river. The two lakes showed similar activity concentrations, but the values are more than ten times higher for the river. It should be noted that the river can not sustain even a single person with food.

Marine Biosphere Objects

In the period from 8,000 BD to 4,000 BD pronounced differences are observed between the radionuclides, with the most mobile radionuclides showing the highest activity concentrations in water. During this period, there is a large fraction of accumulation bottoms in Biosphere Object 17, which receives all releases. This means that fractions of the released radionuclides are retained in sediments, which leads to lower activity concentrations in water. In the period from 4,000 BD to 2,000 AD there is no further accumulation of the radionuclides in sediments, i.e. the radionuclides are directly released to water. Since there is a constant and equal input and output of all radionuclides, their concentrations in water approach the same value. After 2,000 AD, retention of radionuclides in bottom sediments begins again to occur, due to the increase in the fraction of accumulation bottoms. At the end of the simulation period, the activity concentrations in sea water are similar for all radionuclides. This confirms the observation that concentrations in water tend to stabilise with time and become less dependent on K_d values.

During most of the simulation period, the between-object differences in sea water concentrations were small and they approached nearly the same value for the various radionuclides at the end of the period.

8.1.5 Sensitivity and uncertainty analysis

A sensitivity analysis of the ecosystem models was carried out to identify which parameters had the largest effect on the simulation endpoints of interest. The endpoints considered were the fraction of the release that is retained in the ecosystem, the activity concentrations in soil, water and sediments, and the dose rates from external exposure, inhalation, and ingestion of water and food; evaluated at different times after the start of the simulations. A detailed description of the sensitivity study is given in /Avila 2006/. The sensitivity analysis was carried out using the Morris method /Morris 1991/ implemented in the software package Eikos /Ekström and Broed 2006/. With this method, it is possible to screen out parameters that have negligible effects and to rank the parameters by their effect on the endpoints of interest. It is also possible to identify which parameters have non-linear effects or are involved in interactions with other parameters.

From the sensitivity analysis of the ecosystem models, the parameters with the highest impact on the fraction of the releases retained in the objects and the doses were identified. It is reasonable to expect that uncertainties in the LDF values will be determined by the uncertainty in these parameters. However, the influence of the parameters is not linear and depends on multiple parameter interactions. For the landscape model, interactions between objects have also to be taken into account. Hence, for elucidating the effects of the parameter uncertainties on the uncertainties in the predictions for the landscape, it is necessary to make sensitivity studies for the landscape models as a whole. Such studies have not been yet carried out to the needed extend. Preliminary analyses were carried out for the LDF values and these are presently briefly in Section 8.2.5 and in more detail in /Avila et al. 2006/.

8.2 Modelling of landscape doses to humans and biota

8.2.1 Method for calculation of landscape doses

In principle, it is possible to drive the Landscape Model with time-dependent fluxes of radionuclides derived from a model of the repository, and of flow and transport through the geosphere. Such an approach would give time-dependent radionuclide concentrations in the environmental media of which the various Biosphere Objects are composed, and hence time-dependent effective dose rates to individuals utilising those Biosphere Objects. However, radionuclide fluxes from the deep repository would vary slowly with time. It is convenient to decouple the calculation of those fluxes from calculations of their radiological impact, both from a practical point of view and for purposes of transparently demonstrating the nature of all steps of the calculations leading from a canister failure to annual effective dose. Therefore, in conformance with previous SKB practice /SKB 1999/, and using an approach that is widely adopted internationally, radiological impacts are calculated for constant unit release rates of radionuclides to the surface environment. By this approach, single values of LDF, i.e. effective dose rates for unit flux of each radionuclide, are derived. These LDF values can then be multiplied by radionuclide fluxes from the geosphere for radiological impact estimations.

In applying this approach, various cautious assumptions are made concerning the duration of the period of chronic release and the additivity of contributions from different radionuclides. These cautious assumptions are described in more detail below.

The periods of temperate climate of relevance (i.e. a complete interglacial cycle) includes both the period from the present day until the next major episode of climatic cooling, but also part of the subsequent temperate period after that episode of cooling. In order to give the potential for application of LDF values for a complete interglacial cycle, an extended period of release is assumed, beginning after the glacial ice has retreated from the area (approx. 8,000 BC in the Holocene period of temperate climate) and finishing when the first effects of permafrost are starting (taken as 10,000 AD in the current temperate period). This allows the maximum reasonable time span for radionuclides to accumulate in the surface environment. It also ensures that a comprehensive range of temperate environments is studied, and that the post-glacial isostatic and eustatic changes are fully expressed, with the associated changes to the location of the coastline and the characteristics of local marine and terrestrial ecosystems.

In a non-evolving landscape with a constant rate of input of a radionuclide, concentrations of that radionuclide in the various environmental media would be expected to increase monotonically and, if the period of discharge was sufficiently long, would be eventually be expected to stabilise at constant values /Bergström et al. 1999/. However, with an evolving landscape, as is represented in the landscape model, such a concept of equilibrium is not applicable. For example, radionuclides can accumulate in marine or lacustrine sediments, but give rise to an increased radiological impact when, as a consequence of shore level displacement, those sediments are converted to agricultural land. To allow for this, the LDF values used are the maximum values of effective dose rate that apply over the period of release. This is a cautious assumption, as it implies that the geosphere release is sufficiently protracted for the maximum value to be realised. Furthermore, the maxima for different radionuclides occur at different times, so multiplying geosphere fluxes by these maximum values and summing the results, as is done, will over-estimate the overall effective dose rate, as when one radionuclide is exhibiting its maximum effective dose rate others will be exhibiting less than their maximum effective dose rates /Avila et al. 2006/.

Because the individual Biosphere Objects are interconnected and radionuclide discharges can occur to several of them, radionuclide concentrations in environmental media not only vary with time but also differ in the various Biosphere Objects (cf Figure 8-1).

An illustration of the obtained dose vs. the population is plotted in Figure 8-2. Because these plots are based on calculations for finite-sized Biosphere Objects that will fully support specific numbers of people, they exhibit stepwise characteristics. To eliminate these discontinuities, which essentially arise from the representation of the landscape as a finite number of Biosphere Objects, results from the effective dose rate calculation at each time of evaluation are plotted as a complementary cumulative distribution function (CCDF) in which the number of people exceeding a particular effective dose rate is plotted against the effective dose rate) /Avila et al. 2006/. Examination of these CCDFs shows that they typically are well fitted by log-normal distribution functions (see Figure 8-2). In considering whether it is justified to use the smoothed version of the curve for assessment purposes, two different issues arise. We can envisage that if individuals utilises resources from more than one Biosphere Object, the curve would be smoother, as the stepwise distinction of numbers of people associated with particular effective dose rates would disappear. However, the curve would also tend to narrow, as individuals would move away from full utilisation of Biosphere Objects associated with the highest and lowest effective dose rates. Alternatively, if the landscape was decomposed into a greater number of Biosphere Objects, the curve would also become smoother, but it would not narrow. In justifying use of a smoothed curve, we take account of the latter consideration and view smoothing the curve as being an approach that moves from a discrete to a continuous representation of the landscape. However, no narrowing of the curve is permitted, as the emphasis still needs to be placed on the individual making maximum reasonable use of local resources (cf /Avila et al. 2006/).

Once a smooth curve has been generated, it can be used to make an estimate of the effective dose rate to the most exposed individual. This is the effective dose rate at which the CCDF has a total number of individuals exceeding that effective dose rate of 1.0. This is a real upper bound on individual effective dose rate within the context of the modelling assumptions. To choose an effective dose rate higher than this would be to adopt a contaminated area that would support less than one individual. Thus, any individual utilising that area would also have to utilise other areas, so reducing the effective dose rate received.

However, having determined the effective dose rate to the most exposed individual, consideration has to be given to identifying a representative individual from the most exposed group and determining the effective dose rate to that individual. Regulatory guidance indicates that the degree of variation in individual doses within that group should not be greater than a factor of ten, see /SSI 1998, 2005/. For this reason, the effective dose rate to the representative individual from the most exposed group is obtained by finding the arithmetic mean of the fitted log-normal distribution in the interval between the effective dose rate to the most exposed individual and one tenth of that value.

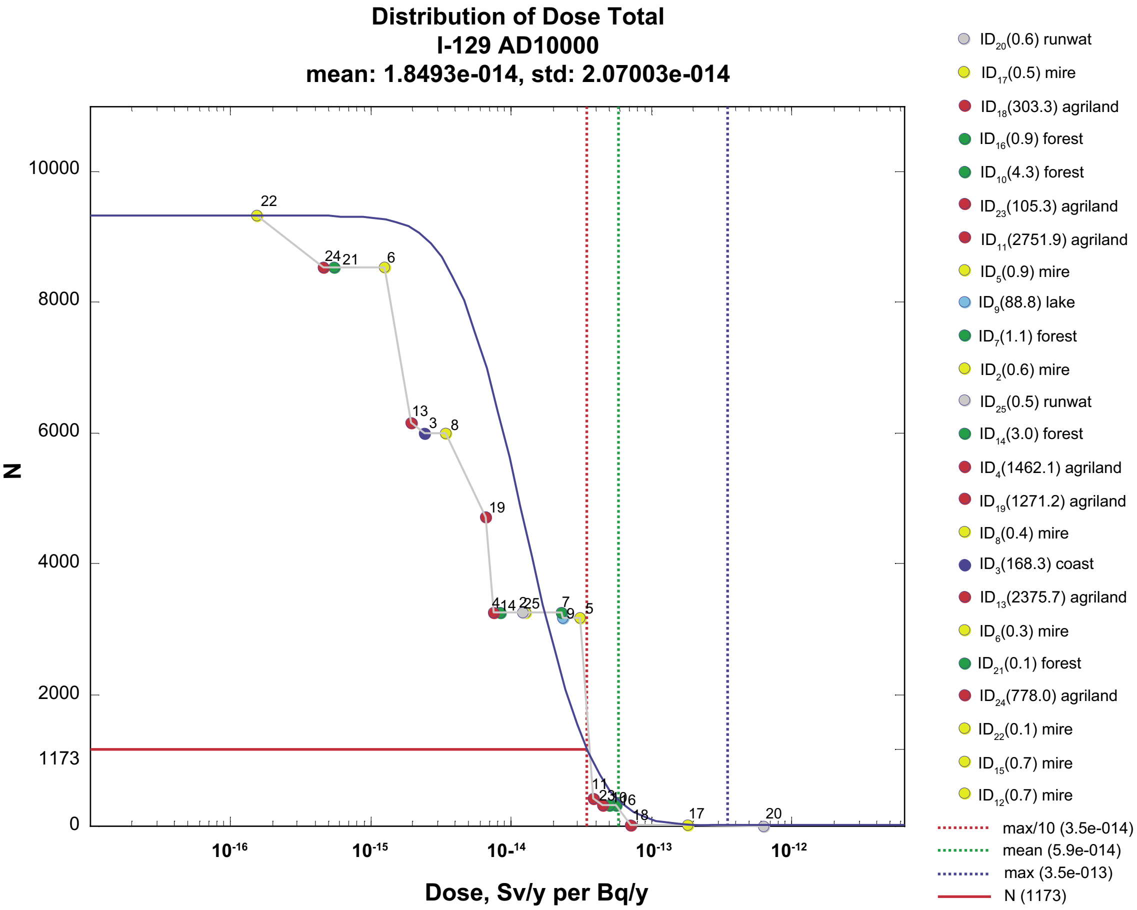


Figure 8-2. *Total effective dose rate from I-129 associated with different Biosphere Objects at 10,000 AD at Forsmark. The blue curve is the fitted log-normal distribution. The legend gives object id-number, ecosystem type and number of people (in brackets) that can be sustained for each Biosphere Object. The Landscape Dose conversion Factor (LDF) is the average for a population receiving an annual effective dose in the range from the maximum dose to 1/10 of the maximum, i.e.* $5.9\cdot10^{-14}$ *Sv·Bq*$^{-1}$ *in this case (green vertical line). The number of people in the most exposed group is 1,173 (red horizontal line)(from /Avila et al. 2006/).*

In summary, the method adopted for calculating effective dose rates and hence individual risks in SR-Can is to:

- Use the landscape model to calculate effective dose rates as a function of time for unit flux of each radionuclide of interest partitioned over the various Biosphere Objects in accordance with results obtained from geosphere flow and transport calculations.
- At each of a set of reference times (for practical convenience taken as every 1,000 years) and for each radionuclide to calculate the CCDF of number of individuals against effective dose rate for all the Biosphere Objects considered in the model.
- Fit a log-normal distribution to each CCDF and use that to calculate the effective dose rate at each reference time and for each radionuclide to the most exposed individual, i.e. the effective dose rate at which the fitted CCDF gives one person exceeding that effective dose rate.
- Find the effective dose rate to a representative individual from the most exposed group at each reference time and for each radionuclide by finding the arithmetic mean of the fitted log-normal distribution in the interval between the effective dose rate to the most exposed individual and one tenth of that value.

- Find the maximum of the effective dose rate to the representative individual over the reference times considered for each radionuclide and define this as the LDF for that radionuclide.
- Compare the LDF with the Well dose concentration factor, which reflects the estimated well capacity measured at the site (section 5.7) and use the maximum value for each radionuclide.

8.2.2 Handling of the climatic development during a glacial cycle

In order to describe the climatic development above the repository at the Forsmark over the entire one million year assessment period, two variants were analysed:

- A base variant where the external conditions during the first 120,000 year glacial cycle are assumed to be similar to those experienced during the latest cycle, the Weichselian (see Section 4.2 and Figure 4-9). The latest glacial cycle contains a number of temperate, permafrost, glacial and submerged phases. The glacial cycle is then repeated eight times to cover the entire 1,000,000 year assessment period.
- A greenhouse variant in which the future climate and hence external conditions are assumed to be substantially influenced by human-induced greenhouse gas emissions.

Below is the modelling of climatic conditions further described.

An interglacial or temperate period

The interglacial is represented by the current temperate period as 8,000 BC to 10,000 AD, for which the development is described in Chapter 4. The conditions during the current temperate period represent the conditions during all the temperate periods found within the latest glacial cycle.

Permafrost

Permafrost conditions occur in several episodes in the reference evolution covering the Weichselian glacial cycle /SKB 2006c/. The first permafrost episode starts about 10,000 AD following the present interglacial (see Chapter 4). The coastline is some distance from the repository at this time and major discharge areas are not located offshore. The situation is similar at the end of an interglacial when global sea levels are falling. To simulate the permafrost conditions, it is assumed that the spatial distribution of Biosphere Objects is similar to that at the end of the temperate interglacial period, except that agricultural land is replaced by forest or mires, reflecting the consideration that significant degree of agriculture would not be tenable in such a context. For calculating the LDF, a release of 1 Bq y^{-1} is assumed until 50,000 AD.

A glacial period

During the glacial period there can be periods when the repository is at the ice margin and submerged under the sea (see Chapter 4). For this period, the LDF for the landscape conditions directly after the ice has melted away is used, i.e. the conditions applicable to conditions at the beginning of an interglacial (see Figure 6-6A), but in the calculation of the LDF the release of 1 Bq y^{-1} is continued for 50,000 years into these landscape conditions.

The greenhouse variant

For the greenhouse variant of the reference evolution, the landscape and ecosystems at the end of the interglacial are used and the LDF is calculated for a continuing release of 1 Bq y^{-1} until 50,000 AD. After that, the same alterations between temperate and permafrost conditions follow as after the first permafrost period in the base variant.

8.2.3 Results of the biosphere modelling of doses to humans and biota

Landscape Dose conversion Factors

The LDF values obtained for Forsmark are presented in Table 8-1. The values range from around 10^{-17} to around 10^{-11} $SvBq^{-1}$. The maximum values occur at different times for the different radionuclides, either during the coastal or the terrestrial periods. The number of individuals in the most exposed group also differs between radionuclides.

The dose conversion factors increase towards the end of the period for all radionuclides (Figure 8-3). The submerged period gives values that are generally 3 to 4 orders of magnitude lower than those for the coastal and terrestrial periods. The differences over different time periods mainly depend on the properties of the ecosystems (e.g volumes, areas, discharge rates). Only a small part of the change is due to the fact that a larger inventory has accumulated towards the end of the period /Avila et al. 2006/.

For the entire Weichselian cycle, the LDF values are highest during the interglacial period and lowest during the glacial period, see tables in /SKB 2006a, Avila et al. 2006/ For the greenhouse variant, the LDF values are similar to the values of the interglacial LDFs.

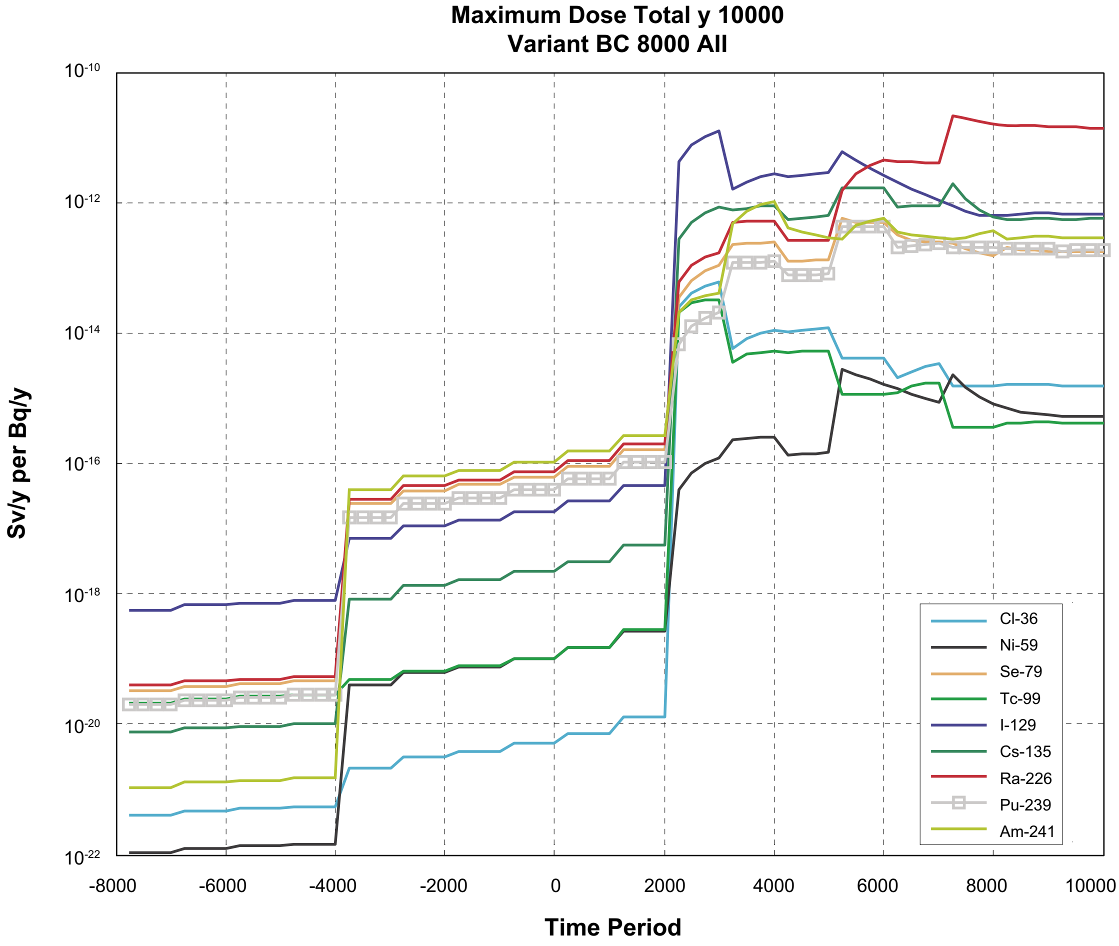


Figure 8-3. The maximum effective dose rate for some radionuclides at different times when 1 Bq y^{-1} has been released starting from 8,000 BC. The results are plotted for each period of 250 years. The stepwise character of the curves is due to the fact that most parameters and classifications are altered on time steps of 1,000 y /Avila et al. 2006/.

Table 8-1. Landcape Dose conversion Factors (LDF) for an interglacial period at Forsmark expressed in units of Sv y^{-1} per Bq y^{-1}. N is the number of persons in the most exposed group. Time is time for maximum LDF. Well DCF in Sv Bq^{-1}, which is equivalent to Sv y^{-1} per Bq y^{-1}, so a direct comparison can be made with the LDF value.

RN	LDF	N	Year (AD)	Well	Maximum
C-14	2.7E–12	19	3,000	2.1E–15	LDF
Cl-36	1.3E–14	128	2,500	3.5E–15	LDF
Ca-41	1.7E–15	41	8,000	5.3E–16	LDF
Ni-59	4.2E–16	67	8,000	2.4E–16	LDF
Ni-63	4.2E–16	23	8,000	5.6E–16	Well
Se-79	6.7E–14	23	3,000	1.2E–14	LDF
Sr-90	1.7E–13	18	8,000	1.0E–13	LDF
Zr-93	6.3E–15	36	6,000	4.0E–15	LDF
Nb-94	1.3E–11	422	4,000	6.2E–15	LDF
Tc-99	4.4E–15	301	2,500	2.5E–15	LDF
Pd-107	2.0E–16	67	3,000	1.4E–16	LDF
Ag-108m	6.9E–11	421	4,000	8.8E–15	LDF
Sn-126	4.2E–13	52	5,250	1.8E–14	LDF
I-129	5.5E–12	42	2,750	4.2E–13	LDF
Cs-135	6.3E–13	19	3,000	7.5E–15	LDF
Cs-137	1.2E–12	19	2,750	4.8E–14	LDF
Sm-151	6.6E–17	68	8,000	3.6E–16	Well
Ho-166m	1.9E–11	422	4,000	7.3E–15	LDF
Pb-210	2.6E–12	22	8,000	2.5E–12	LDF
Ra-226	9.0E–12	22	8,000	1.0E–12	LDF
Th-229	6.9E–12	741	4,000	1.8E–12	LDF
Th-230	8.1E–12	64	10,000	7.7E–13	LDF
Th-232	1.3E–12	119	10,000	8.4E–13	LDF
Pa-231	4.0E–13	89	8,000	2.6E–12	Well
U-233	4.8E–14	414	3,000	1.9E–13	Well
U-234	6.8E–14	47	7,250	1.8E–13	Well
U-235	4.4E–14	414	3,000	1.7E–13	Well
U-236	4.4E–14	414	3,000	1.7E–13	Well
U-238	4.2E–14	414	3,000	1.6E–13	Well
Np-237	1.4E–13	129	3,000	4.0E–13	Well
Pu-239	1.4E–13	103	6,000	9.2E–13	Well
Pu-240	1.4E–13	98	5,500	9.2E–13	Well
Pu-242	1.4E–13	99	6,000	8.8E–13	Well
Am-241	1.6E–12	860	4,000	7.3E–13	LDF
Am-243	3.7E–12	1,033	4,000	7.3E–13	LDF
Cm-244	1.4E–13	113	5,500	4.4E–13	Well
Cm-245	1.7E–12	1,046	4,000	7.7E–13	LDF
Cm-246	1.0E–12	433	4,000	7.7E–13	LDF

Doses to biota

The potential effects on non-human biota from exposure to released radionuclides were also assessed. For radionuclides with decay chains the daughter radionuclides were also considered. Two release cases were considered, the mean annual release base case and the advection/corrosion base case /SKB 2006a/. For these cases, the peak values of the release rates were used as constant release rate to the Forsmark landscape model and simulations were carried out for the whole interglacial period. From the simulations with the landscape model, the maximum values, over all biosphere objects, of the radionuclide concentrations in water of freshwater and sea objects and in soil of terrestrial objects were obtained. These values were then divided by the corresponding Environmental Media Concentration Limits (EMCL), which have been derived in the ERICA project (EU – 6th Framework Programme) using the FASSET methodology /FASSET 2004/. The resulting values are the so-called Risk Quotients (RQ), which are used for screening purposes in the first tier 1 of the graded approach proposed in ERICA for assessment of potential risks to non-human biota. According with the ERICA screening method, if the RQs are below one, then it can be assured that risks to biota are insignificant and no further assessments are required. If the RQ are above one, then more detailed assessments are required.

The results obtained for the mean annual release base case are presented in Tables 8-2 to 8-4, which show the maximum values of the environmental concentrations obtained, the EMCL used, and the calculated values of the RQs. In these tables, the limiting organisms are also indicated. These are the organisms that, according to the predictions with the models used in the derivation of the EMCL, would receive the highest exposure per unit radionuclide concentration in the environmental media. The RQs are below one for all radionuclides, which indicates that risks to non-human biota are insignificant and that there is no need for more detailed assessments. The highest RQ in this case are observed for Po-210, that is generated from the radioactive decay of Ra-226 with values of $1.3 \cdot 10^{-4}$ for freshwater ecosystems, $2.2 \cdot 10^{-3}$ for terrestrial ecosystems and $7.2 \cdot 10^{-6}$ for marine ecosystems.

For the advection/corrosion base case (see Tables 8-5 to 8-7), the RQs are also below one for most radionuclides, which indicates that risks to non-human biota are insignificant and that there is no need for more detailed assessments. However, for Ra-226 and the daughter nuclide Po-210, values above one of the RQs are observed for the three ecosystem types. This means that detailed assessments are required for these cases. A preliminary comparison (see Table 8-8) of the predicted maximal concentrations in soils and waters with background concentrations /FASSET 2004/ shows that the predicted values fall either within or slightly above the interval of variation of the background levels.

Table 8-2. Comparison of predicted maximum values of the radionuclide concentrations in water (Conc. water) of freshwater objects with the Environmental Media Concentration Limits (EMCL) for the mean annual release base case. The calculated values of the Risk Quotients (RQ) and the corresponding limiting organism are also given. In the case of daughter radionuclides (Pb-210, Po-210, Am-241) the first element of the chain that gives the highest concentration is indicated between parentheses.

Radionuclide	Conc. water Bq/m³	EMCL Bq/m³	RQ	Limiting organism
C-14	1.4E–05	6.7E+03	2.0E–09	(Wading) bird, Mammal, Reptile
Cl-36	3.7E–06	2.4E+07	1.6E–13	Zooplankton
Ca-41	7.9E–08	N/A	N/A	N/A
Ni-59	2.8E–05	5.6E+04	4.9E–10	Benthic mollusc
Ni-63	9.3E–13	4.4E+04	2.1E–17	Benthic mollusc
Se-79	9.1E–10	1.2E+04	7.4E–14	(Wading) bird, Reptile
Sr-90	0.0E+00	1.4E+04	0.0E+00	Sea anemones – colony
Zr-93	4.4E–09	N/A	N/A	N/A
Nb-94	6.3E–09	4.6E+00	1.4E–09	Polychaete worm, Sea anemones – polyp
Tc-99	1.1E–10	1.9E+03	5.9E–14	Vascular plant
Pd-107	1.8E–08	N/A	N/A	N/A
Ag-108m	0.0E+00	N/A	N/A	N/A
Sn-126	2.1E–09	N/A	N/A	N/A
I-129	2.2E–06	1.4E+04	1.6E–10	Macroalgae
Cs-135	2.2E–07	1.7E+05	1.3E–12	(Wading) bird
Cs-137	0.0E+00	2.5E+03	0.0E+00	Polychaete worm
Sm-151	0.0E+00	N/A	N/A	N/A
Ho-166m	0.0E+00	N/A	N/A	N/A
Pb-210(Ra-226)	7.4E–06	6.6E+02	1.1E–08	Zooplankton
Po-210(Ra-226)	1.0E–05	1.5E+00	7.2E–06	Zooplankton
Ra-226	6.9E–06	2.3E+01	3.0E–07	Sea anemones – colony
Th-229	2.9E–10	N/A	N/A	N/A
Th-230	3.3E–09	1.7E+01	2.0E–10	Zooplankton
Th-232	1.6E–12	1.9E+01	8.0E–14	Zooplankton
Pa-231	2.3E–09	N/A	N/A	N/A
U-233	1.6E–10	N/A	N/A	N/A
U-234	2.1E–12	2.2E+02	9.9E–15	Sea anemones – polyp and Sea anemones- colony
U-235	1.4E–12	2.4E+02	6.0E–15	Sea anemones – polyp and Sea anemones- colony
U-236	2.2E–12	N/A	N/A	N/A
U-238	2.2E–12	2.5E+02	8.6E–15	Sea anemones – polyp and Sea anemones- colony
Np-237	3.7E–10	1.2E+02	3.0E–12	Sea anemones – polyp and Sea anemones- colony
Pu-239	1.5E–09	1.3E+01	1.1E–10	Zooplankton
Pu-240	1.3E–11	1.3E+01	9.5E–13	Zooplankton
Pu-242	3.4E–09	N/A	N/A	N/A
Am-241	4.3E–15	1.2E+01	3.5E–16	
Am-241(Cm-245)	3.0E–15	1.2E+01	2.5E–16	
Am-243	5.8E–13	N/A	N/A	N/A
Cm-244	0.0E+00	3.7E+00	0.0E+00	Benthic mollusc, Polychaete worm
Cm-245	2.0E–14	N/A	N/A	N/A
Cm-246	0.0E+00	N/A	N/A	N/A

Table 8-3. Comparison of predicted maximum values of the radionuclide concentrations in water (Conc. water) of sea objects with the Environmental Media Concentration Limits (EMCL) for the mean annual release base case. The calculated values of the Risk Quotients (RQ) and the corresponding limiting organism are also given. In the case of daughter radionuclides (Pb-210, Po-210, Am-241) the first element of the chain that gives the highest concentration is indicated between parentheses.

Radionuclide	Conc water Bq/m³	EMCL Bq/m³	RQ	Limiting organism
C-14	3.2E–02	1.6E+04	2.1E–06	
Cl-36	1.1E–02	1.3E+05	8.8E–08	Vascular plant
Ca-41	1.1E–04	N/A	N/A	N/A
Ni-59	7.4E–03	4.6E+04	1.6E–07	Insect larvae
Ni-63	1.8E–10	5.7E+04	3.1E–15	Zooplankton
Se-79	9.0E–08	1.1E+04	8.2E–12	Insect larvae, Crustacean
Sr-90	0.0E+00	4.4E+03	0.0E+00	Mammal
Zr-93	5.1E–07	N/A	N/A	N/A
Nb-94	1.0E–06	7.2E+00	1.4E–07	Vascular plant, Insect larvae
Tc-99	3.6E–07	4.4E+04	8.0E–12	Bird, Mammal, Amphibian
Pd-107	9.8E–06	N/A	N/A	N/A
Ag-108m	0.0E+00	N/A	N/A	N/A
Sn-126	1.6E–07	N/A	N/A	N/A
I-129	6.7E–03	1.0E+05	6.6E–08	Mammal
Cs-135	1.7E–04	8.8E+03	1.9E–08	Insect larvae
Cs-137	0.0E+00	1.6E+03	0.0E+00	Mammal
Sm-151	0.0E+00	N/A	N/A	N/A
Ho-166m	0.0E+00	N/A	N/A	N/A
Pb-210(Ra-226)	3.9E–04	1.1E+02	3.6E–06	Insect larvae
Po-210(Ra-226)	3.6E–04	2.7E+00	1.3E–04	Bivalve mollusc
Ra-226	1.1E–03	1.5E+01	7.7E–05	Vascular plant
Th-229	2.5E–08	N/A	N/A	N/A
Th-230	2.8E–07	6.2E+01	4.5E–09	Zooplankton
Th-232	1.3E–10	7.3E+01	1.8E–12	Vascular plant
Pa-231	1.7E–07	N/A	N/A	N/A
U-233	7.9E–08	N/A	N/A	N/A
U-234	1.1E–09	4.2E+01	2.5E–11	Vascular plant
U-235	6.9E–10	4.6E+01	1.5E–11	Vascular plant
U-236	1.1E–09	N/A	N/A	N/A
U-238	1.1E–09	4.9E+01	2.1E–11	Vascular plant
Np-237	8.1E–08	3.0E+02	2.7E–10	Zooplankton
Pu-239	1.1E–07	4.1E+01	2.6E–09	Vascular plant
Pu-240	9.1E–10	4.1E+01	2.2E–11	Vascular plant
Pu-242	2.4E–07	N/A	N/A	N/A
Am-241	5.3E–13	2.6E+00	2.0E–13	Zooplankton, Mammal, Ampibian
Am-241(Cm-245)	3.1E–13	2.6E+00	1.2E–13	Zooplankton, Mammal, Ampibian
Am-243	7.3E–11	N/A	N/A	N/A
Cm-244	0.0E+00	5.3E+00	0.0E+00	Zooplankton
Cm-245	2.4E–12	N/A	N/A	N/A
Cm-246	0.0E+00	N/A	N/A	N/A

Table 8-4. Comparison of predicted maximum values of the radionuclide concentrations in soil (Conc. soil) of terrestrial objects with the Environmental Media Concentration Limits (EMCL) for the mean annual release base case. The calculated values of the Risk Quotients (RQ) and the corresponding limiting organism are also given. In the case of daughter radionuclides (Pb-210, Po-210, Am-241) the first element of the chain that gives the highest concentration is indicated between parentheses.

Radionuclide	Conc. soil Bq/kg DW	EMCL Bq/kg	RQ	Limiting organism
C-14	1.1E–03	8.5E+01	1.3E–05	Mammal (Deer), Bird
Cl-36	4.1E–05	2.9E+03	1.4E–08	Reptile
Ca-41	1.9E–05	N/A	N/A	N/A
Ni-59	3.1E–02	1.3E+06	2.3E–08	Grasses and Herbs
Ni-63	1.1E–09	1.2E+06	9.8E–16	Grasses and Herbs
Se-79	1.0E–06	5.3E+03	1.9E–10	Lichen and bryophytes
Sr-90	0.0E+00	1.3E+02	0.0E+00	Reptile
Zr-93	3.9E–05	N/A	N/A	N/A
Nb-94	1.5E–05	1.1E+04	1.3E–09	Mammal (Rat)
Tc-99	2.4E–10	1.6E+02	1.6E–12	Bird egg
Pd-107	1.4E–05	N/A	N/A	N/A
Ag-108m	0.0E+00	N/A	N/A	N/A
Sn-126	3.6E–06	N/A	N/A	N/A
I-129	2.1E–04	4.2E+02	4.9E–07	Bird egg
Cs-135	1.1E–04	3.2E+03	3.4E–08	Reptile
Cs-137	0.0E+00	7.6E+02	0.0E+00	Reptile
Sm-151	0.0E+00	N/A	N/A	N/A
Ho-166m	0.0E+00	N/A	N/A	N/A
Pb-210(Ra-226)	1.6E–02	5.0E+03	3.3E–06	Lichen and bryophytes
Po-210(Ra-226)	1.6E–02	7.3E+00	2.2E–03	Mammal (Rat), Mammal (Deer)
Ra-226	1.7E–02	4.2E+00	4.2E–03	Soil Invertebrate (worm), Detritivorous invertebrate, Flying insects
Th-229	2.1E–05	N/A	N/A	N/A
Th-230	2.3E–04	1.6E+03	1.4E–07	Lichen and bryophytes
Th-232	1.1E–07	1.8E+03	5.7E–11	Lichen and bryophytes
Pa-231	2.1E–05	N/A	N/A	N/A
U-233	6.1E–08	N/A	N/A	N/A
U-234	8.1E–10	1.7E+03	4.8E–13	Lichen and bryophytes
U-235	5.3E–10	1.8E+03	2.9E–13	Lichen and bryophytes
U-236	8.4E–10	N/A	N/A	N/A
U-238	8.1E–10	2.0E+03	4.1E–13	Lichen and bryophytes
Np-237	3.4E–07	6.2E+02	5.5E–10	Gastropod
Pu-239	3.6E–06	1.1E+03	3.4E–09	Lichen and bryophytes
Pu-240	3.1E–08	1.1E+03	2.9E–11	Lichen and bryophytes
Pu-242	8.1E–06	N/A	N/A	N/A
Am-241	2.7E–10	6.5E+02	4.1E–13	Flying insects
Am-241(Cm-245)	1.6E–10	6.5E+02	2.5E–13	Flying insects
Am-243	4.2E–08	N/A	N/A	N/A
Cm-244	0.0E+00	7.4E+02	0.0E+00	Soil Invertebrate (worm), Flying insects, Gastropod
Cm-245	2.6E–10	N/A	N/A	N/A
Cm-246	0.0E+00	N/A	N/A	N/A

Table 8-5. Comparison of predicted maximum values of the radionuclide concentrations in water (Conc. water) of freshwater objects with the Environmental Media Concentration Limits (EMCL) for the advection/corrosion base case. The calculated values of the Risk Quotients (RQ) and the corresponding limiting organism are also given. In the case of daughter radionuclides (Pb-210, Po-210, Am-241) the first element of the chain that gives the highest concentration is indicated between parentheses.

Radionuclide	Conc. water Bq/m³	EMCL Bq/m³	RQ	Limiting organism
C-14	2.9E–03	1.6E+04	1.9E–07	
Cl-36	1.0E+01	1.3E+05	8.0E–05	Vascular plant
Ca-41	1.2E–01	N/A	N/A	N/A
Ni-59	2.2E+02	4.6E+04	4.9E–03	Insect larvae
Ni-63	3.4E–14	5.7E+04	6.0E–19	Zooplankton
Se-79	7.5E–03	1.1E+04	6.8E–07	Insect larvae, Crustacean
Sr-90	1.8E–13	4.4E+03	4.2E–17	Mammal
Zr-93	3.1E–01	N/A	N/A	N/A
Nb-94	1.3E–01	7.2E+00	1.8E–02	Vascular plant, Insect larvae
Tc-99	2.0E–02	4.4E+04	4.6E–07	Bird, Mammal, Amphibian
Pd-107	1.0E–01	N/A	N/A	N/A
Ag-108m	4.9E–15	N/A	N/A	N/A
Sn-126	8.4E–02	N/A	N/A	N/A
I-129	1.2E+01	1.0E+05	1.2E–04	Mammal
Cs-135	6.4E+00	8.8E+03	7.3E–04	Insect larvae
Cs-137	5.1E–14	1.6E+03	3.2E–17	Mammal
Sm-151	1.8E–14	N/A	N/A	N/A
Ho-166m	3.1E–15	N/A	N/A	N/A
Pb-210 (Ra-226)	2.2E+01	1.1E+02	2.0E–01	Insect larvae
Po-210 (Ra-226)	2.7E+01	2.7E+00	9.9E+00	Bivalve mollusc
Ra-226	6.9E+01	1.5E+01	4.8E+00	Vascular plant
Th-229	6.7E–01	N/A	N/A	N/A
Th-230	1.7E–01	6.2E+01	2.8E–03	Zooplankton
Th-232	4.1E–07	7.3E+01	5.7E–09	Vascular plant
Pa-231	1.6E–02	N/A	N/A	N/A
U-233	3.1E–04	N/A	N/A	N/A
U-234	6.0E–04	4.2E+01	1.4E–05	Vascular plant
U-235	7.4E–06	4.6E+01	1.6E–07	Vascular plant
U-236	1.3E–04	N/A	N/A	N/A
U-238	1.1E–04	4.9E+01	2.2E–06	Vascular plant
Np-237	2.1E–02	3.0E+02	7.0E–05	Zooplankton
Pu-239	3.3E+00	4.1E+01	7.9E–02	Vascular plant
Pu-240	1.7E–03	4.1E+01	4.2E–05	Vascular plant
Pu-242	5.1E–01	N/A	N/A	N/A
Am-241	4.0E–06	2.6E+00	1.5E–06	Zooplankton, Mammal, Ampibian
Am-243	3.0E–04	N/A	N/A	N/A
Cm-244	9.7E–15	5.3E+00	1.8E–15	Zooplankton
Cm-245	1.8E–05	N/A	N/A	N/A
Cm-246	7.8E–09	N/A	N/A	N/A

Table 8-6. Comparison of predicted maximum values of the radionuclide concentrations in water (Conc. water) of sea objects with the Environmental Media Concentration Limits (EMCL) for the advection/corrosion base case. The calculated values of the Risk Quotients (RQ) and the corresponding limiting organism are also given. In the case of daughter radionuclides (Pb-210, Po-210, Am-241) the first element of the chain that gives the highest concentration is indicated between parentheses.

Radionuclide	Conc. water Bq/m³	EMCL Bq/m₃	RQ	Limiting organism
C-14	3.9E–04	6.7E+03	5.8E–08	(Wading) bird, Mammal, Reptile
Cl-36	1.4E+00	2.4E+07	6.0E–08	Zooplankton
Ca-41	1.6E–02	N/A	N/A	N/A
Ni-59	3.0E+01	5.6E+04	5.3E–04	Benthic mollusc
Ni-63	4.6E–15	4.4E+04	1.1E–19	Benthic mollusc
Se-79	8.3E–04	1.2E+04	6.7E–08	(Wading) bird, Reptile
Sr-90	2.4E–14	1.4E+04	1.7E–18	Sea anemones – colony
Zr-93	4.0E–02	N/A	N/A	N/A
Nb-94	1.7E–02	4.6E+00	3.8E–03	Polychaete worm, Sea anemones – polyp
Tc-99	2.9E–03	1.9E+03	1.5E–06	Vascular plant
Pd-107	1.3E–02	N/A	N/A	N/A
Ag-108m	7.2E–16	N/A	N/A	N/A
Sn-126	1.0E–02	N/A	N/A	N/A
I-129	1.6E+00	1.4E+04	1.2E–04	Macroalgae
Cs-135	3.9E–01	1.7E+05	2.3E–06	(Wading) bird
Cs-137	6.6E–15	2.5E+03	2.6E–18	Polychaete worm
Sm-151	2.5E–15	N/A	N/A	N/A
Ho-166m	4.1E–16	N/A	N/A	N/A
Pb-210 (Ra-226)	4.0E+00	6.6E+02	6.1E–03	Zooplankton
Po-210 (Ra-226)	1.7E+00	1.5E+00	1.2E+00	Zooplankton
Ra-226	9.1E+00	2.3E+01	3.9E–01	Sea anemones – colony
Th-229	1.1E–01	N/A	N/A	N/A
Th-230	2.7E–02	1.7E+01	1.6E–03	Zooplankton
Th-232	6.3E–08	1.9E+01	3.3E–09	Zooplankton
Pa-231	2.0E–03	N/A	N/A	N/A
U-233	3.9E–05	N/A	N/A	N/A
U-234	7.6E–05	2.2E+02	3.5E–07	Sea anemones – polyp and Sea anemones– colony
U-235	9.4E–07	2.4E+02	4.0E–09	Sea anemones – polyp and Sea anemones– colony
U-236	1.6E–05	N/A	N/A	N/A
U-238	1.4E–05	2.5E+02	5.5E–08	Sea anemones – polyp and Sea anemones– colony
Np-237	2.7E–03	1.2E+02	2.2E–05	Sea anemones – polyp and Sea anemones– colony
Pu-239	4.1E–01	1.3E+01	3.1E–02	Zooplankton
Pu-240	2.2E–04	1.3E+01	1.6E–05	Zooplankton
Pu-242	6.4E–02	N/A	N/A	N/A
Am-241	8.6E–07	1.2E+01	7.0E–08	
Am-243	5.0E–05	N/A	N/A	N/A
Cm-244	1.5E–15	3.7E+00	4.0E–16	Benthic mollusc, Polychaete worm
Cm-245	1.7E–06	N/A	N/A	N/A
Cm-246	7.7E–10	N/A	N/A	N/A

Table 8-7. Comparison of predicted maximum values of the radionuclide concentrations in soil (Conc. soil) of terrestrial objects with the Environmental Media Concentration Limits (EMCL) for the advection/corrosion base case. The calculated values of the Risk Quotients (RQ) and the corresponding limiting organism are also given. In the case of daughter radionuclides (Pb-210, Po-210, Am-241) the first element of the chain that gives the highest concentration is indicated between parentheses.

Radionuclide	Conc soil Bq/kg DW	EMCL Bq/kg	RQ	Limiting organism
C-14	1.0E–04	8.5E+01	1.2E–06	Mammal (Deer), Bird
Cl-36	5.4E–02	2.9E+03	1.9E–05	Reptile
Ca-41	4.4E–02	N/A	N/A	N/A
Ni-59	1.4E+02	1.3E+06	1.1E–04	Grasses and Herbs
Ni-63	1.7E–14	1.2E+06	1.4E–20	Grasses and Herbs
Se-79	8.0E–03	5.3E+03	1.5E–06	Lichen and bryophytes
Sr-90	1.8E–14	1.3E+02	1.4E–16	Reptile
Zr-93	1.1E+00	N/A	N/A	N/A
Nb-94	1.3E–01	1.1E+04	1.2E–05	Mammal (Rat)
Tc-99	2.2E–05	1.6E+02	1.4E–07	Bird egg
Pd-107	3.9E–02	N/A	N/A	N/A
Ag-108m	4.1E–14	N/A	N/A	N/A
Sn-126	7.9E–02	N/A	N/A	N/A
I-129	4.4E+00	4.2E+02	1.0E–02	Bird egg
Cs-135	1.7E+00	3.2E+03	5.4E–04	Reptile
Cs-137	7.6E–15	7.6E+02	1.0E–17	Reptile
Sm-151	2.5E–14	N/A	N/A	N/A
Ho-166m	4.7E–15	N/A	N/A	N/A
Pb-210 (Ra-226)	9.9E+01	5.0E+03	2.0E–02	Lichen and bryophytes
Po-210 (Ra-226)	9.9E+01	7.3E+00	1.4E+01	Mammal (Rat), Mammal (Deer)
Ra-226	7.1E+01	4.2E+00	1.7E+01	Soil Invertebrate (worm), Detritivorous invertebrate, Flying insects
Th-229	2.1E+01	N/A	N/A	N/A
Th-230	5.6E+00	1.6E+03	3.5E–03	Lichen and bryophytes
Th-232	1.3E–05	1.8E+03	7.2E–09	Lichen and bryophytes
Pa-231	5.6E–02	N/A	N/A	N/A
U-233	8.7E–05	N/A	N/A	N/A
U-234	1.7E–04	1.7E+03	1.0E–07	Lichen and bryophytes
U-235	2.1E–06	1.8E+03	1.2E–09	Lichen and bryophytes
U-236	3.7E–05	N/A	N/A	N/A
U-238	3.2E–05	2.0E+03	1.6E–08	Lichen and bryophytes
Np-237	1.0E–02	6.2E+02	1.7E–05	Gastropod
Pu-239	8.6E+00	1.1E+03	8.0E–03	Lichen and bryophytes
Pu-240	3.4E–03	1.1E+03	3.1E–06	Lichen and bryophytes
Pu-242	1.5E+00	N/A	N/A	N/A
Am-241	1.1E–04	6.5E+02	1.7E–07	Flying insects
Am-243	9.8E–03	N/A	N/A	N/A
Cm-244	2.8E–14	7.4E+02	3.8E–17	Soil Invertebrate (worm), Flying insects, Gastropod
Cm-245	9.1E–05	N/A	N/A	N/A
Cm-246	4.0E–08	N/A	N/A	N/A

Table 8-8. Comparison of the predicted values, for the advection/corrosion base case, of concentrations in soil, marine water and freshwater with background levels reported in /FASSET 2004/.

Radionuclide	Media	Unit	Predicted	Background	Comments
Ra-226	Soil	Bq/kg dw	7.1E+01	12–170	Range reported for Swedish soils
	Marine water	Bq/m^3	9.1E+00	Median – 2 95 perc – 3	
	Fresh water	Bq/m^3	6.9E+01	0.5–100	Global range
Pb-210	Soil	Bq/kg dw	9.9E+01	12–170	Assuming equilibrium with Ra-226
	Marine water	Bq/m^3	4.0E+00	Median – 2 95 perc – 4	
	Fresh water	Bq/m^3	2.2E+01	0.5–100	Assuming equilibrium with Ra-226
Po-210	Soil	Bq/kg dw	9.9E+01	12–170	Assuming equilibrium with Ra-226
	Marine water	Bq/m^3	1.7E+00	Median – 2 95 perc – 3	Assuming equilibrium with Ra-226
	Fresh water	Bq/m^3	2.7E+01	0.3–9	Global range

8.2.4 Results of the biosphere modelling of doses to humans using specific scenarios

A key feature in managing uncertainties in the future development of the repository system is the reduction of the number of potential situations of exposure to analyse by selecting a set of representative scenarios. Below three different exposure scenarios are presented.

The drilling case

The potential exposure to large quantities of the radiotoxic material is an inescapable consequence of the deposition of spent nuclear fuel in a final repository, and consequently intrusion into the repository needs to be considered in repository design and safety assessment. In this case the radiological consequences of a drilling that affects a canister in the repository were studied. The drilling angle is assumed to be 85° as this will make the longest hole through the canister and bring most fuel to the surface. The cuttings are assumed to be spread on the ground, but the cores containing spent nuclear fuel are removed. It is assumed that the purpose of the drilling is to reach great depth and that the drill rig therefore is placed at a low point in the terrain. When the backfilled tunnel is reached the borehole is assumed to be grouted and the drilling continued. The buffer is assumed to be grouted as well, the drilling continued and the canister penetrated. When the drill core containing the canister and fuel is brought to the surface the anomalous situation is taken to be recognised and the drilling is stopped. The site and the borehole are abandoned without further measures. About a month later, a family moves to the site and operates a domestic production farm there. The abandoned borehole is used as a well by the family. The consequences for the repository and the annual effective doses to the family are assessed.

If a canister is penetrated and the safety functions of the buffer and backfill are lost and the borehole is used as a well for drinking and irrigation, the annual effective doses to representative members of critical groups will exceed the individual limit on annual effective dose for members of the public but not the annual effective dose due to background radiation. Assuming the site-specific mean capacities of wells, at Forsmark the dose limit is only exceeded if the intrusion occurs during the first 500 years after closure. If it is assumed that the instant release fraction and crushed material from the fuel elements is brought to the surface, that the land is used for cultivation the same year as the intrusion occurs and that a person spends time in the contaminated area, then the annual absorbed and effective doses may reach very high levels. The exposed person in the example given would be severely injured. One could expect that if the borehole is used as a well, the contaminated area immediately adjacent to the hole will be used for the pump and not for cultivation

The pulse case

The LDF values are calculated for constant releases over long time periods. These long time periods imply that near steady state situations develop and that the effect of downstream accumulation should be considered in the doses calculations. For a pulse release, steady state does not develop for many radionuclides and downstream accumulation is very low compared to the levels in the object that receives the release. Moreover, the annual average lifetime risk will be lower for pulse releases with a duration that is less than a lifetime (< 50 years). Preliminary analyses show that, for pulse releases with a duration of 1 year, using the LDF values in the dose calculations would overestimate the doses by about one order of magnitude, /Avila 2006/.

In these preliminary analyses annual doses resulting from unit releases of the dominant radionuclides to representative landscape objects (forests, lakes, mires, seas and agricultural lands) were calculated. The doses were integrated over 50 years to obtain estimated of annual average lifetime doses. For all radionuclides and ecosystems, except for agricultural lands, the maximum doses occurred the first year and declined rapidly over time. For agricultural lands, however, the peak dose rate may occur after more than 1,000 years for some radionuclides /Avila 2006/.

In the Sr-Can assessment /SKB 2006a/ the LDF values divided by 50, the assumed lifetime, were used as a cautious factor for estimating the risk of pulse releases.

The gas release case

Model calculations have shown that C-14 and Rn-222 may be released from nuclear waste disposals in gaseous form and may enter the biosphere via soil as a diffuse source /SKB 2006a/. C-14 may be released as methane (CH_4) or carbon dioxide (CO_2). It is assumed that if C-14 is released as methane from the repository, it will be oxidised to carbon dioxide by soil organisms. Radon is a noble gas and will not undergo chemical transformations. For C-14, exposure may occur via inhalation or ingestion, for Rn-222 only inhalation of Rn-222 and its radioactive daughter products needs to be taken into account.

Ingestion dose from C-14

The ingestion dose is estimated by means of a modified specific activity model. The key assumption is that C-14 is released during a relative short time, which may be in the range of a few to tens of days. If the release occurs during the vegetation period, C-14 is metabolised by the photosynthesis and enters via this pathway the human food chain. A release during the vegetation period is more likely, since then the soil is not frozen, which facilitates the exchange of gases from deep soil to the lower atmosphere. For a specification of the boundary assumptions, see /Avila 2006/. The release would cause an additional exposure of 1.8 μSv (Table 8-9). However, wind speed and mixing height vary with the weather conditions. Varying wind speed and mixing height in the ranges of 1–10 m s^{-1} and 10–50 m respectively, the resulting effective dose varies in the range of 0.15–7.3 μSv. The release in winter would not cause an ingestion dose due to the missing photosynthesis.

Table 8-9. Ingestion dose due to a pulse release of C-14, from /Avila 2006/.

Quantity	Value
Assumptions *Total release (Bq)*	1.00E+10
Area (m²)	1.00E+04
Radius of the area (m)	56.4
Release (Bq m⁻²)	1.0E+06
Carbon content of air (g m⁻³)	0.13
Seconds per year (s a⁻¹)	31,536,000
Conversion factor: µSv per Bq C-14 per g C-12	52.9
Factor for local production	0.1
Exposure (effective dose, µSv)	
Wind speed = 2 m/s, Mixing height = 20 m	1.8 µSv
Range: Wind speed: 1–10 m/s Mixing height 10–50 m	0.15–7.3 µSv

Inhalation of C-14 and Rn-222 outdoors

The same boundary conditions as above are assumed and the calculations are presented in /Avila 2006/. For C-14, an inhalation rate of 8,100 m^3 a^{-1} is assumed /ICRP 1995/and an inhalation dose factor of 6.2 E–12 Sv Bq^{-1} /ICRP 1996/ is taken. For a wind speed in the range of 1–10 m s^{-1} and a mixing height of 10–50 m, this causes an inhalation dose of about 0.00018–0.009 µSv (Table 8-10).

For Rn-222, a release rate of 25 GBq is assumed. The dose is calculated using a dose conversion factor of 47 µSv a^{-1} per Bq m^{-3}. This dose factor assumes an equilibrium factor of 0.6 /UNSCEAR 2000/, which is typical for outdoor conditions where the unattached fraction of the Rn-222 daughters is high. For a wind speed in the range of 1–10 m s^{-1} and a mixing height of 10–50 m, this causes an inhalation dose varying in the range of 0.4–20 µSv.

Table 8-10. Outdoor inhalation dose due to a pulse release of C-14 and Rn-222, from /Avila 2006/.

Quantity	Value C-14	Rn-222
Assumptions		
Total release (Bq)	1.0E+10	2.5E+10
Area (m²)	1.0E+04	1.0E+04
Radius of the area (m)	56.4	56.4
Release (Bq m⁻²)	1.0E+06	2.5E+06
DoseFactor	6.2E–12 Sv Bq⁻¹	47 µSv a⁻¹ per Bq m⁻³
Underlying equilibrium factor	not applicable	0.6
Exposure (effective dose, µSv)		
Wind speed = 2 m s⁻¹, Mixing height = 20 m	0.0022 µSv	11 µSv
Range: Wind speed: 1–10 m s⁻¹ Mixing height 10–50 m	0.00018–0.009–µSv	0.4–20µSv

Inhalation of C-14 and Rn-222 indoors

The activity concentration of C14 and Rn-222 indoors is calculated from the release (Bq m^{-2}), the ground area of the house A (m^2), the volume of the house V (m^3) and the ventilation rate, see /Avila 2006/.

The same release inside and outside the house is assumed, which is very cautious since walls and floors inhibit the diffusion of C-14 and Rn-222 from soil to indoor air. For the ventilation rate a value of 2 h^{-1} is assumed, which should typical for an average over winter and summer. In winter, it is less due to the lower temperatures, whereas it is higher in summer. However, also in winter a minimum value for the ventilation is not much less than 1 h^{-1} to maintain a reasonable air quality indoors. An occupancy factor of 0.5 is assumed, this means that people stay 50% of their time in their house. The same dosimetric parameters are assumed as above, however, for the dose conversion factor of Rn-222, a value of 32 µSv a^{-1} per Bq m^{-3} is assumed due to the lower equilibrium factor of 0.4, which is a typical indoor value /UNSCEAR 2000/.

The resulting indoor exposures for a house of with a volume of 1,000 m^3 and a ventilation rate of 2 h^{-1} are 0.14 µSv and 230 µSv for C-14 and Rn-222 respectively (Table 8-11). For house volumes of 500–1,500 m^3 and ventilation rates of 1–5 h^{-1} the inhalation dose varies for C-14 from 0.038 to 0.57 µSv and for Rn-222 from 60 to 900 µSv.

The highest dose from a gas pulse occurs in buildings for Rn-222, with 7.2 µSv/year. It is below the regulatory limits for an annual average life time risk for a repository, and it is considerably lower than the consequences of today limits of 200 Bq/m^3 for radon in buildings in Sweden, which gives about 2 mSv.

Table 8-11. Indoor inhalation dose due to a pulse release of C-14 and Rn-222, from /Avila 2006/. Annual life time risk is estimated by dividing the dose with 50 years.

Quantity	Value C-14	 Rn-222
Assumptions		
Total release (Bq)	1.0E+10	2.5E+10
Area (m^2)	1.0E+04	1.0E+04
Ground area of the house (m^2)	100	100
Release (Bq m^{-2})	1.0E+06	2.5E+06
DoseFactor	6.2E–12 Sv Bq^{-1}	32 µSv a^{-1} per Bq m^{-3}
Underlying equilibrium factor	not applicable	0.4
Occupancy factor	0.5	0.5
Exposure (effective dose, µSv)		
House volume = 1,000 m^3, Ventilation rate = 2 h^{-1}	0.14 µSv	230 µSv
Range: House volume = 500–1,500 m^3, Ventilation rate = 1–5 h^{-1}	0.038–0.57–µSv	60–900 µSv

8.2.5 Uncertainties in the LDF values

For elucidating the effects of the parameter uncertainties on the uncertainties in the LDF values, it is necessary to make sensitivity analyses for the whole landscape model, similar to the studies that were done for the ecosystem models /Avila 2006/. Such studies have not yet been carried out to the needed extent. Preliminary analyses have been done by varying important parameters one-at-a-time within their range of variation, while keeping other parameters at their best estimate values. These analyses show, for example, that the effect of the K_d on the maximum total dose rate was different in different periods with practically no effect in some periods (for example the sea period) and pronounced effects in other periods, particularly in periods when ecosystem shifts occur. The effect of the K_d was also different for different radionuclides. The maximum LDF values are obtained at different time periods for the different cases and the values differ by a factor of 10 or more. Similar responses of the LDF values were observed when making one-at-a-time variations of other important parameters.

The analysis of the results /Avila et al. 2006/ indicates that the topography, which affects the drainage area, the hydrology, the sedimentation environment and the size of the biosphere objects are also important factors. The topography is a robust property that is rather well understood at the sites and is predictable in time, especially where the regolith is thin and the topography is mainly determined by the solid rock. Several of the radionuclide- independent parameters that have the highest effect on the retained fractions, such as the area of the objects, the catchment areas, the run-off, depend on the topography of the sites. During the sea period, the fraction of accumulation bottoms and the water velocity in the bottom sediments has the largest effect on the retained fraction of the releases. These parameters are more difficult to estimate. However, the accumulation during the sea period does not seem to have a significant impact on the maximum dose rates and the LDF values.

The permafrost case was not studied in Forsmark, but in Laxemar two alternative cases were considered, one with mires and other with forests prevailing in the landscape /Avila et al. 2006/. The differences between these cases were within a factor of ten. The assumptions and parameter values for the other climatic stages have higher uncertainties and thus it is expected that differences of one order of magnitude will be within the uncertainty ranges of the interglacial stage.

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Appendix 1

Parameters describing the Biosphere Objects that was identified and delimited as targets for a modelled radionuclide release at the Forsmark site. The definition of the parameter and the method behind the calculation of the parameter value is described in Chapter 5 under the specific ecosystem. The column "Object" denotes which ecosystem the parameter describes, while the column "SiteSpecificData" show whether site specific data has been used to calculate the value.

Object	Parameter	SiteSpecific-Data	Units	Mean	Median	Min	Max	Std
Sea	z_uppers	No	m	0.02		0.005	0.05	
Sea	porosity_upper	Yes	–	0.6		0.25	0.85	
Sea	density_upper	Yes	$kg \cdot m^{-3}$	767		92	1,700	
Sea	z_deeps	Yes	m	6		0	40	
Sea	porosity_bottom	Yes	–	0.386	0.386	0.140	0.650	0.217
Sea	density_bottom	Yes	$kg \cdot m^{-3}$	2,186		2,100	2,300	
Sea	sed_growth	Yes	$m \cdot y^{-1}$	0.001		–0.01	0.01	
Sea	part_conc	Yes	$kg \cdot m^{-3}$	2.8E–04	0.00026	0.00013	0.00055	0.00010
Sea	v_sinking	Yes	$m \cdot y^{-1}$	60		4	117	
Sea	v_sediment	Yes	$m \cdot y^{-1}$	0.016	0.016	0.013	0.021	0.003
Sea	productivity_food	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.0053	0.0054	0.0052	0.0054	
Lake	z_uppers	Yes	m	0.084	0.025	0	0.4	0.071
Lake	porosity_upper	Yes	–	0.98	0.98	0.97	0.98	0.004
Lake	density_upper	No	$kg \cdot m^{-3}$	100		50	200	
Lake	z_deeps	Yes	m	0.87	0.71	0.16	1.75	0.598
Lake	porosity_bottom	Yes	–	0.93	0.94	0.81	0.97	0.05
Lake	acc_bottom	Yes	–	0.98		0.5	1	
Lake	sed_growth	Yes	$m \cdot y^{-1}$	0.00066	0.00053	0.00035	0.00135	
Lake	part_conc	Yes	$kg \cdot m^{-3}$	0.00059	0.00044	0.00023	0.00164	0.001
Lake	v_sinking	No	$m \cdot y^{-1}$	183		36.5	3,600	
Lake	v_sediment	Yes	$m \cdot y^{-1}$	0.016	0.016	0.013	0.021	0.003
Lake	productivity_plants	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.406				
Lake	productivity_animal	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.079				
Lake	productivity_food	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.0040	0.0040	0.0032	0.0047	0.0011
Lake	productivity_edible	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.016				
Mire	z_uppers	Yes	m	1	0.9	0.2	2.7	0.9
Mire	porosity_upper	Yes	–	0.89	0.9	0.76	0.95	0.05
Mire	density_upper	No	$kg \cdot m^{-3}$	100		80	120	
Mire	runoff	Yes	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.226				
Mire	productivity_food	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	1.9E–04		1.7E–08		
Agricultural land	z_uppers	No	m	0.25		0.2	0.3	
Agricultural land	porosity_upper	Yes	–	0.333	0.326	0.260	0.420	0.075
Agricultural land	density	Yes	$kg \cdot m^{-3}$	1,867	1,900	1,600	2,100	212
Agricultural land	z_deeps	Yes	m	1.6		0.2	17	
Agricultural land	porosity_bottom	Yes	–	0.208	0.207	0.14	0.298	0.049
Agricultural land	density_bottom	Yes	$kg \cdot m^{-3}$	2,186	2,200	2,100	2,300	69
Agricultural land	z_saturated_zone	Yes	m	1				

Object	Parameter	SiteSpecific-Data	Units	Mean	Median	Min	Max	Std
Agricultural land	porosity_saturated_zone	No	m	0.3		0.25	0.4	
Agricultural land	Loss_soil	No	Kg m^{-2} y^{-1}	0.005		0.002	0.020	
Agricultural land	precipitation	Yes/Modeled	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.597				
Agricultural land	runoff	Yes	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.226				
Agricultural land	percolation	Yes	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.074				
Agricultural land	Fdsts	Yes	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.057				
Agricultural land	Fsads	Yes	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.197				
Agricultural land	productivity_plants	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.12	0.12	0.11	0.14	0.01
Agricultural land	productivity_animal	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.0057				
Agricultural land	productivity_food	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.13		0.11	0.14	0.01
Agricultural land	productivity_edible	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.14		0.11	0.14	0.01
Agricultural land	bioturbation	No	$kg \cdot m^{-2} \cdot y^{-1}$	2		1	3	
Forest	z_uppers	Yes	m	0.34	0.32	0.00	0.92	0.14
Forest	density_upper	Yes	$kg \cdot m^{-3}$	1,818	1,833	1,350	2,300	267
Forest	precipitation	Yes/Modeled	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.597				
Forest	evaporation	Yes/Modeled	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.455				
Forest	transpiration	Yes/Modeled	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.197				
Forest	InterceptionFraction	Yes/Modeled	–	0.21				
Forest	waterContent	Yes	$m^3 \cdot m^{-3}$	0.19	0.17	0.07	0.43	0.08
Forest	biomass_understorey	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.052	0.056	0.038	0.069	0.013
Forest	biomass_leaves	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.40	0.37	0.01	2.11	0.23
Forest	biomass_tree	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	5.33	4.84	0.00	34.80	3.10
Forest	productivity_food	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.0003		0		
Forest	productivity_understorey	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.025	0.025	0.009	0.041	0.013
Forest	productivity_leaf	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.103	0.097	0.000	0.504	0.057
Forest	productivity_wood	Yes	$kgC \cdot m^{-2} \cdot y^{-1}$	0.121	0.111	0	0.645	0.07
Forest	loss_understorey	Yes	y^{-1}	0.358	0.388	0.059	0.646	0.217
Forest	loss_litter	Yes	y^{-1}	0.4		0.1	0.7	
Forest	loss_leaves	Yes	y^{-1}	0.22		0.1	0.27	
Forest	loss_wood	No	y^{-1}	0.004				
Forest	lifelenght_tree	No	y	300		20	400	
Forest	food_leaves_moose	No	–	0.47		0.43	0.5	
Forest	food_mush_moose	No	–	0.07		0.59	0.08	
Forest	food_plants_moose	No	–	0.26		0.07	0.45	
Forest	food_wood_moose	No	–	0.016				
Forest	food_leaves_deer	No	–	0.3		0.12	0.48	
Forest	food_mush_deer	No	–	0.07		0.06	0.07	
Forest	food_plants_deer	No	–	0.57		0.34	0.81	
Forest	food_wood_deer	No	–	0.009				
Forest	weight_deer	No	kgC	5.55		4.58	6.41	
Forest	weight_moose	No	kgC	81.30		6.30	103.05	
Running water	runoff	Yes	$m^3 \cdot m^{-2} \cdot y^{-1}$	0.226				
Well	wellcapacity	Yes	$m^3 \cdot y^{-1}$	167,680				