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Landscape Forsmark – data, methodology and results for SR-Site

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The original report, dated December 2010, was found to contain factual errors which have been corrected in this updated version. The corrected factual errors are presented below.

Updated 2013-08

Location	Original text	Corrected text
Page 212, Table 7-6, raw 14, column 1	Aqu_z_regoMid_pg	Aqu_z_rego_pg
Page 212, Table 7-6, raw 14, column 2	Depth of postglacial clay in aquatic middle regolith layer…	Depth of aquatic postglacial sediments…
Page 217, Heading	Aqu_z_regoMid_pg	Aqu_z_rego_pg

Summary

This report presents an integrated description of the landscape at the Forsmark site during the succession from present conditions to the far future. It was produced as a part of the biosphere modelling within the SR-Site safety assessment. The report gives a description of input data, methodology and resulting models used to support the current understanding of the landscape used in SR-Site. It is intended to describe the properties and conditions at the site and to give information essential for demonstrating understanding. The report relies heavily on a number of discipline-specific background reports concerning details of the data analyses and modelling.

Long-term landscape development in the Forsmark area is dependent on two main and partly interdependent factors, i.e. climate variations and shoreline displacement. These two factors in combination strongly affect a number of processes, which in turn determine the development of ecosystems. Some examples of such processes are erosion and sedimentation, groundwater recharge and discharge, soil formation, primary production and decomposition of organic matter.

The biosphere at the site during the next 1,000 years is assumed to be quite similar to the present situation. The most important changes are the natural infilling of lakes and a slight withdrawal of the sea with its effects on the near-shore areas and the shallow coastal basins. The climate during the rest of the temperate period may vary considerably, with both warmer and colder periods. The main effect of temperature changes will be on the vegetation period. Changed temperatures may give rise to drier or wetter climate and to changed snow cover and frost characteristics, and this can in turn affect the dominant vegetation and mire build-up.

The description of the Forsmark ecosystem succession during a glacial cycle is one of the main features of the SR-Site biosphere modelling. The future areas potentially affected by deep groundwater discharge are defined as biosphere objects containing specific ecosystems. In this work we have divided the landscape into three types of ecosystems, terrestrial, limnic and marine. During the site investigation and site description phase, the Forsmark ecosystems were investigated in terms of abiotic and biotic properties. Processes and features of relevance for describing the systems, and for calculating transport of radionuclides within and between them, were identified.

The landscape development model is defined by putting all available surface system information together in time and space. In this work, a description of the Forsmark landscape is produced, with all the features, processes and properties needed to provide a representation of the future that can be used in the modelling of potential future radionuclide releases. The model has distributed information in grid cells with a scale of a few tens of metres for both abiotic and biotic properties, and for the time scales needed to describe the far future. However, the landscape development model is not a prediction of what is to come, but a realistic description of a relevant future. This example, which is built on extensive site data and process understanding, is considered relevant also for all future interglacials to come.

We believe that this dynamic modelling approach, with its final simulated succession model, gives us a useful tool to explain the results, not only to the initiated reader but to the public and non professionals searching for information on how site-specific data used in risk calculations are extracted and how the site understanding is implemented in the dose calculations. We argue that this landscape description and the data extracted from modelling done within the framework of this report is the state of the art supporting tool for predicting risk for humans and environment, in case of future releases from a repository for spent nuclear fuel.

Sammanfattning

I denna rapport presenteras en integrerad beskrivning av landskapet i Forsmark under dess succession från dagens förhållanden till de som kommer att råda i framtiden. Rapporten producerades som en del av biosfärmodelleringen inom säkerhetsanalysen SR-Site. Den ger en beskrivning av indata, metodik och resulterande modeller som använts för att underbygga förståelsen av det landskap som beskrivits i SR-Site. Avsikten med rapporten är att beskriva egenskaper och förhållanden på platsen och ge den information som behövs för att demonstrera platsförståelse. Det som presenteras i rapporten bygger på mer detaljerade beskrivningar som redovisats i ett antal disciplinspecifika underlagsrapporter.

Den långsiktiga landskapsutvecklingen i Forsmark beror i huvudsak på två delvis sammanhängande faktorer: klimatvariationer och strandlinjeförskjutning. Kombinationen av dessa två faktorer har stor påverkan på ett antal processer, vilka i sin tur bestämmer utvecklingen av ekosystemen i området. Några exempel på sådana processer är erosion och sedimentation, in- och utströmning av grundvatten, jordmånsbildning, primärproduktion och nedbrytning av organiskt material.

Biosfären i Forsmark bedöms under de närmaste 1 000 åren vara likartad med den som finns i dag. De viktigaste förändringarna orsakas av den naturliga igenfyllningen av sjöarna och en mindre förskjutning av havets strandlinje med effekter på strandnära områden och grunda havsvikar. Klimatet kan komma att variera under resterande del av den inledande interglaciala perioden, varvid både varmare och kallare perioder kan förekomma. Den viktigaste effekten av temperaturförändringarna är dess inverkan på vegetationsperiodens längd. Temperaturförändringarna kan ge upphov till torrare eller våtare klimat och till förändringar i snö- och tjälförhållanden, som i sin tur påverkar dominerande vegetation och utvecklingen av myrmarker.

Att beskriva ekosystemens succession i Forsmark under en glaciationscykel är ett huvudmoment i SR-Sites biosfärmodellering. Områden där utströmning av djupt grundvatten från förvaret skulle kunna ske i framtiden identifieras som biosfärsobjekt med specifika ekosystem. I detta modelleringsarbete har landskapet delats in i tre olika typer av ekosystem: terrestra, limniska och marina. Under platsundersöknings- och platsbeskrivningsskedet undersöktes ekosystemen i Forsmark i termer av sina abiotiska och biotiska egenskaper. Även processer och egenskaper av betydelse för beskrivningen av systemen, och för beräkningar av radionuklidtransport mellan och inom dem, identifierades.

Landskapsutvecklingsmodellen har utvecklats genom sammansättning av all tillgänglig information om ytsystemet i tid och rum. I detta arbete produceras en beskrivning av landskapet i Forsmark, med alla de egenskaper och processer som behövs för att beskriva de framtida förhållanden som används i modelleringen av potentiella framtida radionuklidutsläpp. Modellen innehåller distribuerad information om både abiotiska och biotiska egenskaper i gridceller med storlekar på något eller några tiotal meter, och för det långsiktiga tidsperspektiv som behandlas i analysen. Det skall dock noteras att landskapsutvecklingsmodellen inte skall ses som en prediktion av framtiden, utan som en realistisk beskrivning av en relevant framtid. Detta exempel, som bygger på omfattande platsinformation och processförståelse, betraktas som relevant också för framtida glaciationscykler.

Vi anser att den presenterade dynamiska modelleringsmetodiken och den resulterande slutliga successionsmodellen är ett användbart verktyg för att förklara modelleringsresultaten, inte bara för redan initierade utan även för allmänheten och icke-specialister som vill veta hur de platsdata som använts i riskberäkningarna har tagits fram och hur platsförståelsen har använts. Vi anser vidare att det beskrivna modelleringsarbetet och den resulterande landskapsbeskrivningen representerar state-of-the-art vad gäller underlag och stödjande verktyg för prediktioner av risker för människa och miljö i samband med framtida utsläpp från förvar för använt kärnbränsle.

Contents

1 Introduction

1.1 Background

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co, SKB. Spent nuclear fuel from the power plants is planned to be placed in a geological repository according to the KBS-3 method /SKBF/KBS 1983/. In this method, copper canisters with a cast iron insert containing spent fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock. Around 12,000 tonnes of spent nuclear fuel is forecast to arise from the Swedish nuclear power programme, corresponding to roughly 6,000 canisters in a KBS-3 repository.

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

According to the regulations from the Swedish Radiation Safety Authority, SSM, a safety assessment of the planned repository, evaluating features, events and processes that potentially may lead to release of radionuclides, has to be performed before starting a construction of the repository (SSMFS 2008:21, /SSM 2008/). The evaluation of the long-term safety of the repository is reported in the SR-Site main report /SKB 2011/ and, accordingly, it is an important supporting document to the application.

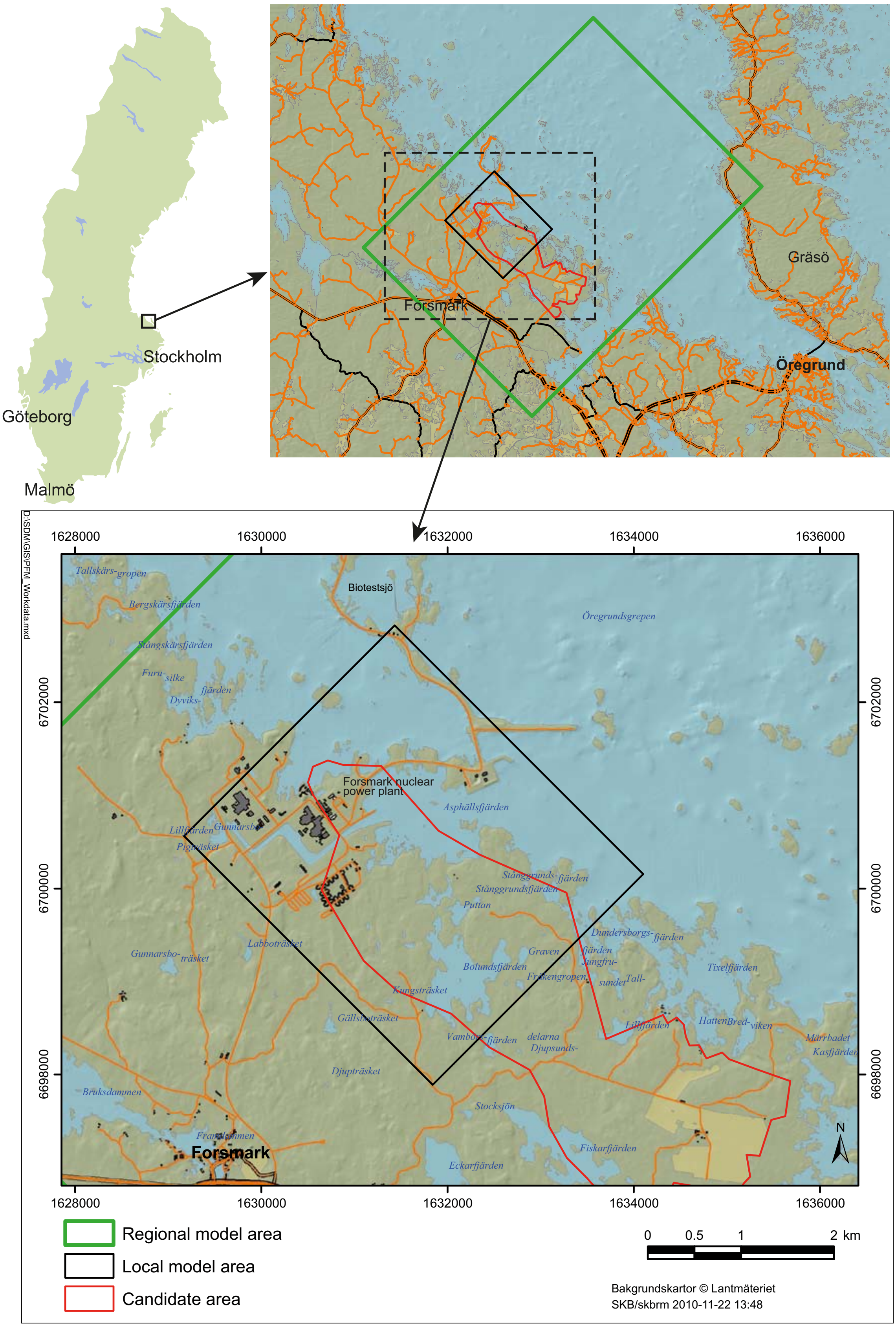


***Figure 1‑1.** The Forsmark site and the model areas used in the site characterisation; for a description of the different model areas, see /SKB 2008/. Within the assessment SR-Site, the areas described and modelled are discipline specific and are shown specifically later in this report.*

1.2 SR-Site Biosphere

The safety assessment SR-Site is focused on three major fields of investigation: the performance of the repository, the geosphere and the biosphere. The biosphere part of SR-Site, SR-Site Biosphere, mainly describes the information needed to calculate effects on humans and the environment in case of a radionuclide release. The calculated effects are then used to show compliance with regulations related to the future repository performance for time spans up to one million years (safety after closure). Because of the uncertainties associated with the prediction of future development of the site in this time frame, a number of future scenarios are analysed to describe a range of possible site developments. The following sections briefly describe the SR-Site Biosphere project and how the knowledge from this report was utilised in the project.

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

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

1.2.1 Site understanding

To construct realistic descriptions and make assumptions of future conditions at Forsmark, a good site understanding is needed. The past and present biosphere at Forsmark is well known and described in a number of SKB-reports, as well as in scientific articles. This knowledge is summarised and synthesised in /Lindborg 2008/ and /Söderbäck 2008/. Information from the site descriptions (SDM-Site reports produced by SKB and reported in 2008), together with generic data, are used as baseline to build conceptual models describing process understanding, and discipline-specific models describing the future development of the Forsmark site.

During the site investigation phase that preceded this safety assessment, all the scientific disciplines used in site development and radionuclide modelling aimed at building site understanding. A conceptualisation of the present surface system at Forsmark was a preparatory task for the safety assessment /Lindborg 2008/. A major aim of this conceptualisation was to identify present ecosystems at the site and divide them into functional components. These entities were then described in terms of biotic and abiotic features and properties. The ecosystems were described with a focus on ecosystem processes, and on transport and accumulation of matter, within and between ecosystems. Hydrological models and chemical information were used to describe mass balances for water and for a number of elements, both in individual ecosystems and at a landscape level.

1.2.2 Site development

In SR-Site Biosphere, we have used the current site information to develop descriptions of possible future development of Forsmark. One main driver for site development is climate change. As a main reference case for future climate in SR-Site, the last glacial cycle is used as an analogue /SKB 2010a/. In this analogue, the reference glacial cycle starts when the Weichselian ice retreats from Forsmark around 8800 BC and continues until c. 120,000 AD when the cycle is completed. During the reference glacial cycle, a number of climate-driven conditions appear, from submerged conditions directly after the ice sheet has withdrawn to recurrent temperate, periglacial and glacial domains /SKB 2010a/.

The different environmental conditions and the transitions between them are described in the landscape development model, see Chapters 4 and 5 in this report. This model uses input from a range of discipline-specific models, e.g. hydrology, chemistry, sedimentation, ecosystems, shoreline displacement and climate. The final output is a landscape development model describing site development and the associated properties under different future conditions. The final result is a synthesised description of Forsmark as it develops during a glacial cycle.

1.2.3 Radionuclide modelling in the biosphere

Based on the present and the historical descriptions, together with plausible future developments, we made calculations of radionuclide concentrations in the future biosphere. The first step was to identify a suitable spatio-temporal framework to use for the calculations. This was done by using the results from hydrogeological modelling of groundwater flow paths from repository depth up to the surface. After identifying discharge areas, future time-series data from these specific areas, so called biosphere objects, could be extracted from the landscape development model, see Chapter 7 in this report.

Transport and accumulation of potentially released radionuclides in the biosphere was calculated by using information on site-specific properties and processes. This radionuclide model for the biosphere was further tuned by using site-specific understanding on ecosystem functions and processes. Data was derived either directly from the site investigations, or from models describing the future site development. The model was run by adding a constant release rate of 1 Becquerel per year of all radionuclides to each biosphere object in turn /Avila et al. 2010/. The final output from the radionuclide modelling was a set of Landscape Dose conversion Factors (LDFs) that was used in different scenarios in SR-Site as input to calculations of risk /SKB 2011/. This final result from the biosphere assessment used in the risk calculation in the main SR-Site project is discussed in the biosphere synthesis report /SKB 2010b/.

1.3 This report

This report presents the integrated description of the landscape at the Forsmark site during the succession from present conditions to the far future. The report gives a description of input data, methodology and resulting models used to support the current understanding of the landscape used in the safety assessment SR-Site. It is intended to describe the properties and conditions at the site and to give information essential for demonstrating understanding. The report relies heavily on a number of discipline-specific background reports concerning details of the data analyses and modelling. Figure 1-2 illustrates the reports and background material used in this work and also the hierarchy of the reports produced within the SR-Site project.

The report is divided into chapters and sections that will guide the reader through the work done in compiling data on the Forsmark landscape development during a glacial cycle (roughly 120,000 years). The glacial cycle and the climate domains are described using information from /SKB 2010a/ and references therein.

Chapter 1 (this chapter) is an introduction to the project and describes the overall framework. It also puts the present report into the safety assessment context.

Chapter 2 describes the overall methodology and the strategy behind the work sequence from site investigation, site characterisation, to the final landscape development model. It shows how the sub tasks and discipline-specific models are used to build the overall model. Further, the chapter describes how this report is linked to other tasks within SR-Site Biosphere and the SR-Site main project.

Chapter 3 is a short compilation of the future climate domains and conditions considered in the landscape development model. This chapter is the linkage to the climate modelling done in SR-Site. It also provides the input needed to define the alternative landscapes that may appear in the far future.

Chapter 4 is the first of two chapters describing discipline-specific models; this chapter describes the abiotic parts. Aims, methodology, site understanding and final results are presented for each discipline separately.

Chapter 5 is the second discipline-specific chapter, describing the biotic parts and land-use. At the end of this chapter, a synthesis is made of all the supporting discipline-specific models and the overall landscape development model is presented.

Chapter 6 links the geosphere modelling with the biosphere. The flow paths generated in the bedrock development models are used to identify discharge areas at the surface in time and space. The radionuclide transport processes identified in the near-surface bedrock and the Quaternary deposits/sediments (regolith) are discussed.

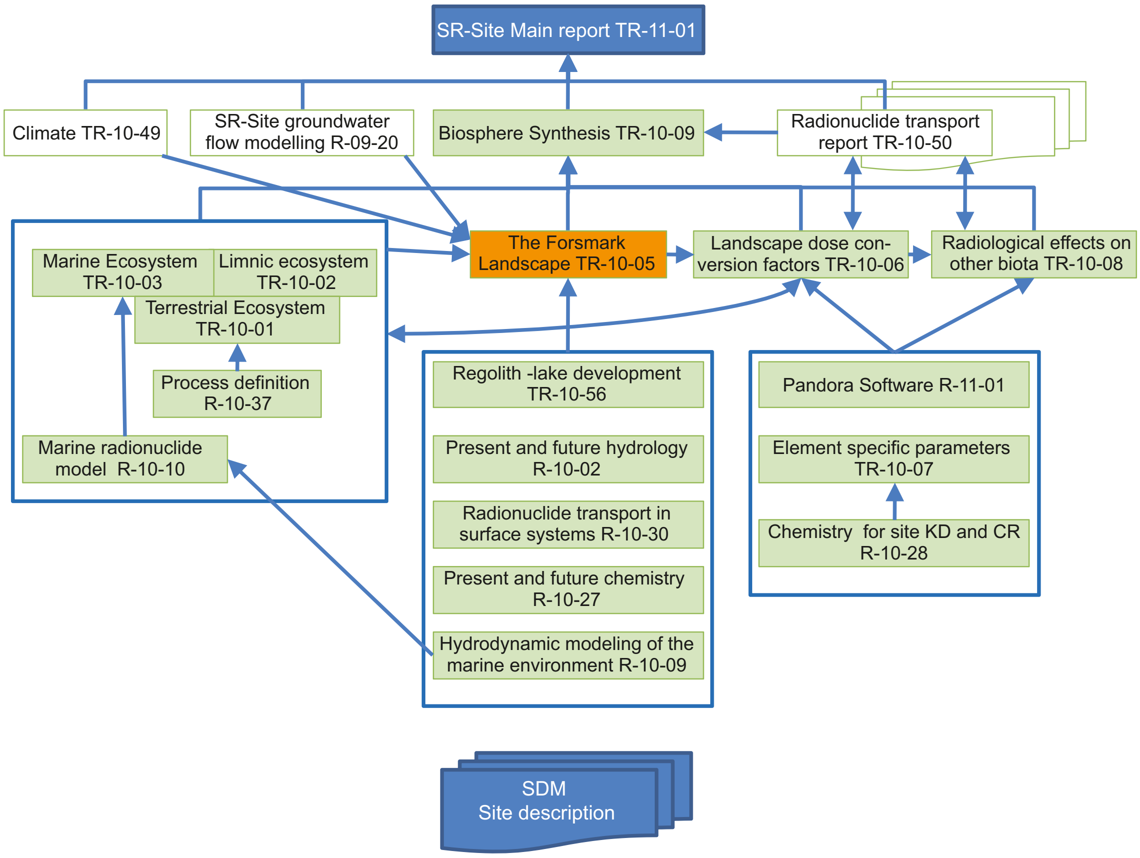


Figure 1-2. *The hierarchy of reports produced in the SR-Site Biosphere project. This report is marked orange.*

Chapter 7 uses the above chapters (4, 5 and 6) to identify the areas affected by hypothetical radionuclide releases, and then to describe these areas (biosphere objects) in terms of physical, chemical and biological properties needed to calculate concentrations of radionuclides in different media over time for each biosphere object.

Chapter 8 is a discussion on the methodology and results. It also discusses the overall understanding that is presented in this report regarding the landscape development and how radionuclides behave in this landscape during different future landscape regimes.

Chapter 9 is a reference list.

Appendix 1 is a map of Forsmark (at the present and in the future).

The reader should use this report as a compilation of properties, features and processes in discipline-specific models covering the Forsmark present and future landscapes. The report also provides the integration between the scientific fields and the overall linkages between the bedrock and the surface system, using transport simulations in and between different domains, from the upper bedrock to the surface. The aim with this report can be summarised as follows.

- Describe how the surface system of Forsmark develops during a glacial cycle.
- Discuss the main features and processes involved in the landscape succession.
- Describe the methodology behind the resulting models.
- Show the final landscape model results and how these are integrated with the radionuclide transport model.

1.4 The Forsmark site

The Forsmark area is described thoroughly in /SKB 2008/. The following text is a summary of the reports produced in the SurfaceNet project as a part of the site description /Lindborg 2008/.

The area represents a typical coastal site at the shoreline of the Baltic Sea in northern Uppland, Sweden. Post-glacial land uplift, in combination with the flat topography, implies fast shoreline displacement that has resulted in a very young terrestrial system that contains a number of newborn shallow lakes and wetlands. The lakes themselves are also of a specific type that is only found in northern Uppland. Shallow and with sediments rich in calcium, the lakes are unique in Sweden. Hydrologically, the area also differs from the regional pattern. High water flows in the upper part of the bedrock are associated with a complex network of gently dipping and sub-horizontal, open and partly open fractures in the upper part of the bedrock.

The latest deglaciation in Forsmark took place during the Preboreal climatic stage, c. 10,800 years ago /Fredén 2002, Persson 1992, Strömberg 1989/. Forsmark is situated below the highest coastline, and when the latest deglaciation took place, the area was covered by c. 150 m of water. The closest shore/land area at that time was situated c. 80 km to the west of Forsmark. The shoreline displacement has strongly affected landscape development, see Figure 1-3, and still causes a continuous and relatively predictable change in the abiotic and biotic environment, e.g. in water and nutrient availability. The first parts of Forsmark emerged from the sea around 500 BC. Thus, the post-glacial development of the surface system is determined mainly by the development of the Baltic basin and by the shoreline displacement /Söderbäck 2008/.

Figure 1-3. *Aerial photo of Forsmark, heading north. The shoreline displacement effects on the landscape are considerable and newly formed lakes are seen just inside the shoreline.*

The study area is characterised by a small-scale topography with limited variations in altitude and is almost entirely located below 20 m.a.s.l. (metres above sea level). Till is the dominant Quaternary deposit (QD), whereas granite is the dominant rock type. The annual precipitation and runoff are 560 and 150 mm, respectively. The largest lakes in the area are Lake Fiskarfjärden, Lake Bolundsfjärden and Lake Eckarfjärden. The lakes are small (the largest lake is c. 0.6 km^2) and shallow, with mean and maximum depths ranging from approximately 0.1 to 1 m and 0.4 to 2 m, respectively. Sea water flows into the most low-lying lakes during events with very high sea levels. Wetlands are frequent and cover 25 to 35% of some of the delineated sub-catchments.

No major water courses flow through the central part of the site investigation area. The brooks downstream of Lake Gunnarsboträsket, Lake Eckarfjärden and Lake Gällsboträsket carry water most of the year, but can be dry for long periods during dry years such as 2003 and 2006. Many brooks in the area have been deepened for considerable distances for drainage purposes.

The horizontal hydraulic conductivity and specific yield of the till are, based on measurements, considered typical or slightly higher than in the surrounding region. Groundwater levels in QD are very shallow, on average less than 0.7 m below ground during 50% of the time. Shallow groundwater levels imply a strong interaction between evapotranspiration, soil moisture and groundwater. Diurnal fluctuations of the groundwater levels, driven by evapotranspiration cycles, are evident in many groundwater wells. Furthermore, groundwater level measurements in the vicinity of the lakes show that the lakes may act as recharge sources to till aquifers in the riparian zone during summer.

There is a close correlation between the topography and the groundwater levels in the regolith. For groundwater levels in the upper bedrock there is no such strong coupling to the topography. This is most evident in the central part of the study area, where the groundwater-level gradients in the bedrock are very small, indicating a high transmissivity. Here, the groundwater levels in the till in general are considerably higher than in the bedrock. The result is that local, small-scale recharge and discharge areas, involving groundwater flow systems restricted to the regolith, overlie the more large-scale flow systems associated with groundwater flow in the bedrock.

The flow systems around and below the lakes are quite complex. The lake water/groundwater level relationship, under natural as well as disturbed conditions, indicates that the lake sediments and the underlying till have low vertical hydraulic conductivities. The groundwater below the lakes often has relict marine chemical signatures, whereas the groundwater in the riparian zone is fresh.

The surface water and shallow groundwater in Forsmark are characterised by high pH-values and high concentrations of major constituents, especially calcium and bicarbonate /Sonesten 2005, Tröjbom and Söderbäck 2006/. The main reason for this is the glacial remnants, mostly in the form of a till layer, that were deposited during the Weichselian glaciation and deglaciation /Fredén 2002/. This till layer has a rich content of calcite, originating from the sedimentary bedrock of Gävlebukten about 100 km north of Forsmark.

The marine ecosystem at Forsmark is situated in a relatively productive coastal area in a region of otherwise fairly low primary production. This is due to up-welling along the mainland /Eriksson et al. 1977/. The surface water has nutrient concentrations ranging from 330 to 790 $\mu g\ L^{-1}$ tot-N and 12 to 25 L^{-1} tot-P. The seabed is dominated by erosion and transport bottoms with heterogeneous and mobile sediments consisting mainly of sand and gravel with varying fractions of glacial clay. The seabed close to the mainland has some areas of rocky bottoms, which are partly covered by coarse till. The modelling results indicate that, although most areas are heterotrophic, the mean character of the whole area is autotrophic, i.e. more carbon is fixed in biomass by primary producers than is released by all organisms /Wijnbladh et al. 2008/.

The characteristics of the limnic ecosystem in the Forsmark regional model area are to great extent determined by the small topographic gradients in combination with the ongoing shore displacement and short distance to the sea, and by the occurrence of calcium-rich deposits. The lakes are classified as oligotrophic hardwater lakes, i.e. they contain high calcium levels, but low levels of nutrients, as phosphorus is precipitated together with calcium. Due to the shallow depths, the theoretical water retention times of the lakes are generally shorter than 1 year.

The terrestrial vegetation is affected by the bedrock, the nature of the QD and human land-use. The QD are mainly wave-washed till, where conifer forests are common. In depressions, a deeper regolith layer is found, with fairly high lime content. The calcareous influence is typical for the north eastern part of Uppland County and is manifested in the flora. The Forsmark area has a long history of forestry, see Figure 1-4, which is seen today as a fairly high percentage of younger and older clear-cuts in the landscape. Wetlands occur frequently and cover 10–20% of the area in the three major catchments and up to 25–35% in some sub-catchments /Johansson et al. 2005/. A major part of the wetlands are coniferous forest swamps and open mires. Arable land, pastures and clear-cuts dominate the open land. Arable land and pastures are found close to settlements. The pastures were earlier intensively used, but are today a part of the abandoned farmland following the nation-wide general regression of agricultural activities /Löfgren 2008/.

Figure 1-4. *The picture shows Forsmark old ironworks in the foreground and the nuclear power plant in the background, looking north east. The Forsmark site is located east of the road between the settlements and out into the sea to the island of Gräsö seen at the horizon.*

2 Overview of methods

This chapter is a guide to understand the general approach to build a site development model, from input data to final results. It should also give the reader an insight into how the different scientific disciplines used in the landscape modelling are integrated, and the ideas behind the biosphere object strategy. The chapter is an overview to provide a context for the rest of the report.

2.1 The Landscape model in the safety assessment

The Landscape development model is used in SR-Site to extract information to the radionuclide model and to function as a knowledge basis for assumptions made at landscape level in the safety assessment.

The landscape description is multi-disciplinary in that it covers all potential properties of importance for the overall understanding of the site development for a safety assessment. The general strategy applied in this work has been to develop discipline-specific models by interpretation and analyses of the quality assured primary data that are stored in the SKB database Sicada and the SKB Geographic Information System (GIS) database, and then to integrate these discipline-specific models into a unified landscape development model. The quantitative, discipline-specific models are also separately reported in the SKB series of SR-Site reports. Below follows a list of relevant background reports that support the landscape development model and the identification of discharge areas (biosphere objects) in time and space.

The main reports, produced within the SR-Site project, used as input in the landscape modelling are:

- A coupled regolith-lake development model applied to the Forsmark site /Brydsten and Strömgren 2010/.
- Chemical conditions in present and future ecosystems in Forsmark – implications for selected radionuclides in the safety assessment SR-Site. /Tröjbom and Grolander 2010/.
- Conceptual and numerical modelling of radionuclide transport in near-surface systems at Forsmark. SR-Site Biosphere /Piqué et al. 2010/.
- High-resolution hydrodynamic modelling of the marine environment at Forsmark between 6500 BC and 9000 AD /Karlsson et al. 2010/.
- Modelling of present and future hydrology and solute transport at Forsmark. SR-Site Biosphere /Bosson et al. 2010/.
- The limnic ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere /Andersson 2010/.
- The marine ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere /Aquilonius 2010/.
- The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere /Löfgren 2010/.

The work has been conducted within the SR-Site Biosphere project group. The members of the project group represent the disciplines of Quaternary geology, soil science, hydrology, hydrogeology, water chemistry, hydrogeochemistry, oceanography, geography, transport properties and ecology. In addition, some group members have specific qualifications of importance in this type of project, e.g. expertise in MIKE SHE hydrological modelling, GIS-modelling and in statistical data analysis.

2.2 Quality assurance

In order to ensure that the work is based on quality assured data and that the model and sub models derived based on these qualified data are correct, a number of quality assurance procedures and instructions in the SKB quality assurance system have been followed. The process from collection of primary data to models in the hands of the end users, as defined by the quality assurance (QA) procedures and routines and applied in the project, is summarised below.

2.2.1 Primary site data

All primary data collected in the field are stored in the SKB databases Sicada and SKB-GIS. Before delivery to the database operator, the data are reviewed and approved by the person responsible for the field activity providing the data (activity leader). The database operator transfers the data to the database and makes an export of the same data from the database. The data export from the database is then checked by the database operator and the activity leader to ensure that no mistakes have been made in the transfer of the data to the database. When everything is correct, the data are approved by the activity leader by signing the data export form.

Primary data collected at the site are brought into the SR-Site modelling from the databases Sicada and SKB-GIS only. Information regarding the procedures for data collection and factors of importance for the interpretation of data can be taken from the documentation of the data collection activity, but the actual data have to be ordered from the databases. Only data that are approved (signed) are allowed for delivery to users of the data. All orders and deliveries of data from the databases are registered, which means that it is possible to trace back all data deliveries.

2.2.2 Generic data

Information from sources other than SKB and the previous site investigation phase are also used. The generic data were treated in standard scientific manner and traceability secured by references to the literature from where the information was gathered.

2.2.3 Data exchange and version handling

As a first step in the SR-Site Biosphere project, a version handling system was implemented (SubVersion). Together with an errand and error tracking system (Trac), this was used to secure the traceability in the project. The SubVersion and Trac software are linked together such that all changes can be traced and the handling of versions and justifications for the decisions made are stored. In the system, all review questions from previous assessments and comments from authorities and external/internal reviewers were handled. Internal reports on errors in data or codes have also been managed in the Trac system.

All identified issues or problems that needed to be solved were documented and placed on an action list until they were handled. The issues, and the chain of actions undertaken to solve each issue are then stored and easy to back track. The integrated SubVersion/Trac platform was the daily tool in communications related to data exchange, version handling and storage questions and actions taken in relation to issues that arose during the work and was used in parallel with SKB quality systems.

2.3 Overall strategy for the landscape description

In this section, the general methodology to construct a landscape development model is described. The text follows a stepwise approach to build site understanding, showing how present day properties and processes at the site are modelled and used to describe the historical development, and how this information is used in the safety assessment to build descriptions of possible and realistic future landscapes is described.

2.3.1 Site understanding

To achieve a site-specific description of the biosphere at a proposed location for a geological repository, a thorough investigation of the different functional entities (e.g. primary producers) and their properties (e.g. primary production) in the ecosystems is needed /Lindborg et al. 2006/. The characterisation of the biosphere is primarily made by identifying and describing important properties in different surface ecosystems, e.g. properties of hydrology and climate /Johansson 2008/, Quaternary deposits and soils /Hedenström and Sohlenius 2008/, chemistry /Tröjbom et al. 2007/ and vegetation /Löfgren 2008/, but also current and historical land-use are factors that affect today's biosphere /Berg et al. 2006/.

The surface system description is used in assessments of the distribution and radiological impacts of releases of radionuclides /Avila et al. 2006, Kumblad et al. 2006a, Jansson et al. 2006/. Here transport and accumulation of radionuclides is modelled by quantifying biogeochemical pathways of the transport, transformation and recycling of organic matter. The description is, therefore, also structured to quantify processes affecting, for example, turnover of organic matter in catchments areas. By placing the emphasis on the fluxes of matter, ecological and physical constraints on a system are visualised, reducing the potential range of future states of the ecosystem and uncertainties in estimating radionuclide flow and in turn radiological consequences to humans and the environment /Kumblad et al. 2006b/. In a radionuclide release scenario, in which hydrologically driven dispersal is fundamental, it is important to use a modelling approach that is not limited to single ecosystems, but includes the whole landscape.

The development of a descriptive model for the surface system can be described in the following steps, see Figure 2-1.

- Development of a general conceptual model that describes stocks and flows of matter (or energy), using functional groups of organisms where possible. This demands a categorisation of the ecosystem into suitable units.
- Collection of site-specific data to adapt the conceptual model to the specific site.
- Development of a descriptive model to quantify stocks and flows of matter at the site for the identified units.
- Description of processes affecting the transfer and accumulation of matter within and between units in the landscape.

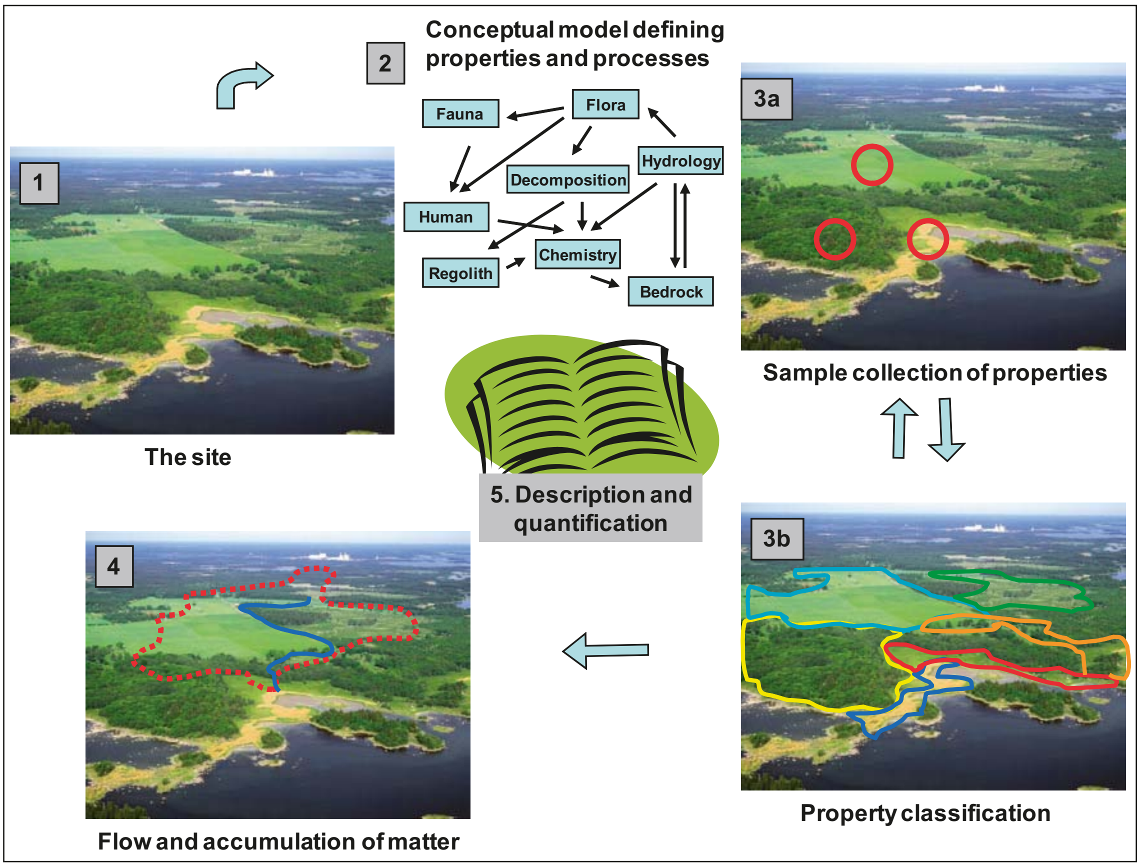


Figure 2-1. Illustration of the steps in the methodology to build a descriptive model.

2.3.2 Conceptual models

A conceptual model (Figure 2-2) is a necessary starting point to identify different properties and processes that may affect the ecosystems that constitute the landscape at the site. In the beginning, the model does not have to be site specific and can be built upon literature and expertise from different fields of science /Löfgren and Lindborg 2003/. This model is the starting point for planning of field surveys and collection of site-specific data. The general conceptual model can, after site-specific data are collected, be adjusted to give a site-specific conceptual model.

Thus, new information may be added or existing data omitted, e.g. a functional group of organisms may need to be re-considered or a biomass unit may be found to be too small to be relevant. One of the more difficult tasks is to find a suitable categorisation and classification of the landscape into more easily handled units. In this report, the landscape is divided into three large-scale units: terrestrial, limnic and marine ecosystems. Further classification was done using units that potentially constitute a basis for budget calculations of organic matter amounts and fluxes. The units were then further divided using functional groups within the food web. The spatial resolution of the gathered data is context dependent.

2.3.3 Site specific data

Large amounts of data are available from the Forsmark site to use for building a landscape description. Both data from the site investigations performed by SKB during 2002 to 2008, and from elsewhere are available /Lindborg 2008/. For a thorough description of discipline-specific input data, and how these data have been treated, we refer to the background reports listed in Section 2.1.

2.3.4 Site descriptive model

The site description of present conditions is essential as a starting point when constructing a landscape development model. By using the conceptual understanding and site-specific data we made a site descriptive model of the Forsmark landscape. This description is reported in /Lindborg 2008/ as a part of the SKB site description phase, and is further used and developed in this work.

2.3.5 Site development

In the safety assessment the past glacial cycle is used as an analogue for future climate conditions /SKB 2010a/. This means that data and models describing the Forsmark history are used as input in the site development work. It is also important to realise that we in this report do not seek to predict the future; we give relevant examples of possible futures to show the system performance under different landscape conditions.

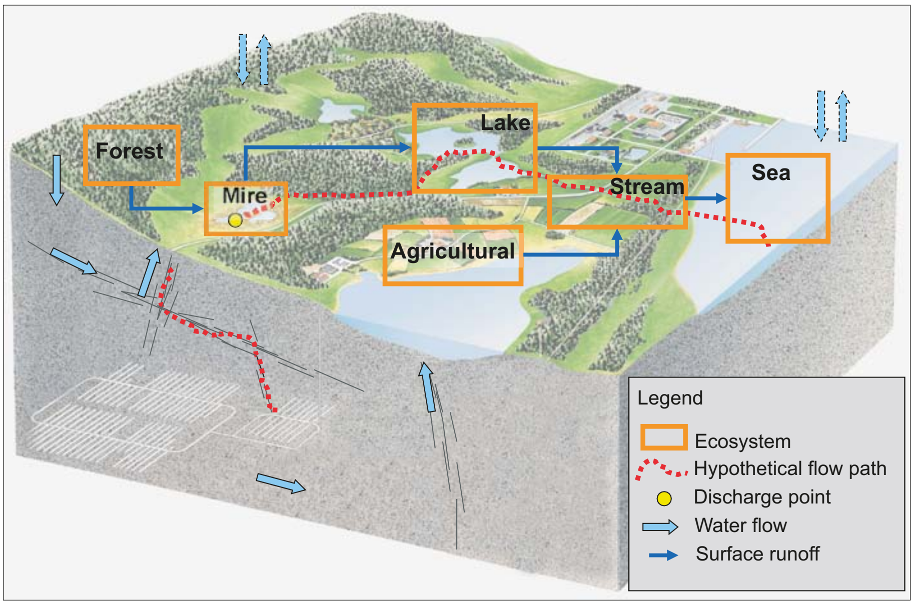


Figure 2-2. Conceptual model describing the whole system and the ecosystems identified.

2.3.6 Process description

The site descriptions identified a number of processes important for site understanding /Lindborg 2008/. In the safety assessment, this work has been further developed with focus on processes that may affect the site development /Andersson 2010, Löfgren 2010, Aquilonius 2010/. In this report we have listed and treated the identified long term processes that may affect the landscape succession, from sea to terrestrial land, and the processes involved in the transport from the bedrock to the surface system. The overall strategy in treating processes has been to define and describe processes within each sub model. These descriptions are found under the discipline-specific headings in Chapter 4 and 5 in this report.

2.3.7 Historical description

A detailed account of the geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas is given in a separate background report /Söderbäck 2008/. That report largely consists of a synthesis of information derived from the scientific literature and other sources, not related to the site investigations. However, the site investigations have also generated much information that contributes to our understanding of the past development of the sites, and this information is utilized in the descriptions given in /Söderbäck 2008/ and also herein.

2.3.8 Future development of the site

The future development of the Forsmark landscape is the main feature in this report and constitutes a fundamental input to the final radionuclide modelling. The general idea is to use the defined long term processes that affect the landscape and apply them on different domains. The discipline specific models are then combined to a final landscape development model. Main input to this work is the present geometry, shoreline displacement, regolith and sedimentation rates, ingrowth of vegetation, possible land-use, climate and hydrology.

By using historical data and present day site understanding, the future landscape is then presented for an interglacial. To be able to describe other future climates like glacial, periglacial, submerged under water and greenhouse climates, the landscape is also described under conditions other than the present temperate domain.

2.3.9 Discharge areas in space and time

The link to the hydrogeological understanding is made by using simulated discharge points of groundwater from the repository. As for the biosphere, the geosphere is described and modelled for the far future. These exercises are used as input to the landscape modelling to identify where in the landscape we can expect discharge areas during different future conditions. The areas are strongly connected to low elevation ecosystems like lakes, watercourses, wetlands and the sea. By using these future ecosystems that correspond to the deep groundwater discharge areas we can define so called biosphere objects. These objects are used in the extraction of dynamic data to the biosphere radionuclide model.

2.3.10 Output data from the biosphere objects

Biosphere objects are located all over the future landscape. In Chapter 7, a detailed account is given of the nature of such objects and the pattern they show depending on shoreline displacement and other characteristics of succession in the landscape. For each biosphere object and each time step (time step size depending on parameter) we extract a number of parameters. These parameters can be grouped in specific data types that tell the story of how the biosphere object behaves during landscape development.

Data on geometric features like sizes of areas and volumes of domains are presented. Distributions of land-use possibilities, natural vegetation or ecosystem types are other types of data that can be retrieved. Processes are switched off or on depending on thresholds in time or within the landscape itself. All this information is the best estimate of how Forsmark will respond to changes in a dynamic future with the reference glacial cycle /SKB 2010a/ as the main driver.

3 Climate issues related to landscape development at Forsmark

Management of used nuclear fuel involves time perspectives of one hundred thousand years or longer. In such time perspectives, the climate of Scandinavia will most likely undergo major alterations, ranging from warm conditions like we experience today to full glacial condition of an ice age, see the SR-Site climate report /SKB 2010a/. Even if climate does not have a direct influence on safety of the storage facility, environmental factors secondarily related to climate will most likely have such an influence. These are, for example, growth and decay of ice sheets and permafrost, or displacement of the shore-line, which is especially important in a coastal setting like Forsmark. These factors, in turn, will affect water discharge, geochemistry, and stress in the bedrock which are important to safety of the repository. Climate-induced factors are all crucial for development of the biosphere and utilisation of natural resources by humans.

The SKB primary approach to handling the complex issue of future climates is by constructing a reference glacial cycle. The case constitutes one example of how climate characteristics may alter during a glacial cycle that is the time of a full glaciation, interrupted by warmer periods (interstadials) and a longer time of warmer conditions (interglacials) separating glaciations. The reference glacial cycle constitutes a repetition of conditions reconstructed for the last glacial cycle /SKB 2010a/. Supplementing the reference glacial cycle are other cases of possible future climate development, with a potentially greater influence on repository safety. Descriptions of the climate system and its components are found in Chapter 2 in /SKB 2010a/.

3.1 Climate development at Forsmark

Given the uncertainties related to future climate development, the SR-Site approach is to analyse the extremes within which climate in Sweden may vary in the future /SKB 2010a/. Within these limits, a number of so-called climate domains have been identified, describing regions within which characteristic climate-related processes of importance for repository safety operate /SKB 2010a/. The identified climate domains are denominated:

- The temperate climate domain.
- The periglacial climate domain.
- The glacial climate domain.

The temperate climate domain is defined as an environment without permafrost or the presence of ice sheets. The temperate domain has the warmest climate of the three climate domains and is dominated by a temperate climate in a broad sense, with cold winters and either cool or warm summers. Precipitation falls all year round, i.e. there is no dry season. Precipitation may fall as rain or snow, depending on the season. During a period of temperate domain, the Forsmark area may be submerged by water. Climates dominated by global warming are included in the temperate climate domain (Figure 3-1).

The periglacial climate domain is defined as an environment with fully or partly perennially frozen ground surface without being covered by an ice sheet, see Figure 3-2. The permafrost occurs either in sporadic, discontinuous, or continuous form. Although true for most of the time, regions belonging to the periglacial domain are not necessarily the same as regions with a climate that supports permafrost. For example, at the end of a period with permafrost the climate may be relatively warm in a certain area, such that the presence of permafrost is not supported. In consequence, in that area permafrost may persist but be diminishing.

However, as long as permafrost is present, the region is defined as belonging to the periglacial climate domain, regardless of prevailing air temperature at the ground surface. This way of defining the domain is used because in this case the presence of permafrost is more important for the development of ecosystems and human societies than the actual temperature. In general, the permafrost domain has a climate colder than the temperate domain and warmer than the glacial domain. Depending on season, precipitation may fall either as snow or rain. Within the periglacial climate domain, part of the region may be submerged by water.

Figure 3-1. Photograph from Forsmark illustrating the present temperate domain. This type of landscape is also used to describe future temperate domains and may be submerged during parts of the glacial cycle.

Figure 3-2. A picture from Greenland used as an example of a future periglacial domain at Forsmark.

The glacial climate domain is defined as an environment that is covered by glacial ice. The ice sheet may have a frozen or thawed bed, which is only partly dependent on prevailing climate conditions. Similar to the periglacial domain, areas belonging to the glacial domain may not have a climate that supports the presence of an ice sheet. For example, when climate got significantly warmer following the last glacial maximum 23,000 years ago, glacial conditions still prevailed for another 10,000 years in Forsmark before the area was deglaciated /SKB 2010a/.

In addition, a climate supportive of glaciation does not necessarily imply presence of an ice sheet. It takes several thousands of years for an ice sheet in Fennoscandia to build up to a size that covers the mid-Swedish coastal area where Forsmark is located. During such a long time, climate will most likely periodically return to milder conditions further delaying the build up of an intermediate size ice sheet. However, in general, the glacial domain has the coldest climate of the three climate domains. Snow is the predominant form of precipitation.

An additional circumstance closely related to the climate domains is the periods of submerged conditions, when land is invaded by the sea usually following glaciation. Submerged conditions are not considered a climate domain, but their crucial role in defining environmental conditions has justified it having its own denomination in estimates of climate domain duration.

3.2 Climate cases and their function in analysis of surface systems

The climate domains are used to describe the development of climate-related issues for the future 120,000 year long reference glacial cycle, see Chapter 4 in /SKB 2010a/. The reference glacial cycle is not to be seen as a prediction of future climate development at Forsmark, but as one example of a conceivable future evolution that covers climate-related conditions and sequences that could be expected in a glacial cycle time perspective, i.e. around 120,000 years (Section 4.4 in /SKB 2010a/). The reference glacial cycle is supplemented by five additional climate cases that describe alternative possible future developments of climate and climate-related processes at Forsmark (Table 3-1, /SKB 2010a/).

The additional climate cases are selected to address relevant possible climate developments not covered by the reference glacial cycle. They are designed to fulfil needs within specific parts of the SR-Site programme. For example, maximum possible ice-sheet thickness is one parameter of interest for the analysis of hydrostatic pressure at repository depth. The Maximum ice-sheet configuration climate case was therefore created to analyse repository performance under influence of a thicker ice sheet (Section 4.5.4 in /SKB 2010a/).

Since this particular climate case is of peripheral importance to development of the surface systems, it is not considered by the biosphere programme and therefore not further elaborated in this report. The same applies to additional climate cases with increased ice-sheet duration and severe permafrost, which both primarily serve the purpose of analysing extended stress on repository performance rather than development of surface systems.

The biosphere programme has chosen to describe and to perform dose modelling based on the two climate cases that constitute the SR-Site Main scenario /SKB 2010a/, i.e. the reference glacial cycle and the global warming climate case. The reference glacial cycle comprises all three climate domains as well as submerged conditions. The global warming climate case describes a climate development influenced by anthropogenic burning of fossil fuel.

3.2.1 The reference glacial cycle

Periods of a temperate climate domain correspond to 26% and periglacial climate domain occupies 34% of the total time of the reference glacial cycle, whereas periods with glacial climate domain occupy 24% and periods with submerged conditions occupy 16% of the reference glacial cycle, see Table 3-2 and Figure 3-3.

Table 3-1. Climate cases in the SR-Site safety assessment (see /SKB 2010a/). Only climate cases 1 and 2 are used in the analysis of surface systems.

Climate case		Short description
1	Reference glacial cycle	Repetition of reconstructed last glacial cycle conditions
2	Global warming	Longer period of initial temperate conditions than in case 1
3	Extended global warming	Longer period of initial temperate conditions than in case 2
4	Extended ice-sheet duration	Longer duration of ice-sheet coverage than in case 1
5	Maximum ice-sheet configuration	Largest ice configuration in past two million years
6	Severe permafrost	Favourable for early and deep permafrost growth

Table 3-2. Duration of climate domains in the SR-Site reference glacial cycle. From Section 4.5 in /SKB 2010a/.

Climate domain	Duration (% of reference glacial cycle)	Duration (years)
Temperate climate domain	26%	31,200
Periglacial climate domain	34%	40,800
Glacial climate domain	24%	28,200
Submerged conditions	16%	19,200

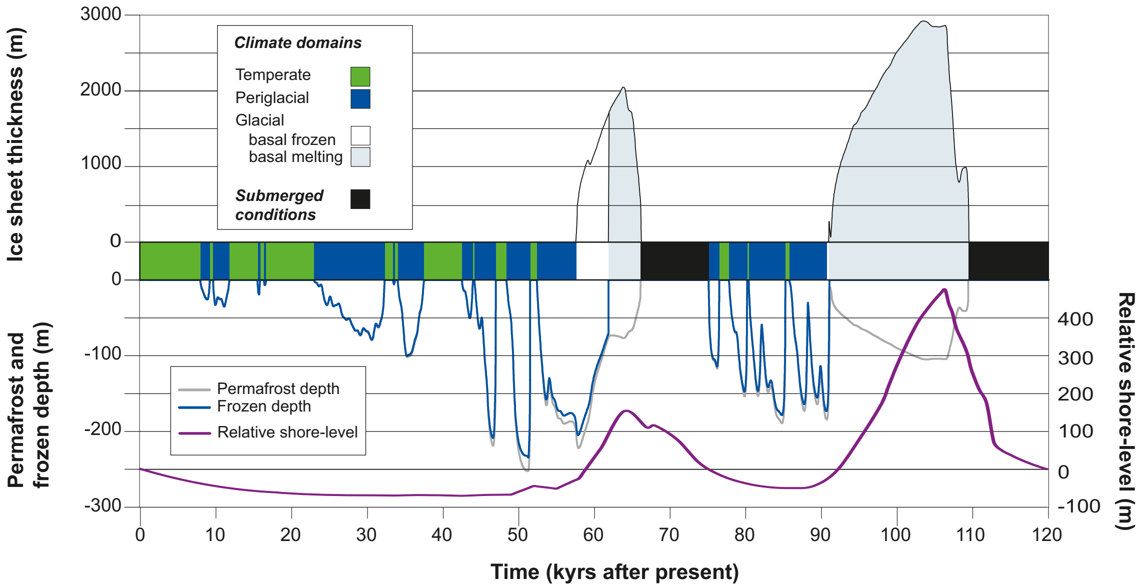


Figure 3-3. *Evolution of important climate-related variables at Forsmark for the coming 120,000 years in the SR-Site reference glacial cycle. From Section 4.5 in /SKB 2010a/.*

The climate succession bar in Figure 3-3 and Table 3-3 shows that the Forsmark site is dominated by temperate climate conditions for the first 25,000 years, although shorter periods of periglacial climate domain occur around 10,000 year after present. Subsequently, up to the first period of glacial climate domain, temperate conditions are gradually replaced by periglacial conditions. The ice-free interstadial period around 80,000–90,000 years after present is dominated by periglacial climate domains.

The trend with gradually more dominating periglacial climate domains is a natural result of the progressively colder climate during the first and major part of a glacial cycle. This progressively cooling trend during the glacial cycle also means that the second period with glacial climate conditions is longer than the first. This trend is not interrupted until the final deglaciation at the very end of the scenario, when ice-free conditions dominate again in a warm interglacial climate.

Periods of temperate climate domain occur in Forsmark in the early phase of the glacial cycle, during short periods of the interstadial between the two major ice advances, and during the interglacial period following the glacial maximum. As a result of the general cooling trend, periods of temperate climate domain in the initial interglacial and early phases of the reference glacial cycle are warmer and longer than those occurring during interstadials in the later part of the glacial.

During the first 50,000 years of the reference glacial cycle, and in the period between the two ice advances, the increasingly colder climate results in progressively longer periods of periglacial conditions. Forsmark is exposed to two major ice advances and retreats during the reference glacial cycle, the first around 60,000 years after present and the second after about 90,000 years after present. Prior to both of these glaciated periods, the Forsmark site is situated above sea level with prevailing permafrost conditions when the ice sheet advances towards and over the site. Snow and ice accumulating above permafrost give rise to prolonged frozen ground conditions at the base of the ice sheet, which is replaced by basal melting during the second major period of glacial climate domain. The period of basal frozen conditions is ~4,000 years long.

An important attribute of the reference glacial cycle evolution is the periods of submerged conditions following the second and final period of glacial domain. As a result of isostatic loading by the ice sheet, the land is depressed several hundred metres, which causes water of the Baltic Basin to inundate Forsmark as the area is deglaciated. Submerged conditions are not concluded until isostatic rebound has caused the land above the repository to emerge, some 10,000 years after deglaciation.

Table 3-3. Sequence of climate-related events for the reference glacial cycle, including the full Holocene. From /SKB 2010a/.

Event	Time for transition between events	Climate domain
Deglaciation Start of Holocene interglacial (locally defined as time of deglaciation of Forsmark)	10,800 before present (BP) (8800 BC)	–
Holocene interglacial	–	Temperate climate domain (incl. submerged conditions)
Present	0 BP (2010 AD)	
End of Holocene interglacial (locally defined as first occurrence of permafrost in the Reference glacial cycle)	7400 after present (AP) (9,400 AD)	–
Periglacial and temperate conditions (progressively longer periods of permafrost conditions)	–	Permafrost and temperate climate domains (progressively shorter phases of temperate climate conditions)
End of periglacial and temperate conditions Start of glacial conditions	57,600 AP (59,600 AD)	–
First phase with glacial conditions	–	Glacial climate domain
Deglaciation at site Start interstadial conditions	66,200 AP (68,200 AD)	–
Interstadial conditions	–	Mainly permafrost climate domain (incl. submerged conditions and short temperate periods)
End of interstadial conditions Start of glacial conditions	90,800 AP (92,800 AD)	–
Second and main phase with glacial conditions	–	Glacial climate domain
Deglaciation/start of interglacial (locally defined as time of deglaciation of Forsmark)	109,500 AP (111,500 AD)	–

3.2.2 The global warming climate case

The global warming climate case describes future climate development influenced by anthropogenic emissions of greenhouse gases and associated perturbation of the natural climate system, see Section 5.1 in /SKB 2010a/. Perturbations cause the occurrence of air temperatures several degrees warmer than present in central Sweden and at Forsmark within the first part of the reference glacial cycle. Subsequently, following reduced emissions, temperatures are envisaged to slowly decline for the rest of the long initial period with temperate climate conditions.

The global warming climate case is shown in Figure 3-4. The temperate climate domain dominates with ~78,000 years (65% of the time), permafrost conditions for ~28,000 years (23% of the time), glacial conditions for ~11,000 years (9% of the time) and submerged conditions prevail for ~3,000 years (~3% of the time) /SKB 2010a/.

The climate at Forsmark is dominated by an initial ~58,000 year long period with temperate climate conditions according to the global warming climate case. The variation in air temperature and precipitation is considerable within this temperate period, initially with air temperatures and precipitation rates considerably higher than at present in the early phase due to global warming. In time, they are gradually reduced. During this initial long warm period, it is likely that climate within the temperate domain will vary significantly, with a range that is larger than during the preceding parts of the Holocene.

As exemplified by global- and regional-scale climate modelling, a global warming climate may result in the Forsmark region experiencing a mean annual air temperature increase by ~3.5°C and an increase in mean annual precipitation by ~20% as compared to the climate during 1961–2000 which is chosen as the reference period, see the climate report, Section 5.1. These conditions are envisaged for a period a few thousand years after present. Details of the modelled global warming climate for Forsmark are further described in /SKB 2010a/, Section 5.1.7, and /Kjellström et al. 2009/.

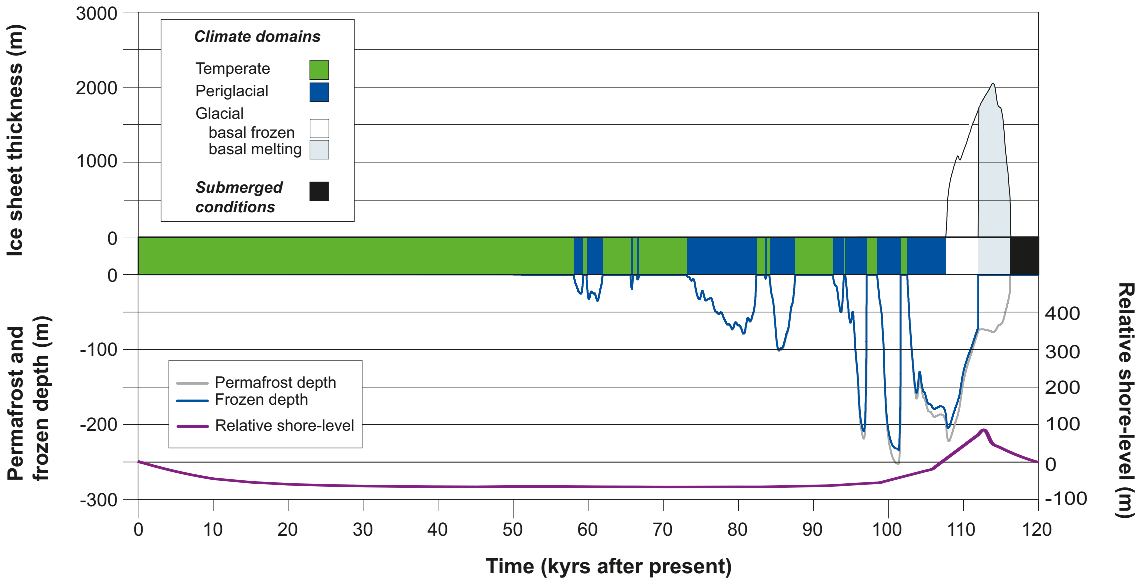


Figure 3-4. *Development of climate-related conditions at Forsmark as a time series of climate domains and submerged conditions for the global warming climate case. From Section 5.1 in the climate report.*

During the second half of the global warming climate case (Figure 3-4), climate varies according to the same pattern and within the same range as during the first part of the reference glacial cycle (Figure 3-3). Consequently, the climate-related processes will be identical in the two climate cases but displaced by 50,000 years.

An important question related to future global warming climates is changing sea level and shoreline position, which may result from melting of present glaciers and ice sheets. This is of particular importance for Forsmark, which is an area of low relief in a coastal position on the Bothnian Bay.

Present-day knowledge of future sea-level rise in a warming climate contains major uncertainties (further described in Sections 5.1 and 5.2 in /SKB 2010a/). The global warming climate case is designed to allow the Greenland ice sheet to collapse and melt completely during the next thousand years. However, due to isostatic and gravitational effects, the so called GIA-modelling performed for SR-Site suggests negligible change in sea level around Fennoscandia, including Forsmark, despite the significant input of melt-water to the ocean from a melting Greenland ice sheet (further described in Section 5.1 in /SKB 2010a/).

However, additional large uncertainties remain in the future sea level, associated with the response of the West Antarctic ice sheet and with thermal expansion of ocean water. This may, in contrast to what is shown in Figure 3-5, result in the Forsmark site being subject to submerged conditions for an initial period of several thousands of years in the global warming climate case, see further /SKB 2010a/, Sections 5.1 and 5.2, and /Brydsten et al. 2009/ and in Section 4.1 of this report.

In the long run, the results of the GIA modelling indicate that eustatic change will not dominate isostacy at this particular location. Figure 3-5 shows evolution of shore-level at Forsmark following both the reference glacial cycle with an intact Greenland ice sheet (grey curve) and global warming with a melted ice sheet (green curve). In this resolution both curves follow an identical evolution during the period in question, i.e. the first few tens of thousands of years after present.

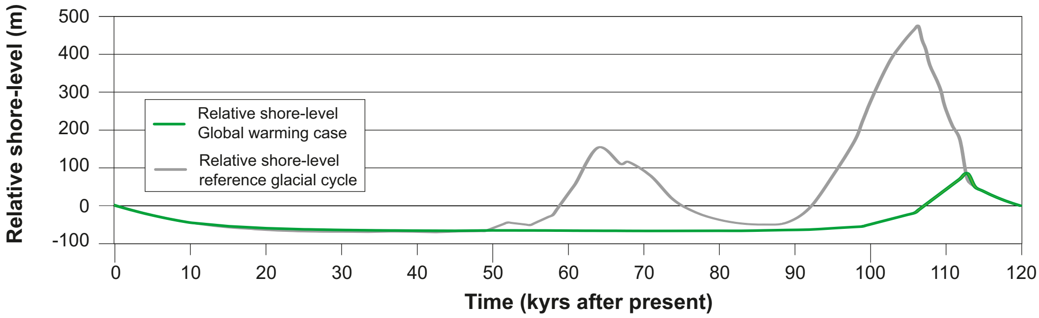


***Figure 3-5.** Shore-level evolution at Forsmark for the global warming variant of the reference evolution. For comparison, the shore-level evolution for the reference glacial cycle is also shown. Negative numbers indicate that the area is situated above the contemporary sea-level. Uncertainties in future shore level are discussed in the text. From /SKB 2010a/.*

3.3 Transitions between climate domains

In Figure 3-3 and Figure 3-4, changeovers between climate domains are shown as if they occur immediately. This follows from the choice of time-scale, but also from the original use of the time-bar to facilitate quantification of climate domain duration at the central part of the repository, rather than for the entire Forsmark area. Over a larger area, all changeovers involve longer or shorter periods of transition (see /SKB 2010a/).

All changes are indeed immediate when considering an infinitely small location. For example, a specific location is either covered by ice sheet or it is not. There is no intermediate form between the two. When considering a larger area like Forsmark which is several hundred km^2, the transitional period signifies that two climate domains are present at the same time but in different parts of the area. The proportions of ice-covered (glacial) and non ice-covered (periglacial, temperate or submerged) domains is determined by migration of the ice margin. In the case of the periods with periglacial climate domain, they start when the first permafrost develops. Subsequently, there is, within the periglacial climate domain, a gradual development from initially patchy, through discontinuous and finally continuous permafrost coverage. Permafrost also grows by gradual expansion in the vertical direction and develops deeper and deeper if cold temperatures prevail for a long period of time.

Transitions between temperate and periglacial domains are directly governed by climate, primarily temperature. When temperatures drop and reach a certain threshold, parts of the ground most favourable for permafrost initiation will remain frozen during summer. Prevailing cold conditions for several years will cause permafrost patches to expand into areas of less favourable conditions, and eventually coalesce into a discontinuous and finally continuous permafrost extension. The process works in the same way in the opposite direction – continuous permafrost disintegrates and becomes thinner and patchy until the ground is thawed, whereby the area enters a state of temperate climate domain. The duration of such a full transition in the reference glacial cycle is approximately 2,000 to 5,000 years /SKB 2010a/.

In contrast to permafrost, ice sheets and oceans are coherent features sharply confined by an ice margin or by a shore line. The existence of a confining sharp lateral boundary has implications for propagation and spatial transitions when ice sheets and oceans are concerned. For example, a water body like the ocean spreads its extension by a rise in sea-level relative to surrounding land, whereby land becomes inundated by water. With time, the shore line moves landward and gradually submerges the land, see Figure 3-6.

Migration of the shore line and gradual expansion of submerged conditions can be described as a spatially time-transgressive process, in the meaning that changeover occur continuously and in a certain general direction. The reverse process of a retreating shore line makes new land become exposed above the sea surface in a likewise time-transgressive fashion. This transition is by far the slowest of all climate domain transitions, which is because the rebound of the Earth's crust following unloading an ice sheet is very slow /SKB 2010a, Section 3.3/. It takes about 12,000 years to transfer the entire Forsmark area from fully submerged just before the first islet emerges through the sea surface (1000 BC), until the last marine embayment is turned into a lake (11,000 AD).

***Figure 3-6.** Islet recently emerged from a submerged position. Isostatic rebound of the land causes new ground to reach a terrestrial position, whereby the ground surfaces are exposed to transforming processes like bedrock weathering and colonization of plants. The continuous rising of the land creates a landscape composed of features associated with the succession going from sea to land. Parts of the landscape at higher altitude have a longer exposure-time for terrestrial transforming processes, and lower altitudes are relatively less altered.*

Propagation of an expanding ice sheet functions in a similar spatially time-transgressive fashion as expansion of the ocean, see /SKB 2010a/. If climate favours expansion of an ice sheet, the ice-sheet margin propagates into formerly not ice-covered terrain. With continuing favourable conditions for glacial expansion, more and more land will be ice covered. In the reference glacial cycle, the ice-sheet margin advances over Forsmark at a speed of about 50 m/year /SKB 2010a/. The duration of this ice sheet advance, from one end to the other of the Forsmark area, is about 250 years. Deglaciation of Forsmark is faster and occurs by retreat of the ice margin of about 300 m/year, which makes a total duration of 50 years for the ice margin to retreat from one end of the area to the other, see Table 3-4.

Propagation and retreat of ice sheets and oceans are directly and indirectly governed by changes in climate. The nature of the responses by ice sheets and oceans are however typically slow, because of inertia of the system. In addition, for the understanding of the relationship between changes in climate and transitions between climate domains, spatial effects need to be considered. This can be illustrated by glacial development following a shift to a climate favourable to ice-sheet expansion. Most of the time during the reference glacial cycle, glaciers are present in Fennoscandia as valley glaciers or a small mountain-centred ice sheet /SKB 2010a/.

Table 3-4. Approximate durations of full transitions between climate domains over the Forsmark site for the SR-Site reference glacial cycle. From /SKB 2010a/.

Transition	Approximate duration in reference glacial cycle	Relative speed of transition
Temperate- to periglacial climate domain with continuous permafrost coverage	~2,000 to ~5,000 years	40 to 100×
Periglacial- to glacial climate domain	~250 years	5×
Glacial climate domain to submerged conditions	~50 years	1×
Submerged conditions to temperate climate domain	~12,000 years	240×

These glaciers expand as a response to climate cooling and/or increased precipitation, but it takes many thousands of years for the ice-sheet margin to advance all the way from the mountain range to the Forsmark area. The implication of this is that the transition to a glacial climate domain occurs many thousands of years after the introduction of climate conditions favourable of glacial expansion. This illustrates the importance of remembering that the climate domains are not defined by climate itself – they are climate-driven process domains where transition can result from a climate shift that occurred thousands of years earlier.

Many of the analyses of surface systems within SR-Site are focused on the development of the present landscape, influenced by the transgressing shore line which divides the area into a submerged and a terrestrial part. This domain transition will continue for another 9,000 years into the future and therefore constitutes a significant part of the first interglacial time period considered in SR-Site. The shoreline is of course a place of special attention since it is the most dynamic part of the landscape as it experiences a marine transgression. It is along the shoreline that coastal processes determine development; unconsolidated sediments are eroded and transported to deeper areas, waterborne nutrients create a productive littoral zone where flooding regularly occurs, and much of the marine primary production is concentrated to the shallow waters in the vicinity of the shore line /Aquilonius 2010/.

This coastal zone migrates continuously as a consequence of the isostatic rebound, which means that traces of coastal processes ascend with the land and can be found higher up from the current shoreline. Furthermore, as soon as land emerges from the sea, other types of processes start to dominate landscape development; terrestrial processes create a zonation as a consequence of exposure. Areas on higher altitudes have been exposed to these transforming processes during a longer period than have areas at lower altitudes. For example, land higher up is more weathered, soil-forming processes have created soils with a higher degree of maturity, and wetlands have accumulated more gyttja and peat. Studies of these terrestrial environments in different successive stages constituted a fundamental part of the SR-Site surface systems programme.

Lower-lying land, i.e. of a younger terrestrial age, is assumed to develop in the same direction as the older parts of the terrestrial landscape, and the development of older land higher up in the terrain is assumed to continue along the same successional path until shifts in climate regimes are projected to alter the dominant processes of transformation. Such a concept of “space-for-time substitution” is used in many disciplines of the SR-Site biosphere project. It is applied to knowledge from the site investigations, but also in numerical models and studies of analogue areas currently experiencing climate regimes different from today’s Forsmark.

3.4 Permafrost landscape

Permafrost is defined as frozen ground that remains frozen for more than two subsequent years. Permafrost occurs at high latitudes and in mountain regions of mid latitudes. Climates associated with present regions with permafrost generally have daily temperatures below 0°C for at least nine months of the year, and below –10°C for at least six months of the year. Temperatures rarely exceed 20°C at any time and precipitation is typically low /Summerfield 1991/. Most areas of permafrost experience surface temperatures above freezing during summer, whereby the ground surface starts to melt.

Seasonal thawing and freezing result in an active layer overlying the permafrost (Figure 3-7). The active layer is the most dynamic part of the permafrost system where water moves freely during the warm season and where both dissolved elements and solid particles are transported. The underlying permafrost table inhibits percolation of meltwater and the active layer is therefore usually water logged. The active layer reaches its maximum depth at the end of the melting season, usually in early autumn. For example, in mid western Greenland thawing of the ground starts when snow melts in May and the maximum depth of the active layer usually occurs in mid October /Van Tatenhove and Olesen 1994/.

As a result of freezing penetrating downwards at unequal rates in the autumn and winter, water may be trapped between the permafrost below and the freezing active layer above. In addition, water courses and lakes have an insulating effect on propagating cold from above. As a result, groundwater often remains in liquid state under water courses and lakes. These water pockets, called taliks, develop partly because of the release of latent heat of fusion as water changes its state from liquid to solid.

An additional factor is the build up of pressure exerted when water expands as it freezes. Closed talik, open talik, and through talik are distinguished (Figure 3-7). These terms refer to whether the talik is closed or open to the surface, or open to both the surface and unfrozen layers beneath the permafrost, respectively. Open and through taliks can be, but are not necessarily, positioned underneath a lake or smaller pond. These through taliks formed under lakes and ponds are of special importance to the SR-Site safety assessment because such features could possibly enable discharge of deep groundwater to the surface-water system /French 2007/.

Since discharge areas are more restricted in a periglacial environment, concentrations of contaminants released from a repository could be higher in these confined water bodies. Furthermore, these lakes and associated through taliks are likely sources for future human water utilization as well a likely locations for settlements. Formation of taliks and their role in hydrological processes are further elaborated in Section 4.3 of this report.

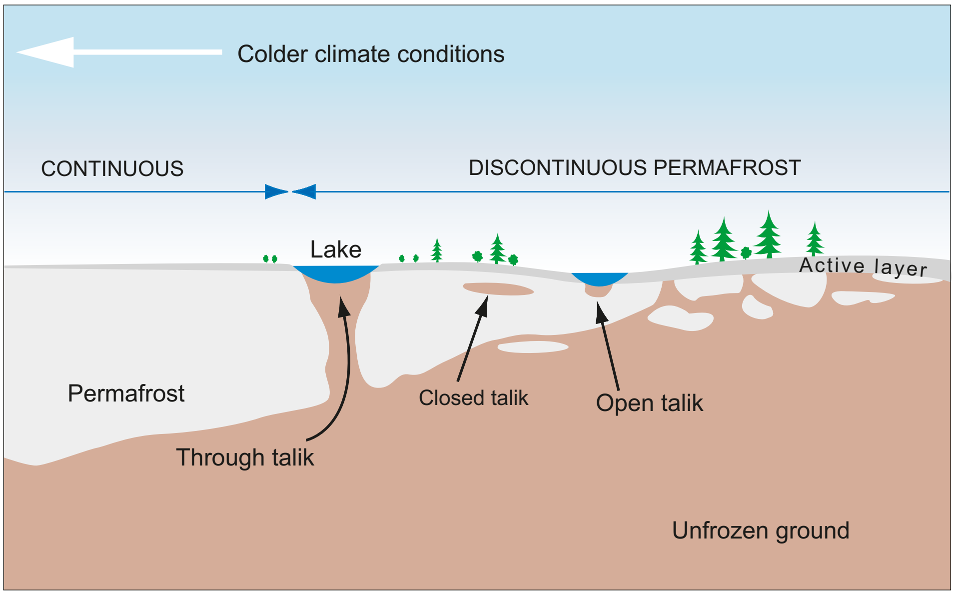


***Figure 3-7.** Figure illustrating the fundamental features of the permafrost environment.*

4 Present state and succession of abiotic processes in the landscape

This chapter presents a description of the present state and the expected succession for a set of processes or modelling disciplines. The processes are divided into the following categories: geometry (Section 4.1), geology (Section 4.2), hydrology (Section 4.3) and hydrochemistry (Section 4.4). The process descriptions in this chapter serve as a background and basic input to the ecosystem descriptions presented in Chapter 5. Although referred to as "abiotic" in the chapter heading, it may be noted that some of the process categories discussed, especially chemistry, clearly include important biotic components.

4.1 Geometry

4.1.1 Introduction

The term topography is used to describe the shape of the land surface. Strictly speaking, however, topography also includes other surface objects such as vegetation, soils and anthropogenic features. Major landforms such as mountains and larger hills are mainly formed by solid rock processes whereas smaller landforms such as hills and stream channels are mainly produced by surface processes.

The overall topography in the Forsmark region is flat in an overall Swedish perspective. The Precambrian bedrock (part of the Subcambrian peneplain) is overlain by till with no or only minor morphological features. The till is in negative morphometric areas (channels and pits) overlaid by glacial clay that tends to flatten the surface. Geological processes during the Holocene, such as postglacial sedimentation in the sea and the lakes, wave-generated sediment dynamics in the sea, and infill processes in lakes, have flattened the surface even more.

The altitude range of the bedrock in the model area is –59 to +27 metres. The average thickness of the till is c. 60 centimetres and of the glacial clay c. 4 centimetres. Thus, the overall topography in the model area is controlled by the bedrock topography. The bedrock surfaces generally dip towards north-east but many bedrock lineaments (joints and faults) change that general picture. One major fault runs in a north-south direction west of the island Gräsö and has caused the deep channel called the Gräsörännan.

The topography has an effect on many processes in the landscape such as the lake formation, the groundwater hydrology, the surface hydrology, the sediment dynamics in the sea and therefore also the dynamics of radionuclides. The topography of a landscape is often described with a digital elevation model (DEM) and this has been done also for Forsmark. The DEM is a required input to most models generated within the SR-Site project. A high accuracy of the DEM is therefore important for the whole project. A description of the DEM for Forsmark is given below.

4.1.2 A digital elevation model of the Forsmark area

To use the geometry in different types of models there is a need to express the altitudes in the area with a digital elevation model (DEM). The DEM for Forsmark has been produced in many versions with successively more input data and data with higher accuracy. The latest version is presented in /Strömgren and Brydsten 2008/ and a short summary of that model is presented in the following.

The DEM is constructed in GIS by an interpolation of scattered point altitudes to a regular grid. In this model, Kriging interpolation was used. Kriging is a geostatistical interpolation method based on statistical models that include autocorrelation (the statistical relationship among the measured points). Kriging weights the surrounding measured values to predict an unmeasured location. Weights are based on the distance between the measured points, the prediction locations, and the overall spatial arrangement among the measured points.

Normally, a DEM has a constant value for sea surface and constant values for lake surfaces. For the Forsmark area, the DEM has negative values in the sea that represent water depth, but constant positive values for lake surfaces to represent the lake elevations or varying values to represent lake-bottom elevations.

Input data for the interpolation have many different sources, such as existing DEMs, elevation lines from digital topographical maps, paper nautical charts, digital nautical charts, and depth soundings in both lakes and the sea. All data are converted to point values using different techniques. The Kriging interpolation was performed in ArcGis 9 Geostatistical Analysis extension.

The DEM for the Forsmark area has a resolution of 20 metres and uses a RT 90 2.5 Gon W map projection and a RH 70 elevation system. The final digital elevation model has a size of approximately 30·30 kilometres, a cell size of 20 metres, 1,501 rows and 1,501 columns, a total number of DEM cells of 2,253,001, and a file size of approximately 8.8 MB (ESRI Grid format). The extension is 1619990 West, 1650010 East, 715010 North, and 6684990 South in the RT 90 coordinate system. All models presented in this report use the DEM representing lake bottoms rather than lake surfaces. This model is illustrated in Figure 4-1.

An analysis of the elevation model confirms existing knowledge of the area being extremely flat. The range in elevation is only approximately 109 metres with the highest point at 51.1 metres above sea level in the south-west part of the DEM, and the deepest sea point at –58.8 metres in the northern part of the so-called Gräsörännan.

Many of the geomorphological features that can be seen in the stretched DEM (Figure 4-1) are negative (channels and passes) and are associated with lineaments in the bedrock. Most conspicuous are the northwest southeast striking lineaments, i.e. along the mainland shoreline and one parallel to that on the mainland. This direction of the lineaments can also be seen on the island Gräsö. Another lineament direction is approximately north – south exemplified by the western shoreline of Gräsö. The artificial channel that is the inlet of cooling water to the nuclear power plant can also be seen in the central part of the DEM.

Positive geomorphological elements (ridges and peaks) are rare. Drumlins (ridges parallel to ice movement made up of till and often with a bedrock core) can be seen close to the southern border of the DEM and a large esker runs in a northern direction from the southern border up to the central part of the DEM. Distinct positive elements are also the artificial fillings east of the power plant (many road banks and one pier).

Figure 4-2 shows the DEM as a hillshade image. A hillshade is a grid that encodes the reflectance value of an elevation surface given a light source at a certain theoretical position in the 'sky'. In this example the light source is from NE with an azimuth of 45 degrees. Light from this angle reinforces the appearance of elements elongated in NW directions. The figure clearly illustrates some of the features already mentioned, i.e. bedrock lineaments, artificial cuttings and fillings, drumlins and the esker.

Because the DEM is used as input to many models that generate results used in the landscape model, the accuracy of the DEM is important for the conclusions drawn in this report. The accuracy of the DEM is discussed in /Strömgren and Brydsten 2008, Hedenström et al. 2008, Strömgren and Brydsten 2009/, and is summarised here.

The accuracy of the DEM is influenced by

(i) the resolution of the DEM (20 metres in the Forsmark DEM),

(ii) the density of measured point altitudes,

(iii) the accuracy of single measured point altitudes,

(iv) the choice of interpolation method.

Input data to the interpolation are derived from many different sources (see Figure 4-3) where the accuracy differs a lot between and also within the data sets. In general, the data from the terrestrial areas are both of higher accuracy and higher density compared with the marine area. In the marine area, there are higher quality data in the coastal area close to Forsmark compared with deeper parts of the sea and coastal areas north and south of Forsmark.

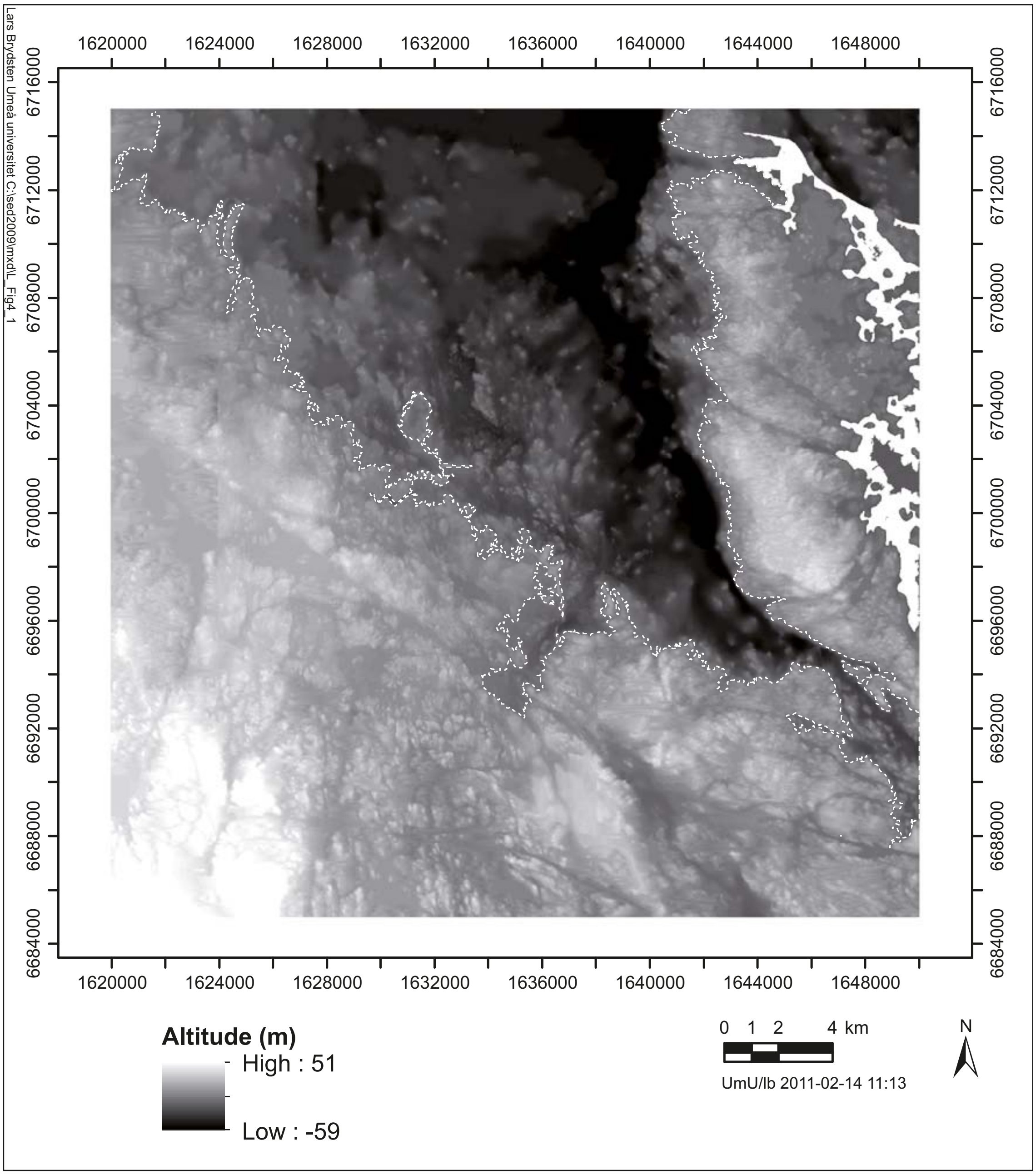


Figure 4-1. Digital elevation model, DEM, of the surface of Forsmark. The white line represents the 1970 AD shoreline.

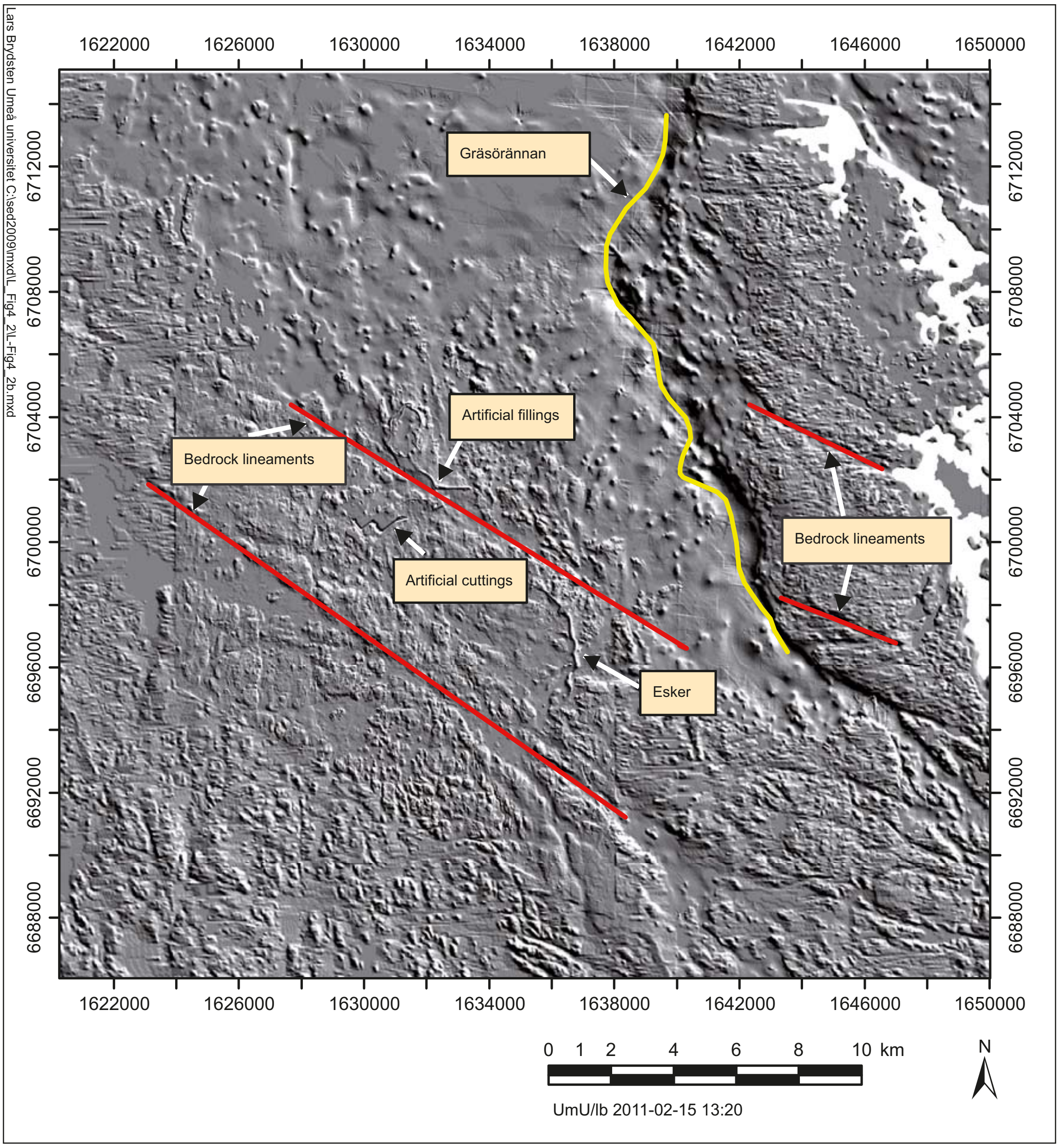


Figure 4-2. *A hillshade image of the Forsmark DEM produced with a light source from NE and an azimuth of 45 degrees.*

/Strömgren and Brydsten 2009/ used geostatistical methods to calculate accuracy of different areas of the DEM. In the area of the sea shoreline data sources, the mean errors and the dispersion from the mean errors are small. In the areas of the 10- and 50-metre DEMs, the dispersion from the mean errors is larger. In the shallow bays and in the detailed area of the measurements from the Geological Survey of Sweden (SGU), the mean error and dispersion from the mean error are small. In the area of base map data, the mean error and dispersion from the mean error are larger.

In the regional area based on measurements by SGU, the dispersion from the mean error is even larger. In areas with only data from the digital nautical chart/nautical chart, the mean error and dispersion from the mean error are very large. In this area, errors larger than 35 m have been calculated. Based on the standard error (SE) values in /Strömgren and Brydsten 2009/ the DEM can be classified into Excellent (SE <1), Good (1 <SE <2) and Acceptable (SE >2) (Figure 4-3).

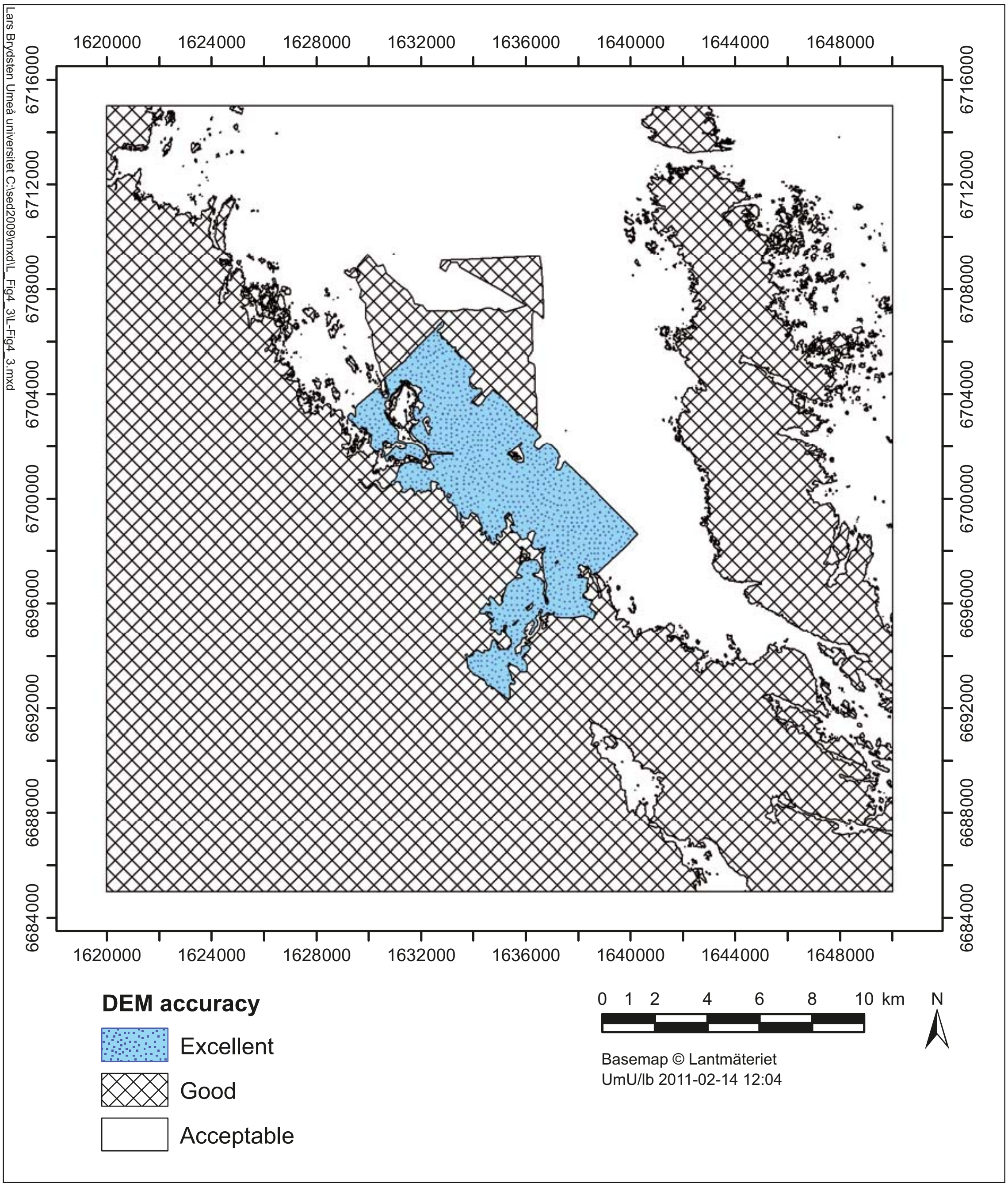


Figure 4-3. *Classification of the accuracy of the DEM based on calculations of errors in altitude values shown in /Strömgren and Brydsten 2009/.*

4.1.3 Glacial isostatic adjustment in the Forsmark area

The pattern of elevation is constantly changing throughout the glacial – interglacial cycle. Many processes control these changes such as glacial isostatic adjustment (GIA) and transport of sediments. The changes in DEM due to sediment dynamics are discussed later in this report.

Glacial isostatic adjustment (GIA) is the response of the solid earth to mass redistribution during a glacial cycle /Whitehouse 2009/. During glacial periods, the ice sheets at higher latitudes grow and the relative sea level falls. The opposite occurs during interglacial periods; the ice sheets melt and the relative sea level rises. The movement of water from the sea to the ice sheets acts as a load on the lithosphere under the ice and a rebounding under the sea. Thus, GIA is the deformation that takes place due to melting or growing of ice sheets.

The relative sea level (RSL) is defined as the height of the contact between the ocean surface and land. A rise in the RSL can be caused by an increased ocean surface height or a decreased height of the land, for example due to ice loading.

In the Forsmark area, there has been a rebound of the lithosphere since the Last Glacial Maximum (LGM) and also a rising ocean sea level during the same period. The positive glacial isostatic adjustment (causing the land area to expand) has been stronger than the eustatic rise (causing the sea area to expand); thus the RSL has decreased and new land has developed. During some short periods since the LGM, the Baltic Sea has been a lake and the RSL in those periods was not affected by the eustatic level but instead by the lake level. The implications for RSL of these lacustrine stages of the Baltic Sea are discussed later in this report.

The present RSL change rate in Forsmark is approximately 6 mm a^{-1} with a north – south gradient of c. 1 mm 100 km^{-1} with increasing rate to the north /Fredén 2002/. The change in RSL in the Forsmark area during the last (Weichsel) glaciation has been studied by /Hedenström and Risberg 2003/. Lake basins were investigated regarding elevation and age of their isolation events. In /Påsse 2001/ there is a compilation of RSL data for Fennoscandia. Unfortunately, there is not an RSL station in the Forsmark area but there are stations north, east and south of Forsmark. /Påsse 2001/ also gives a method for transforming RSL data (altitude and age) into an equation that simplifies the use of the RSL in mathematical models.

Using data from nearby stations and the method from /Påsse 2001/, /Brydsten 1999/ compiled an equation for Forsmark. This equation was later updated with data from /Hedenström and Risberg 2003/ and is published in /Söderbäck 2008/. Figure 4-4 shows the temporal RSL change both modelled with the RSL equation and data from the study in /Hedenström and Risberg 2003/.

The oldest measured RSL is c. 4500 BC and the highest altitude within the Forsmark area is c. 60 metres so it is impossible to extend the measured data set to older dates. The gentle sloping part of the RSL curve (c. 8000–6000 BC) coincides with one of the lacustrine phases of the Baltic, the Ancylus stage. In the Baltic Proper this stage shows a transgression, i.e. a rise in the RSL but at Forsmark the RSL curve only flattens out. At the time of the first lacustrine stage, the Baltic Ice Lake, the Forsmark area was covered by the ice sheet and therefore there was no effect on the Forsmark RSL curve.

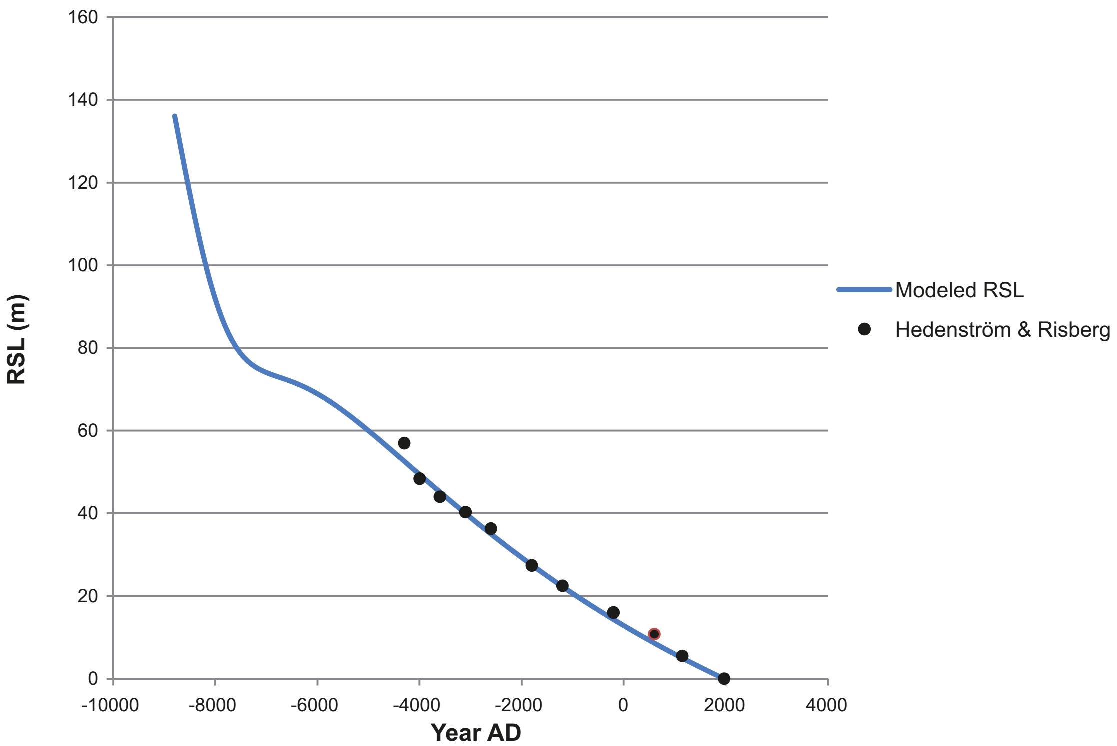


***Figure 4-4.** The measured RSL positions from /Hedenström and Risberg 2003/ displayed on the modelled RSL curve from /Söderbäck 2008/.*

During the Ancylus stage, the eustatic part of the RSL equation is replaced by the RSL equation for lake thresholds /Påsse 2001/. At the beginning of the stage the lake outlet was at Degerfors and during the late stage through the Danish sounds, across the so-called Darss Sill.

The RSL model can probably be extended some time into the future but not longer than to the beginning of next glacial stage because only the remaining uplift after Weichsel is included in the equation. The model of future glacial stages presented in /Kjellström et al. 2009/ states that next glacial stage will begin at c. 57,000 AD. In the same report, the RSL curve for Forsmark covering the complete Weichsel glacial cycle is presented. In Figure 4-5 both models are illustrated.

The RSL curve from /Whitehouse 2009/ (the blue curve in Figure 4-5) shows errors early in the period and the Holocene curve has errors after c. 50,000 AD. For these reasons a combination of the two curves has been produced (Figure 4-6) /SKB 2010a/. One of the SR-Site Biosphere project assumptions is that the next 120,000 years will be an echo of the last 120,000 years (Weichsel), a time period that encompasses an interglacial-glacial cycle. This involves fixed RSL values of c. 0 m at 2009 AD and 122,009 AD. The period 110,500–120,000 AD (9500 BC – 2000 AD) is best represented by the RSL equation from 2001 since this is based on measured values /Hedenström and Risberg 2003/.

The RSL equation does not involve parameters suitable for representing the next glaciation or thereafter, so for the period from the next glaciation to 110,500 AD, the Whitehouse curve is the only data that are available. The Whitehouse curve is nearly level at c. 20,000 AD (c. 60 m) and this value is comparable with the value /Påsse 2001/ gives as remaining uplift after the Weichsel at the same point of time (c. 55 m); thus, the values from Whitehouse are used for the period 20,000–110,500 AD. Finally the period from 2000–20,000 AD is calculated with a change rate of –0.00644 m a^{-1} at 2000 AD /SMHI 2009/ and a successively lower change rate to connect to –60 m at 20,000 AD since there are no processes during that period that can cause an increasing RSL change rate provided a constant climate.

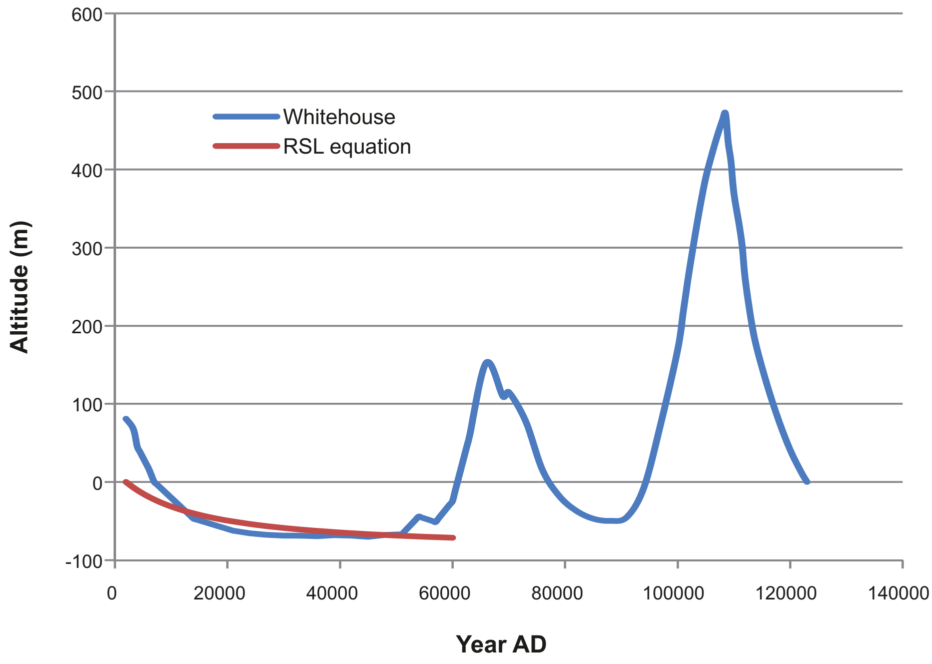


Figure 4-5. *The RSL curves from /Whitehouse 2009/ and the RSL equation curve /Söderbäck 2008/.*

The criteria for the new curve are:

(i) will start at –0.062 m altitude at 2009 AD with a change rate of –0.00644 m a^{-1} in the RH70 national height system /SMHI 2009/, and

(ii) will exhibit a continuous decrease in RSL change rate and join the value in the Whitehouse curve at 20,000 AD and –60.25 m, and

(iii) use the Whitehouse curve for the period 20,500–110,500 AD, and

(iv) use the RSL equation curve during the period 111,000–122,000 AD.

The new RSL curve for the next glacial-interglacial cycle is shown in Figure 4-6.

4.2 Regolith

4.2.1 Introduction

This section describes the present understanding of the properties and distribution of regolith at Forsmark. Regolith refers to the unconsolidated deposits overlying the bedrock and includes both the Quaternary deposits and the soils. The term Quaternary deposits (QD) is used since the regolith in the Forsmark area was deposited during the Quaternary period. In terrestrial areas, the upper part of the regolith that has been affected by climate and vegetation is referred to as soil. The spatial distribution and physical and chemical properties of the regolith are important inputs to modelling the transport of water, elements and various compounds between the geosphere and the biosphere.

The bedrock and the regolith form the geometrical framework for the surface systems of the Forsmark area. Since the regolith continuously develops, the geometrical framework of the landscape will change over time. The knowledge of the formation of the regolith at Forsmark during the latest glaciations and present interglacial is essential for the understanding of the future evolution of the distribution of QD. Furthermore, soil properties are important factors determining the vegetation type in the terrestrial ecosystem hence the regolith data contributes to the prediction of future vegetation and land-use when the sea floor has emerged and become part of the terrestrial system.

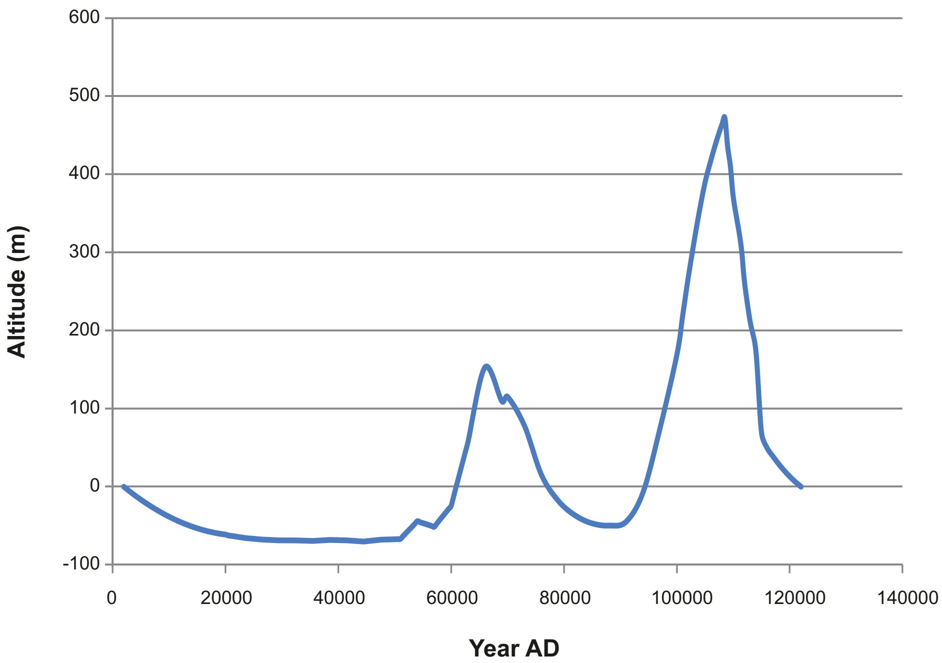


Figure 4-6. *The RSL curve for the next glacial-interglacial cycle /SKB 2010a/.*

The distribution of regolith at the Forsmark site is visualised on a surface map /Hedenström and Sohlenius 2008/ and in a regolith depth model (RDM) that shows the stratigraphy and thickness of different deposits /Hedenström et al. 2008/. The safety assessment analysis focuses on processes involved throughout a glacial cycle (about 120,000 years). The knowledge of the genesis of the regolith during the present interglacial is thus of large importance when modelling the future evolution of the area.

/Brydsten and Strömgren 2010/ have modelled the distribution of regolith throughout an interglacial. The observed present and modelled past and future distributions of regolith have been used to model the land-use during an interglacial (see Chapter 5). The land-use model is used within SR-Site as an input to model the human exposure to radionuclides that have reached the surface system.

For a comprehensive description of the genesis and distribution of QD in Sweden, the reader is referred to /Lindström et al. 2000/ and /Fredén 2002/. The distribution and properties of regolith in the Forsmark area are discussed by /Hedenström and Sohlenius 2008/.

4.2.2 Conceptual model and present distribution of regolith

The QD in the Forsmark area have been deposited in the varying environments that have occurred during and after the latest glaciation. In these environments, QD with very different properties have, and still are, formed. The younger QD are always superimposed upon older deposits and it is therefore easy to determine the relative age of the deposits. The regolith in the Forsmark area has only been subjected to soil-forming processes for a relatively short period and most of the soils are therefore immature and lack distinct soil horizons.

The terrestrial part of the Forsmark area is today dominated by till deposited during the latest glacial. At the floor of the sea, in Öregrundsgrepen, large areas are covered with clay. That general distribution of QD is typical for the County of Uppsala and the region around Lake Mälaren. In that region the topographically high areas are dominated by till and outcrops whereas the valleys are covered with clay. One feature typical of the Forsmark area and the surrounding coast is the high content of calcium carbonate in the soils.

The development of the Forsmark area from the latest deglaciation to the present is summarised in Figure 4-7. In Sweden, the highest altitude covered by sea water in an area is referred to as the highest coastline. Due to the pressure of the ice sheet, the whole of the Forsmark model area was situated below the highest coastline after the latest deglaciation. In the Forsmark area, the latest deglaciation occurred c. 8800 years BC and most of the regolith in the area was formed shortly before or after that event.

Since the deglaciation, water depth has successively decreased as an effect of the isostatic land uplift, and during the last two thousand years there has been a significant increase of land areas in the Forsmark region (Figure 4-7). Since the area is flat the growth of new land is relatively fast. Lakes and wetlands are continuously formed in the uplifted areas. The lakes are slowly filled with sediment and peat and will develop into fens. If the climate permits the fens will later develop into bogs.

The QD are subdivided into two main groups according to genesis and depositional environment: glacial and postglacial deposits.

Glacial deposits are deposited either directly from the continental ice sheet or from water derived from the melting ice. Glacial till was deposited directly by the glacier ice and consists of material eroded from bedrock and older regolith and transported with the ice flow before deposition. Till is the most common type of QD in Sweden and often contains all grain sizes from clay particles to large boulders. The grain-size distribution of till may differ depending on the physical properties of the local bedrock, the properties of older regolith and the glacial processes involved in the transport and deposition of the till. The ground surface in till areas is often characterised by the occurrence of boulders. The size and frequency of these boulders varies considerably from area to area. In areas with crystalline bedrock, sandy till with normal boulder frequency occurs commonly, whereas in areas with sedimentary bedrock, the till often contains clay.

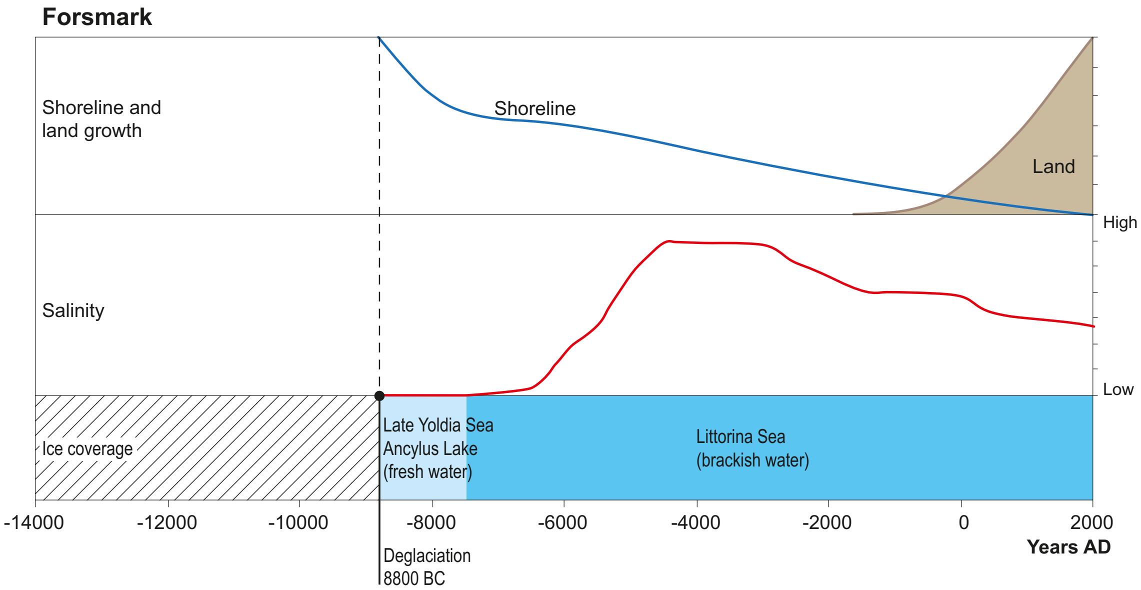


***Figure 4-7.** The development of the Forsmark area from the latest deglaciation to the present. The red curve shows variations in salinity of the Baltic Sea and the brown area represents the successively increasing land area /Söderbäck 2008/.*

In Forsmark the dominating recorded ice-flow directions were from north and northwest. The till in the area consists consequently of material that has been transported from these directions. In Forsmark till covers around 65% of the terrestrial area and 30% of the marine area (Table 4-1) /Hedenström and Sohlenius 2008/. The till is relatively fine grained and in some areas clayey (clay content 5–15%). This is because the till contains redistributed sedimentary bedrock and possibly also pre-glacial clays. The sedimentary bedrock, mainly limestone, originates from the floor of the Bothnian Bay and has consequently been transported several tens of kilometres.

Most of the material in the till in the Forsmark area originates, however, from the local bedrock /Bergman and Hedenström 2006/. In the terrestrial part of the Forsmark area, three main types of till have been defined (Figure 4-8): sandy till with a normal boulder frequency, clayey till and till with high frequency of large boulders in the surface /Hedenström and Sohlenius 2008/. The clayey till is partly used for agriculture whereas the other two till types are dominated by forest. The grain size distribution of the till in the marine areas has not been investigated; however, it is probable that the three till types are present also in the marine area. Most of the till in the Forsmark area was probably deposited during the latest glaciation. At some sites a compact clayey till has been observed below the sandy till. This till may predate the latest deglaciation, but it has not been possible to determine the absolute age of that till unit.

***Figure 4-8.** Different types of till in the Forsmark area: A) sandy till with a normal frequency of boulders, B) clayey till with a low frequency of boulders, C) till with a high frequency of large boulders.*

Table 4-1. The areal coverage (%) of the different QD (at a depth of 0.5 m) and bedrock exposures in the Forsmark model area. The first column gives the proportion within the entire model area, the second column represents the terrestrial areas, excluding lakes, and the right-hand column gives the proportion of the Quaternary deposits at the sea floor (from /Hedenström and Sohlenius 2008/).

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

During the deglaciation, large quantities of glacial melt-water were produced. The melt-water was concentrated to tunnels under the ice and to fractures on the ice surface seeking their way to the ice front. Rock material was transported, sorted and rounded by the running water and deposited in cavities within the ice or at the ice margin. These deposits are called glaciofluvial and are characterised by well-sorted sediments, often forming eskers of sand and gravel. The only glaciofluvial deposit in the Forsmark area is the "Börstilåsen" esker along the coast in the eastern part of the terrestrial area. The esker is mainly built up by gravel that, at least partly, rests directly on the bedrock.

The finest particles, clay and silt, were transported with the melt-water and deposited in deep and calm water further from the ice margin. These deposits are referred to as glacial clay and silt and are mainly found in areas below the highest shoreline, e.g. in Uppland. The glacial clay is the most common fine-grained glacial deposit in the Forsmark area and is characterised by varves, i.e. layers representing summer and winter accumulation. Glacial clay often occurs in valleys both below and above the present sea level and is frequently used for agriculture. In the Forsmark area, only 4% of the terrestrial area has glacial clay as the surface layer but glacial clay covers c. 40% of the marine area (Table 4-1). It can consequently be assumed that the area with glacial clay will increase in the future.

A characteristic of the glacial deposits is that they are minerogenic in composition, i.e. they contain very little (or no) organic matter. The till and glacial clay in the Forsmark area have relatively high contents of $CaCO_3$, which originates from a large limestone area situated at the floor of the Bothnian Sea, north of the model area.

Postglacial deposits comprise the youngest group of regolith and have been formed after the glacial ice sheet melted and retreated. Processes forming postglacial deposits are still active predominantly along the coast, in lakes and in wetlands. In general, postglacial deposits overlie till and, locally, glacial clay or bedrock. Clay, organic sediment, peat, sand and gravel are the dominating types of deposits.

After the deglaciation the water depth was around 150 metres deeper than at present, well below the wave base, and postglacial clay started to settle and covered large parts of the sea floor. These sediments were deposited after erosion and redeposition of older QD, such as glacial clay. The erosion of older deposits often occured in areas subjected to wave washing when the water depth decreased as an effect of the land upheaval. The relative sea level decrease brought the shallowest part of the sea above the wave base and caused the postglacial sediments to resuspend. These particles were transported out of the area into the Bothnian Sea or re-settled on deeper bottoms within the study area.

When the area became even shallower, the wave power decreased and postglacial clay started to accumulate in sheltered positions, such as bays. The postglacial clay can often be found in the deeper parts of valleys below the highest shoreline and is frequently used for agriculture. Postglacial clay often contains organic material and is then often referred to as clay gyttja (6–20% organic matter) or gyttja (>20% organic matter). Gyttja is often deposited in lakes whereas clay gyttja and gyttja clay more often are formed in bays along the Baltic Sea coast. In areas with calcareous soils, such as the Forsmark area, calcareous gyttja is commonly formed when calcium carbonate precipitates in a lake.

In Forsmark, postglacial clay, clay gyttja and gyttja cover 4% of the terrestrial area and 17% of the marine area (Table 4-1). As is the case with the glacial clay, the area with these postglacial deposits will increase in the future.

Postglacial sand and gravel were, and still are, deposited by currents and waves, which rework glaciofluvial deposits and till as the water depth in the sea gradually decreases. The sand and gravel have subsequently been deposited in more sheltered positions. In the Forsmark area the postglacial sand and gravel often rest directly upon the glacial clay. Presently, postglacial sand and gravel cover 2% of the terrestrial area and 6% of the marine area at Forsmark (Table 4-1).

Peat consists of remnants of dead vegetation which are preserved in areas (often mires) where the prevailing wet conditions prevent the breakdown of the organic material. Peatlands are often subdivided into fens and bogs. The vegetation in the fens obtains nutrients from the groundwater, whereas a bog obtains nutrients mainly from precipitation. The development of fens in Forsmark is often characterised by a first *Phragmites* (reed) stage, later a *Carex* (sedge)/*Bryales* stage, followed by a *Sphagnum* stage (Figure 4-9). Trees may be found during different stages and where deciduous trees dominate in the first stages. If accumulation of peat continues the fen will later develop into a bog. Large bogs may have pine trees, where the hydrological conditions are suitable (see also Section 5.1.2).

Different types of peat are formed in the mires during this succession. The peat is built up by the plants from the mire and the properties of the peat are consequently an effect of the different types of vegetation. The peats formed during the fen stages are often rich in nutrients, whereas the bog peat is poor in nutrients and characterised by low pH. The timing of the succession from lake to fen is further discussed in /Brydsten and Strömgren 2010/, where a sedimentation model is presented. On the QD map, peatlands are subdivided into fens and bogs. In Forsmark, peat covers 8% of the terrestrial area (Table 4-1), a figure that will increase successively as the present lakes are infilled.

Since the wetlands in the Forsmark area are young, almost all peat shown on the QD map is fen peat. The proportion of bog peat is likely to increase in the future. Peatlands shown on the QD map have peat thicknesses of more than 0.5 m and are almost only found in areas situated more than 5 m above the present sea level. These areas have been uplifted above sea level for more than c. 800 years. Wetlands situated at lower altitudes are young and a peat layer thicker than 0.5 m has therefore not yet developed. These wetlands are often located on clay gyttja or till. The wetlands are often not situated in topographically distinct valleys and the conditions for sedimentation of clay have therefore not been favourable. The layers of clay are consequently often thin in the present wetlands.

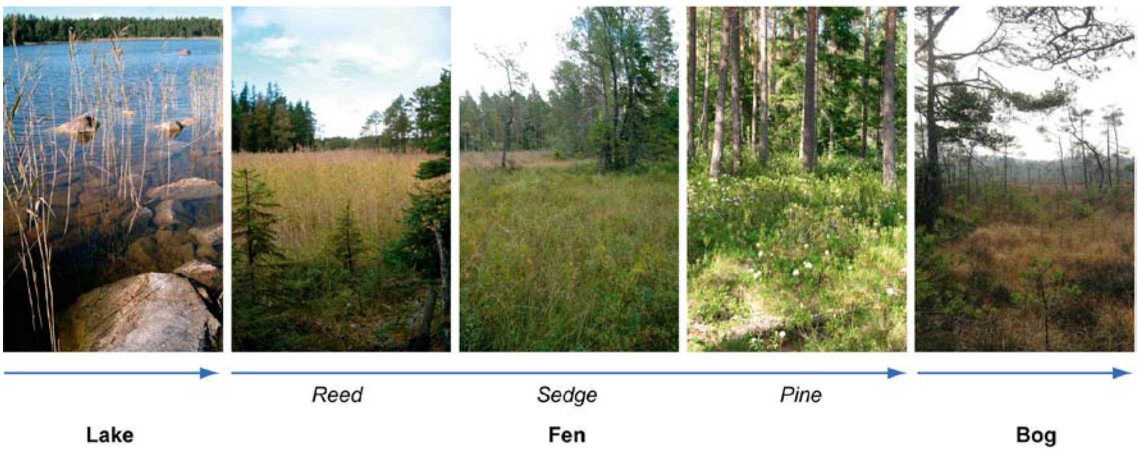


Figure 4-9. *The figure illustrates an example of a successive development of a lake into a fen and finally a bog. The fen is first dominated by reed, thereafter by sedge and finally covered by forest, in this case pine. The bog is characterised by nutrient-poor conditions and decreasing numbers of trees. The succession may also, if undisturbed by ditching, be; lake-reed-fen-poor fen and finally a bog-stage.*

The distribution of QD in the Forsmark area (Figure 4-10) is related to the large-scale bedrock morphology. Even though the landscape in Forsmark is very flat some morphological features affecting the distribution of QD can be distinguished. When looking at the large-scale morphology it is possible to recognise a large valley situated at the floor of the "Öregrundsgrepen", an area which today is completely covered by the Baltic Sea. That valley has a high proportion of different types of clay and is surrounded by two relatively high areas, the island of Gräsö and the terrestrial part of the Forsmark model area. These high areas are dominated by till and exposed bedrock.

When looking at the smaller-scale topography, a number relatively small valleys can be distinguished. In the terrestrial area these valleys are covered by lakes and wetlands. The floors of these lakes and wetlands are to a large extent covered by thin layers of glacial and postglacial clay. In some wetlands a peat layer has started to form. Accumulation of peat and water laid sediment, such as sand and clay, often has a levelling effect on the topography since the sediments are concentrated to local depressions.

The topography of the landscape is therefore flatter compared to the underlying bedrock morphology. Deposits of clay are generally thicker in extensive depressions like "Öregrundsgrepen" compared with the smaller lakes and wetlands, see /Hedenström et al. 2008/. The general stratigraphical distribution of QD in the different environments present in the Forsmark area is shown in Table 4-2. As can be seen in that table, the oldest QD has successively been overlain by different types of younger QD.

Data from the site investigation concerning total depth and thickness of the different types of regolith were used to produce a regolith depth model (RDM) /Hedenström et al. 2008/. In that model the stratigraphical units are shown as six different Z-layers and three lenses. Figure 4-11 and Table 4-3 show the general stratigraphical distribution of these layers. Figure 4-12 shows the modelled regolith depths. The glacial deposits as shown in the regolith depth model were used as an input to the Quaternary deposit model (RLDM), which is presented in Section 4.1 and in /Brydsten and Strömgren 2010/.

The thickness of postglacial deposits through time was modelled in the RLDM (see Section 4.1). The Quaternary development model (RLDM) should predict the course of events described above, especially the dynamics of the clay particles. For the safety assessment, the most important unconsolidated strata are fine-grained sediments, such as glacial clay and postglacial clay or silt. This is because these small grains and/or organic sediments can bind radionuclides more effectively than coarser particles.

Soil refers to the upper part of the regolith in terrestrial areas, which has been affected by climate and vegetation. Soils are characterised by horizons with certain physical and chemical properties. The soil type developed is a result of the interaction between several factors such as the parent material (QD), climate, hydrology, soil organisms and time. In Sweden, the soil-forming processes have been active since the latest deglaciation. In Forsmark, the soils in general are very young and immature since most of the area has been uplifted for less than 1,500 years.

Table 4-2. The general stratigraphical distribution of Quaternary deposits in the environments present in the Forsmark area (from /Hedenström and Sohlenius 2008/). The younger deposits are always superimposed upon the older. Note that the stratigraphy is not complete at all sites (e.g. glacial clay is missing in some lakes).

Environment	Quaternary deposit	Relative age
Bog	Bog peat	Youngest
Fen	Fen peat	
Freshwater lake	Microphytobenthos/Gyttja/Calcareous gyttja	↑
Freshwater lake and shallow coastal basin	Algal gyttja	
Postglacial Baltic basin	Clay gyttja-gyttja clay	↑
Coast	Post-glacial sand and gravel	
Postglacial Baltic basin	Postglacial clay	↑
Late glacial Baltic basin	Glacial clay	
Late glacial	Glaciofluvial sediment	
Glacial	Till	Oldest

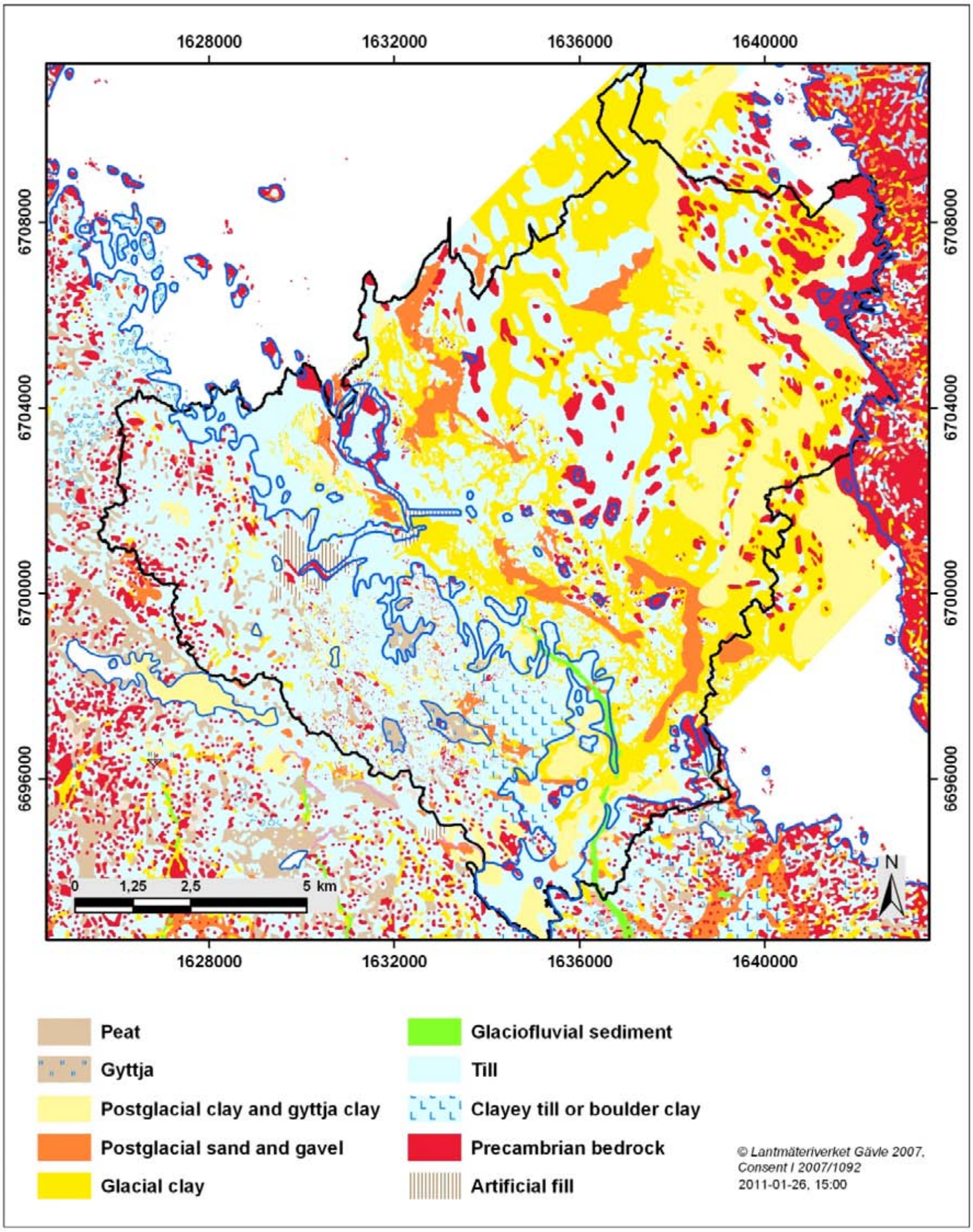


Figure 4-10. *The distribution of Quaternary deposits in the Forsmark area. The area modelled for regolith depths /Hedenström et al. 2008/ and the shoreline are delineated with a thick black line and a blue line, respectively. The white areas represent water covered areas lacking QD data. The map shows the distribution of QD at a depth of 0.5 metres and is based on six different maps, originally presented at different scales. The methods applied to produce these maps are discussed in /Hedenström and Sohlenius 2008/.*

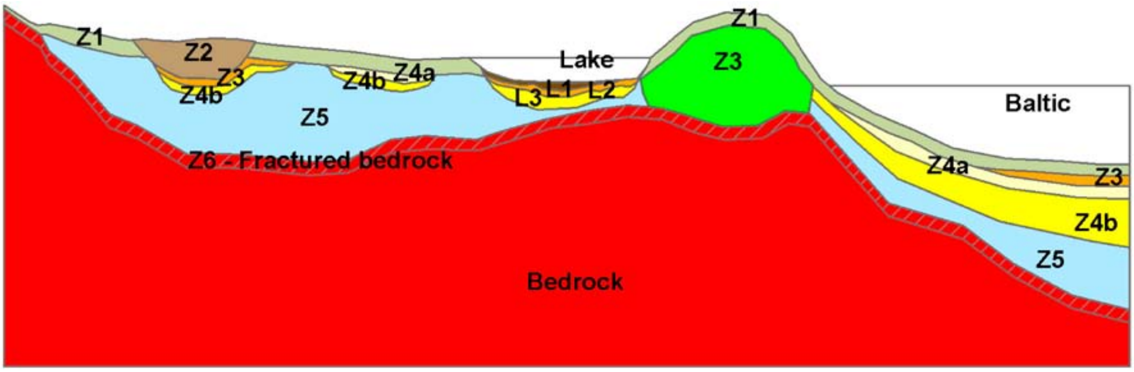


Figure 4-11. *Conceptual model showing the generalised stratigraphical distribution of the seven layers and three lake sediment lenses used for the regolith depth model (from /Hedenström et al. 2008/). The geological representation of the layers is shown in Table 4-3. Note that Z3 represents both glaciofluvial material (green) and post glacial sand/gravel (orange).*

Table 4-3. Description of the layers used in the Forsmark regolith depth model (from /Hedenström et al. 2008/). The geometry of the layers was interpolated both from observed layer thicknesses and calculated average values. The L1–L3 layers were only used to represent the QD in some of the present lakes.

Z1 is the uppermost regolith which has been affected by surface processes, e.g. soil-forming processes in the terrestrial parts or sedimentation/transport/erosion in the limnic/marine parts. On bedrock outcrops, the layer is 0.1 m and 0.6 m in other areas. Z1 is the only layer if the total modelled regolith depth is less than 0.6 m.
Z2 represents both fen and bog peat and is only present where peat is shown on the QD map.
Z3 represents postglacial sand/gravel, glaciofluvial sediment and artificial fill.
Z4a represents postglacial clay including gyttja clay. This layer is only used when postglacial clay/gyttja clay are shown on the QD map.
Z4b represents glacial clay
Z5 represents till, which is present in a major part of the Forsmark model area.
Z6 represents the upper part of the bedrock and has a depth of 0.6 m in the whole area. The layer was distinguished since the upper bedrock has a higher frequency of fissures and thereby higher hydraulic conductivity compared to the underlying bedrock.
L1 represents gyttja (algal gyttja, calcareous gyttja, clay gyttja-gyttja clay) and peat inside the boundary of lakes. When peat is present as surface layer within the lake area, this is included in the L1 lens. The sediment in L1 and Z4a partly consist of the same geological units.
L2 represents postglacial sand and/or gravel inside the boundary of lakes. The sediments in L2 and Z3 consist of the same geological unit.
L3 represents clay (glacial and postglacial) inside the boundary of lakes. The sediments in L3 and Z4a and Z4b consist of the same geological unit.

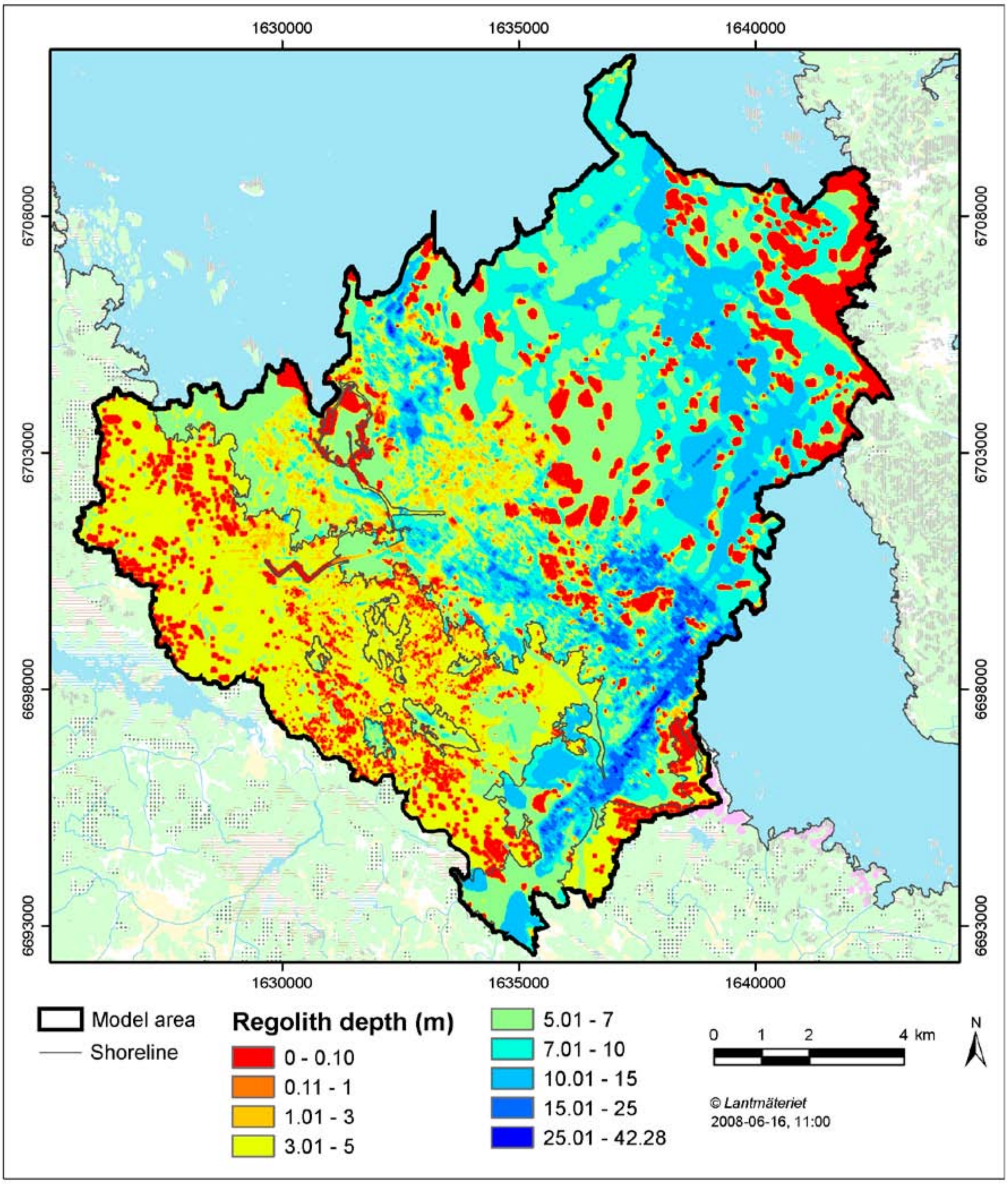


Figure 4-12. *Total modelled regolith depths (from /Hedenström et al. 2008/).*

At many locations with glacial deposits, calcite occurs from the ground surface and downwards. The high calcite content is reflected e.g. in the pH in the surface water /Lundin et al. 2004, Tröjbom and Söderbäck 2006/ and in the composition in the field and bottom layer of the vegetation /Jonsell and Jonsell 1995/. A study from northern Uppland showed that the depth of the carbonate-free zone increases at higher altitudes /Ingmar and Moreborg 1976/, which is explained by a successive leaching of calcite. In the Forsmark area, calcite in the present soils will consequently be leached out during the forthcoming thousands of years. New calcite rich soils will, however, form along the future coast as new land areas are uplifted.

The dominating soil type in the Forsmark area is Regosol, which is characterised by incompletely developed soils horizons. Podsol is the most common soil type in Sweden, but has not yet developed in Forsmark. Histosol is dominated by organic material and frequently occurs in wetlands. That soil type has, however, not yet developed in the youngest wetlands where the peat layers are thin.

4.2.3 The future distribution of regolith

The accumulation of sediment and peat as well as the erosion of sediment on the sea floor will continue in the future. The distribution of QD in the Forsmark area will consequently change throughout the present interglacial. Furthermore, the proportional distribution of QD in the terrestrial part of the Forsmark area will change as new land is uplifted. It is of course not possible to predict the future distribution of QD in detail. It is, however, obvious that the proportion of terrestrial areas with clay will increase as the broad valley of "Öregrundsgrepen" is uplifted. In the present terrestrial area the proportion of peat will increase significantly as the shallow lakes are infilled and the low-lying wetlands are covered by a layer of peat. New lakes will form when the present sea floor is uplifted. Also, these lakes will successively be filled with gyttja and peat. The proportion of land suitable for agriculture will increase significantly in the future as the clay sediment at the floor of "Öregrundsgrepen" is uplifted.

A colder climate may cause an increased proportion of areas covered by peat. In northern Sweden, peat is not only accumulating in the lowest topographical areas but also on gentle slopes, due to a high groundwater level. Even though not developed into bogs these mires are often lacking trees. Furthermore the mires formed in a colder climate, as in northern Sweden, are often a mixture of fen and bog areas. If the climate in Forsmark becomes more similar to the climate in northern Sweden, it is consequently likely that a large portion of the landscape will be covered by peat. A warmer and dryer future climate may also affect the properties of peat-covered areas. Bogs are formed in areas with a high precipitation, and warmer climate with higher evapotranspiration may prevent the development of fens into bogs.

In Chapter 5 a model showing four different plausible land-use development sequences in Forsmark during an interglacial is presented. The land-use model used the modelled distribution of QD from the RLDM to model the four variants of land-use development. The RLDM in turn used the modelled accumulation of peat and sediment to determine the distribution of postglacial QD throughout an interglacial. A sedimentation model showing the timing of the succession for lakes to wetlands was also used for the RLDM /Brydsten and Strömgren 2010/.

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

The distribution of QD after the next glaciation can only be predicted in general terms. It can be assumed that till will deposit also during next glaciation. The thickness and areal coverage of the future till layer can, however, not be predicted. The future till is likely to be fine grained due to the occurrences of clay and sedimentary bedrock on the present sea floor north of Forsmark. These fine-grained deposits will probably be redistributed by the ice during the next glaciation. The geographical distribution and size of future possible glaciofluvial deposits is more or less impossible to predict in the subdued topography of Forsmark. During the next interglacial, it is likely that the Forsmark area will once again be below sea level when the ice has left the area. Clay or other fine-grained deposits will then accumulate on the sea floor.

Regolith suitable for agriculture is consequently likely to occur also after the next glaciation. The topographical conditions will make it possibly for lakes and wetlands to develop also during the next interglacial. Peat and gyttja sediment will accumulate in these environments. It is also possible that some of the present QD will be preserved into the next interglacial. This has been the case in parts of northern Sweden (e.g. /Lagerbäck and Robertsson 1988/). Such a development will cause a future stratigraphy of regolith which is more complex than the present stratigraphy shown in Table 4-2.

4.2.4 Model of Quaternary development

A coupled model for regolith-lake development (RLDM) has been constructed and is applied to the Forsmark area. The study is reported in /Brydsten and Strömgren 2010/ and an extended summary is presented here. The site descriptive model does not cover the temporal change of the regolith, which means that further development is needed to fulfil the needs of the safety assessment. To this end, the /Bydsten and Strömgren 2010/ study presents a model that can predict the surface geology, stratigraphy, and thickness of different strata at any time during a glacial cycle and applies this model to the Forsmark site.

The coupled regolith-lake development model (RLDM) predicts the distribution of Quaternary deposits during an interglacial. The RLDM is divided into two modules: a marine module that predicts the sediment dynamics caused by wind waves and a lake module that predicts the lake infill processes.

The RLDM marine module starts at the time when the area has recently been deglaciated and all Quaternary deposits are of glacial origin (surface geology, stratigraphy, and thickness around 8800 BC). These conditions are generated using the regolith depth model (RDM) /Hedenström et al. 2008/. The RDM is a model in raster format with seven layers (Figure 4-11 and Table 4-3) where each layer is presented as a digital elevation model (DEM) for the upper surface of that particular layer. The uppermost three layers in the RDM are formed during the postglacial period, so the bottom four layers represent the stratigraphy as it existed shortly after the deglaciation. Because the RDM is in a raster format with a cell size of 20 metres, the RLDM has the same extension and resolution as the RDM.

From the deglaciation until 11,500 AD (with 500 year time steps), postglacial clay/silt is added or removed in each raster cell based on the sediment dynamic environment for that date. This sediment dynamic data is output from the sediment dynamic model as presented by /Brydsten 2009/. In a cell where erosion is the predominant process, all postglacial accumulation is resuspended and transported out of the cell. Cells dominated by accumulation get a contribution of 0.06–0.39 m postglacial clay in each time step. The net sedimentation rate varies over time and was calibrated using the sediment dynamic model and measured postglacial clay thicknesses from the marine geological survey /Elhammer and Sandkvist 2003/. For each time step, the RLDM marine module outputs are raster maps of Quaternary surface geology, thickness of postglacial clay, and DEM.

The lakes are modelled with a module within the RLDM based on an equation for net sedimentation rate and an equation for vegetation colonisation /Brydsten 2006/. Each lake is modelled separately. The DEM and the thickness of the marine postglacial clay from the time step before lake isolation is used as the only input to the module. The lake module runs in 100-year time steps until the lake is completely infilled. Raster maps of Quaternary surface geology, DEM, thickness of the marine and limnic postglacial clay (gyttja clay or clay gyttja), and thickness of the peat are outputs from the lake module for each time step.

In a post-processing routine, the outputs from the marine and lake modules are merged into single raster maps for Quaternary surface geology, DEM, and RDM. In a second post-processing routine, the wetlands not originating from infilled lakes are added. These wetlands are partly small infilled local basins and partly hanging wetlands. The extensions of the latter are calculated using the DEM and an equation for topographical wetness index (TWI).

The model suggests that a major part of the study area was covered by postglacial clay shortly after the area was deglaciated, see Figure 4-13. As the water got shallower following isostatic rebound, more postglacial clay resuspended and exposed the glacial sediments beneath. The minimum areal extension of the postglacial clay occurred about 2000 BC (Figure 4-14) and was localised to adeep area west of the island Gräsö. Next, the area of postglacial clay increased again and continues to increase to reach a local maximum around 2500 AD, then it successively decreases until the sea leaves the study area (about 11,500 AD), exposing the greater part of the postglacial clay found in the lakes.

In a small part of the study area (about 1.5%) west of the present island of Gräsö, postglacial clay accumulated during the whole period. The maximum modelled thickness of the postglacial clay is found in this area, about 26.8 metres, of which about 5.6 metres settled in a marine environment.

Most of the lakes are shallow and will infill completely in 2,000 to 6,000 years. Exceptions are the deep lakes situated in the presently deepest parts of today's Öregrundsgrepen. These lakes will exist for about 25,000 years. The last lake will be totally infilled around 35,000 AD.

The RLDM assumes that the climate will not change during the modelled period. However, /Kjellström et al. 2009/ account for results from a climate model applied to a period of 120,000 years, which includes a full glacial cycle; their study shows permafrost climates for some of the period before all lakes at the Forsmark site will be completely infilled. This could be valid for future lakes with long infill times.

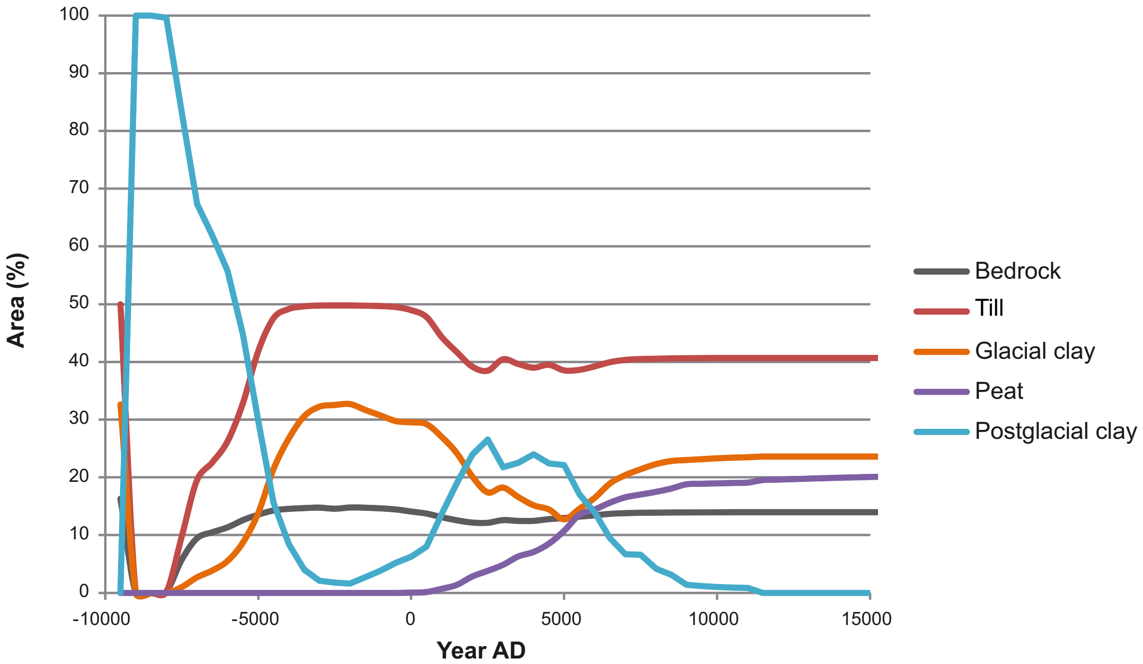


Figure 4-13. The temporal area development of Quaternary deposits for the model area of Forsmark (from /Brydsten and Strömgren 2010/).

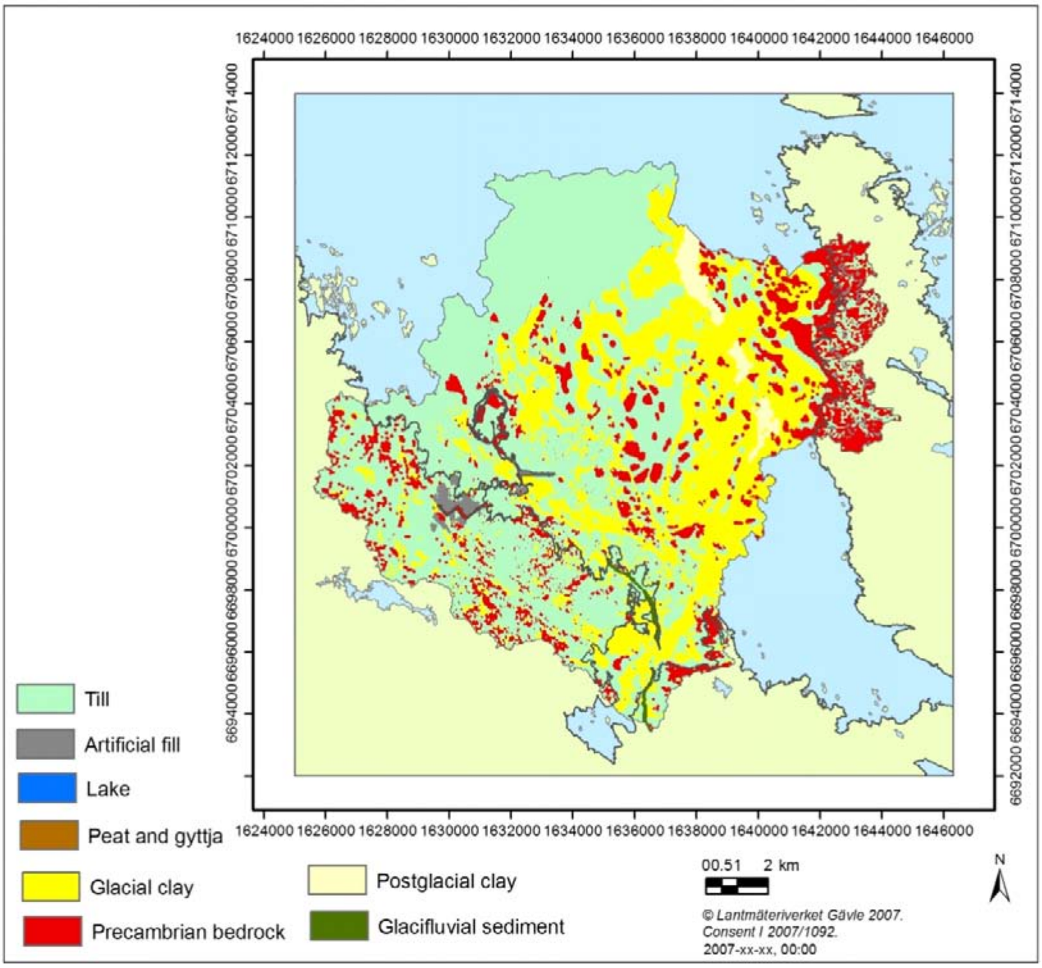


Figure 4-14. Quaternary deposits at 2000 BC. This is the time when the model predicts the minimum extent of postglacial clays.

Both colonisation by vegetation and sedimentation of organic material may decrease with lower water temperature /Löfgren 2010/. Both the modelled infill rate and the sedimentation rate could therefore be overestimated. The infill rate can be measured as the average long-term apparent rate of carbon accumulation (LORCA) in peat. Compared with LORCA, values from regions with cooler climate indicates a reduction in infill rate with 50–95% during permafrost conditions with successively higher reduction in a gradient from the Boreal zone to the High Arctic zone. During the next 50,000 years (during the period when there will be lakes in Forsmark), the climate conditions in Forsmark will probably include periods that will be similar to the climates in Boreal, Subarctic, High Subarctic, Low arctic, and High Arctic zones /Kjellström et al. 2009/. Thus, a RLDM version for permafrost conditions was constructed with a reduction of infill rate by 75% for all periods with permafrost.

The periglacial periods are defined by a permafrost depth greater than zero using data from the permafrost simulations /Hartikainen et al. 2010/. Permafrost depths vary greatly in periglacial environments, even on a local scale. It is common to have open taliks (areas with no permafrost) beneath lakes. The occurrence of taliks will be important for modelling nuclide dynamics, especially for periods with few or no taliks in the study area. /Hartikainen et al. 2010/ describes the conditions of talik formation based on lake mean depth, lake area, and permafrost depth in the lake vicinity. The updated lake module gives the lake mean depths and areas for each time step, and the permafrost model /Hartikainen et al. 2010/ gives the mean permafrost depth for the Forsmark area, so by combining results from these two models it is possible to predict talik formation.

Permafrost conditions will appear in the Forsmark area at around 9400 AD. At that time, 30 of the 42 modelled lakes are already completely infilled and sedimentation processes will not be affected by the changed conditions. By 9400 AD, 10 of the remaining 12 lakes are infilled to more than 75% and will only to a minor degree be affected by climate change. The only two lakes that will be affected considerably by the cooler climate are both large and deep.

The permafrost version of the RLDM was applied to these two lakes. The results show that adjusting the infill rate during permafrost periods will produce lakes with longer infill times and longer periods with taliks. In addition, this adjustment indicates that the model is very sensitive to the chosen reduction of the lake infill rate. Instead of choosing a mean reduction of 75% for all permafrost periods, it should be more accurate to use a variable reduction based on, for example, the mean permafrost depth. However, this requires more accurate climate data (air temperature, permafrost depth, etc.) from the reference sites or more precise climatic definitions of the arctic zones (Subarctic, High Subarctic, Low arctic, and High Arctic zones). If the result from the RLDM permafrost variant also is sensitive in the radionuclide modelling, future efforts should focus on updating the RLDM with variable reduction of the infill rate under permafrost conditions.

The sensitivity analysis and the permafrost models showed that the infill rate is the most sensitive parameter in the RLDM. In the model, the infill rate occurs in two places: in the model of vegetation colonisation in shallow bays that later will become lakes and in the lake module. Both rates are reduced under permafrost conditions. The RLDM could be improved by updating the infill representation with a more process-based algorithm that includes both bottom substrate and nutrient status in the lake phase and beach processes in the marine phase.

It is not possible to predict the export of fine-grained particles out of the model area with RLDM. However, with assumptions that the fluvial input and the input from the outer sea are of minor importance, a rough estimation is that c. ¾ of the fine-grained particles are exported out of the model area and c. ¼ are permanently accumulated within the area.

4.3 Hydrology

4.3.1 Introduction

This section aims to describe and present the overall understanding of the surface hydrology and near-surface hydrogeology in Forsmark during a glacial cycle. Hydrological processes play a substantial role within all ecosystems; water is the driving force for transport of all kinds of dissolved matter. The understanding of the evapotranspiration processes and the interactions between the surface water and groundwater systems is very important when describing the transport of matter within and between different ecosystems in the landscape.

Hydrological data from the site investigations and hydrological modelling results have provided input to the terrestrial, limnic and aquatic ecosystem modelling. With the knowledge of the hydrological conditions of today as a starting point and with supporting information from other disciplines, the development of the landscape from a hydrologic point of view in Forsmark is discussed and described in this section. Conceptual and numerical models from the Site Descriptive Modelling (SDM), describing the hydrology and near-surface hydrogeology in Forsmark today, are the basis for the assumptions made regarding future conditions at the site. Future conditions and different climates are handled within the SR-Site modelling. The different simulation cases presented here represent one possible future under the assumptions made within the SR-Site modelling.

This section describes the hydrological data from the site investigations and the hydrology and near-surface hydrogeology modelling that have been performed within the SDM- and SR-Site projects. For a detailed description of the hydrogeological data and the hydrogeological modelling focusing on the bedrock the reader is referred to /Follin et al. 2008/ and /Joyce et al. 2010/.

The main topics addressed in this section are as follows.

- A summary of the hydrological data and knowledge from the site investigations and a description of the hydrological conditions at the Forsmark site under present conditions.
- A description of the influence of the landscape succession (changes in the QD and soil profiles and lake terrestrialisation) on the overall water balance in the area.
- A description of the influence of different climates on the overall water balance in the area.
- A description of the location and strengths of recharge and discharge areas over time.

4.3.2 Data and modelling

Site data

Data from the site investigations has been evaluated, described and modelled in three different SDM versions, version 1.1 (F1.1) /SKB 2004/, version 1.2 (F1.2) /SKB 2005/ and version 2.3 (F2.3), the final version of the site descriptive model, SDM-Site Forsmark /SKB 2008/. Each model version was preceded by a so-called data freeze. The data freeze for SDM-Site Forsmark was on April 30, 2007.

The five principal datasets of time series used as a basis for the hydrological modelling are the time series of meteorological data, surface water levels, surface water discharge, and groundwater levels in QD and bedrock. The available data from meteorological, hydrological and hydrogeological investigations are described and summarised in /Johansson 2008/ and /Johansson and Öhman 2008/. The locations of the two local meteorological stations, the surface water level stations, and the surface water discharge stations and the catchment area for each discharge station are shown in Figure 4-15.

Numerical and conceptual modelling

The time series described in the above section constitute an important input to the conceptual and numerical modelling of the hydrology and near-surface hydrogeology. The conceptual model presented in Section 4.3.3 and described in detail in /Johansson 2008/ is the basis for the numerical modelling performed within the Site Descriptive Modelling, SDM, and the SR-Site hydrological modelling. The numerical hydrological and near-surface hydrogeological modelling, which has been performed with the hydrological modelling system MIKE SHE, is described in detail in /Bosson et al. 2008/ and /Bosson et al. 2010/.

The first MIKE SHE model F1.2 was reported in /Johansson et al. 2005/. At the time of the development of the F1.2 MIKE SHE model almost no site data were available and therefore not used for calibration or evaluation of the model's performance. The SDM-Site MIKE SHE model was preceded by a pre-modelling activity where a calibration methodology was developed /Aneljung et al. 2007/. The methodology was applied when developing the SDM-Site MIKE SHE model /Bosson et al. 2008/. An extensive sensitivity analysis was performed in order to investigate the model's sensitivity to the hydraulic properties of the QD and the parameters of the unsaturated zone.

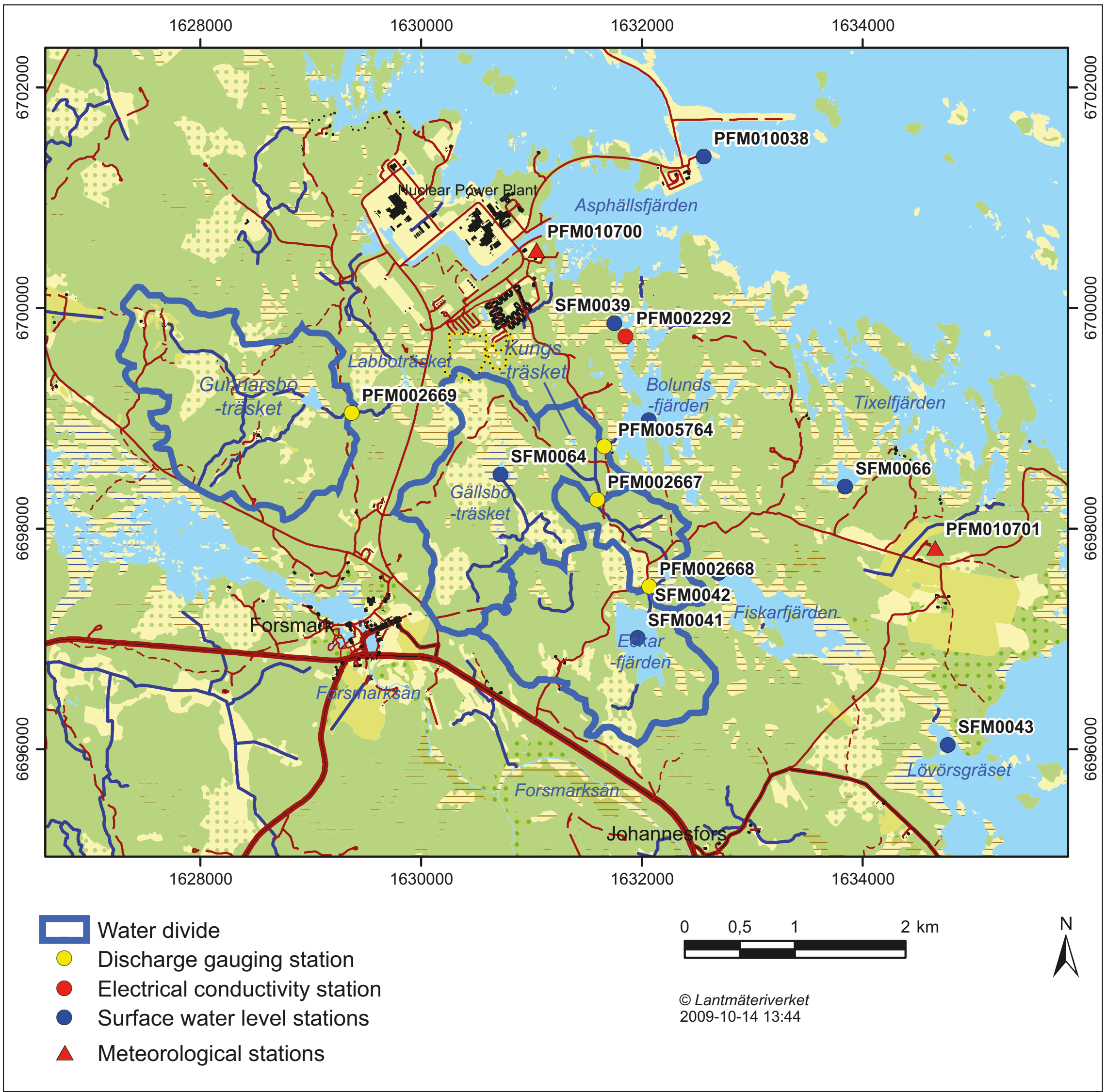


Figure 4-15. *Map showing the location of the meteorological stations, the surface water level stations and the surface water discharge gauging stations in the Forsmark area.*

Also, the sensitivity to the meteorology and evapotranspiration parameters was tested. The model was calibrated to surface water levels and discharges and to groundwater elevations in the QD and upper bedrock from the site investigation period. When calibrating the properties of the upper bedrock and the sediment layers under the lakes the pumping test in HFM14 /Johansson 2008/ was simulated. The available data set was divided into two parts; the first period from May 15, 2003, to July 31, 2005 was used for calibration and the second period from August 1, 2005, to March 31, 2007, was used for testing of the model.

The numerical modelling performed within the site descriptive modelling aimed at describing present conditions in Forsmark. No climate change or shoreline displacement cases were simulated. The model results describe the water balance, surface water levels and discharges and groundwater levels in the bedrock and QD in the area. Also, a lot of effort was put into the description of the fluxes between different model compartments. An important part of the analysis was to use site data and the conceptual model to develop the numerical model; this model development included calibration against measured site data. As supporting information to the flow results, particle tracking and advection-dispersion simulations were performed, see e.g. /Gustafsson et al. 2008/.

With the SDM-Site MIKE SHE model as a starting point, the SR-Site MIKE SHE model was developed. The model area was extended, a new geological description of the bedrock was implemented in the model, and also the description of the unsaturated zone parameters was refined. The SR-Site MIKE SHE modelling focused on future conditions regarding climate and shore-level displacement. Three different times were studied: 2000 AD, 5000 AD and 10,000 AD. A normal temperate climate, wet temperate conditions and a permafrost case have been simulated. Also, different geological models of the Quaternary deposits (QD) have been applied in the model in order to describe the influence of the succession of the QD on the hydrology in the Forsmark area. The development of the SR-Site MIKE SHE model and the modelling results are described in /Bosson et al. 2010/; results from the modelling are presented in Section 4.3.5 below.

4.3.3 Present conditions

General characteristics

The Forsmark area has a flat, small-scale topography. The study area is almost entirely below 20 m.a.s.l. (see Figure 4-16). The surface water divides are marked in Figure 4-16. During the site investigations, 25 "lake-centred" catchments and sub catchments were delineated; catchments and lakes are described in /Brunberg et al. 2004/. There is a strong correlation between the topography of the ground surface and the groundwater level in the QD; thus, the surface-water divides and the groundwater divides for the QD can be assumed to coincide.

There is a strong west-east gradient in the precipitation in north-eastern Uppland. At the SMHI station located c. 15 km west of the Forsmark area the long-term mean precipitation is 690 mm/year, whereas at Örskär, an SMHI station located c. 15 north-east of Forsmark, it is 490 mm/year. The annual corrected precipitation in the Forsmark area during the site investigation period, May 2003 to May 2007, was 563 mm/year. There is also a gradient in the temperature with a slightly milder climate on the coast than at the inland stations. The dominating wind direction in the area is from south-west.

No major water courses flow through the catchments shown in Figure 4-16. Small brooks, which often dry out in the summer, connect the different sub-catchments. The brooks downstream of Lake Gunnarsboträsket, Lake Eckarfjärden and Lake Gällsboträsket carry water most of the year, but can be dry during dry years. The long-term runoff for the area has been estimated to c. 160 mm/year; this is further discussed in the section describing the water balance of the area. The measured mean specific discharge for the largest catchment (station PFM005764, see Figure 4-15) was 4.88 $L/s/km^2$ or 154 mm/year. This value is based on discharge data time series of 35.5 months.

The main lakes in the area, Lake Bolundsfjärden, Lake Fiskarfjärden, Lake Gällsboträsket and Lake Eckarfjärden, all have sizes of less than one km^2. The lakes are in general shallow; all the lakes in the study area have mean depths ranging from 0.1 m to 1 m. The vertical mixing of lake water is mainly driven by wind. Due to the limited depths, the vertical mixing is likely to be almost complete for most parts of the year. The inlet and outlet of the lakes are often located at opposite ends of the lake and, since the horizontal mixing is driven by flow and wind shear, the lakes are assumed to be well mixed also in the horizontal plane. In the shallow near-shore areas covered by reed, water may be more stagnant.

During periods with high sea levels, salt water intrusion from the sea to some of the near-shore lakes may occur. Both during the storm "Gudrun" in January 2005 and during "Per" in January 2007 salt water intrusion occurred in Lake Norra Bassängen and Lake Bolundsfjärden, which could be observed as increased electrical conductivity in the lake water. The surface water levels in the lakes in the area seem to be dependent on the lake threshold and the amount of surface- and groundwater discharging into the lakes. However, the surface water levels in Lake Bolundsfjärden and Lake Norra Bassängen are periodically more dependent on the sea water level /Johansson and Öhman 2008/.

Till is the dominating type of QD. The regolith is often shallow. The mean depth is approximately 5 m and the maximum observed depth is 16 m and is found south-east of Lake Fiskarfjärden. Measurements performed at the site indicate an anisotropy in the hydraulic conductivity of the till, and a decreasing conductivity with depth. Also, the vertical hydraulic conductivity is in general lower than the horizontal one. Most of the lakes are underlain by fine-grained sediments. The typical sediment stratigraphy from the

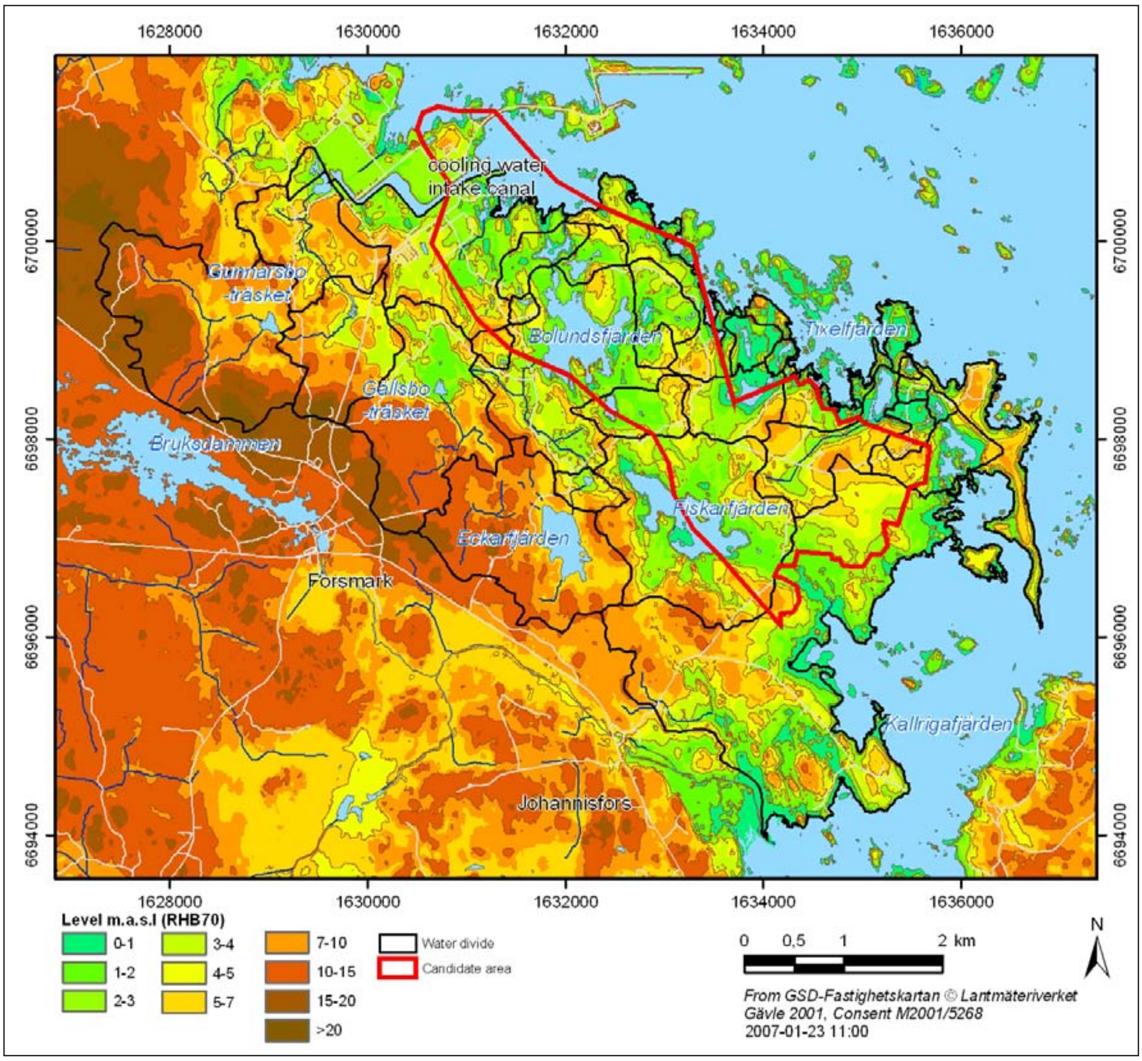


Figure 4-16. *Topographical map of the Forsmark area. Surface water divides are indicated in the figure.*

bottom up is; glacial and/or post glacial clay, sand and gravel, clay-gyttja and gyttja. A detailed description of the regolith in the Forsmark area is given in /Hedenström and Sohlenius 2008/. Bedrock outcrops are frequent, but constitute only 5% of the area. Granitic rock is the dominating bedrock of the area.

Figure 4-17 illustrates the overall conceptual model of the near-surface hydrogeology. Direct groundwater recharge from precipitation is the dominating source of recharge. During summer, some of the lakes in the area may act as recharge areas. Water uptake from plants lowers the groundwater level in the vicinity of the lakes and some of the lakes switch from being a discharge area to being a recharge area. Due to a high infiltration capacity of the upper QD, overland flow rarely occurs, except from saturated areas where the groundwater level reaches the ground surface. The runoff in the brooks is dominated by water of groundwater origin. During intensive rain events or snow-melt, overland flow contributes to the runoff.

The small-scale topography implies that many small catchments are formed with local, shallow groundwater flow systems in the QD. The decreasing hydraulic conductivity with depth and the anisotropy of the tills dominating in the area (higher horizontal than vertical hydraulic conductivities), imply that most of the groundwater will move along very shallow flow paths. Groundwater levels in QD are shallow with mean levels within a depth of less than a metre in most of the area. The groundwater level in the QD is strongly correlated with the topography of the ground surface. This local flow system in the QD overlies a larger scale flow system in the bedrock.

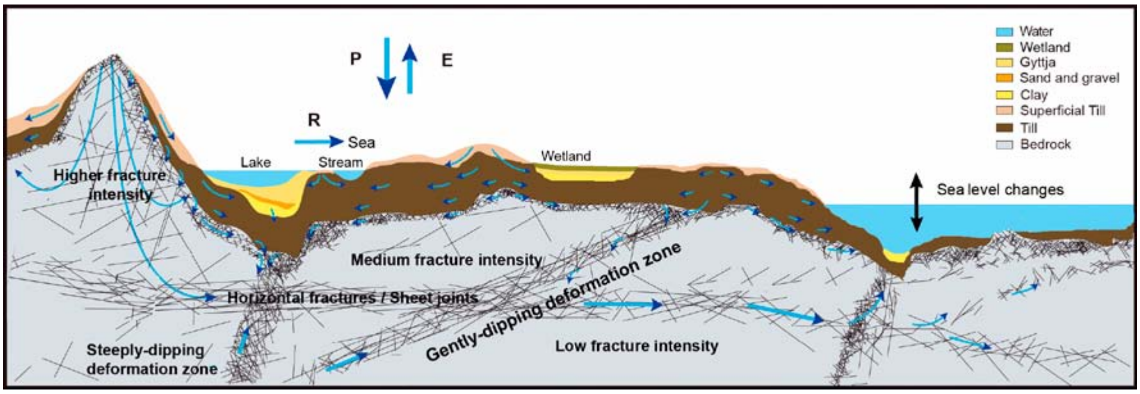


Figure 4-17. *Conceptual model of the hydrology and near-surface hydrogeology at Forsmark /Follin et al. 2008/.*

The upper part of the bedrock is characterised by a high frequency of horizontal fractures or sheet joints. Results from the site investigations indicate that these sheet joints interconnect hydraulically across large distances /Follin et al. 2008, Johansson 2008/. The bedrock between the sheet joints is less conductive. Below the upper c. 200 m of the bedrock there are no fractures/sheet joints of this type, and the overall fracture frequency is very low. The groundwater recharge from the QD to the upper bedrock is easily transmitted in the upper bedrock even at low gradients due to the highly transmissive sheet joints and other structures there. The groundwater level in the upper bedrock within the area selected for the repository is very flat and is not correlated to the surface topography as are the groundwater levels in the QD.

Hydrogeological properties

Slug tests, pumping test, BAT-filter tip permeability tests, laboratory tests of undisturbed samples and grain size distribution analyses have been carried out in order to estimate hydraulic conductivities (K) of the different QD in Forsmark. The major part of the investigations, especially the slug tests, have been done in till. The geometric mean of the K-values obtained from slug tests in till is $5.4 \cdot 10^{-6}$ m/s and the arithmetic mean is $5.3 \cdot 10^{-5}$ m/s; most of the K-values from these tests are in the range 10^{-7}–10^{-4} m/s.

The K-values are associated with different types of till and different depths. In addition, some of the well screens are placed in the till-bedrock interface. This is reflected as a relatively high spatial variability. Considering only the slug tests from wells placed in till gives a geometrical mean value of $1.3 \cdot 10^{-6}$ m/s, whereas the corresponding value for wells placed in the till-bedrock interface is $1.2 \cdot 10^{-5}$ m/s. The hydraulic conductivity is in general one order of magnitude higher at the till-bedrock interface than in the till. Also the till itself has a depth trend in the hydraulic conductivity. The conductivities are considerable higher in the uppermost half metre of the soil profile.

Hydraulic conductivities for other QD-types than till have mostly been measured with the BAT-filter tips. Conductivity values of clay, gyttja and peat were obtained from these investigations. The geometric mean for the clay was $2.9 \cdot 10^{-7}$ m/s and for gyttja $3.3 \cdot 10^{-7}$ m/s. Only one sample was available for peat, which had a K-value of $3.3 \cdot 10^{-7}$ m/s. A more detailed and complete presentation of the hydrogeological parameters of the QD, including porosity and storage parameters, is given in /Johansson 2008/.

For a detailed description of the bedrock properties the reader is referred to /Follin et al. 2008, Follin 2008/. There is a significant hydraulic anisotropy within the tectonic lens at Forsmark. The upper 150 m of the bedrock contains horizontal fracture zones, sheet joints. The transmissivity of the sheet joints is in the range 10^{-6} to 10^{-3} m^2/s and they interconnect hydraulically over large distances. The bedrock in between the horizontal fracture zones is less conductive with a conductivity of about 10^{-11} to 10^{-8} m/s. The deeper bedrock, below 150 m depth, has, in a national perspective, an exceptionally low frequency of flowing fractures. A pumping test performed in a borehole just west of Lake Bolundsfjärden indicated very high transmissivities in combination with low storativities /Follin 2008/.

Unsaturated zone parameters of QD have been investigated at the site and are reported in /Lundin et al. 2005/. The uppermost 50 cm of the soil profile has a higher total porosity, but also a lower capacity for retaining water than the underlying soil (i.e. a higher specific yield). The unsaturated flow parameters used in the modelling are based on data from /Lundin et al. 2005/, site-specific data on saturated hydraulic conductivity in /Juston et al. 2007/, and generic data from the same type of till in /Knutsson and Morfeldt 2002/.

Water balance

The 30-year normal precipitation based on regional measurements from the period 1961 to 1990 is estimated to be 559 mm /Johansson 2008/. Analysing only site data, which are from a relative short time period, the mean annual corrected precipitation is calculated to 563 mm/year. The relatively short time series from the discharge gauging stations in the area make it difficult to draw definite conclusions on the long-term specific discharge in the Forsmark area. The specific discharge varies within the area and between different time periods. The mean specific discharge for the largest catchment, with a time series of 35.5 months, was 154 mm/year.

Estimates of storage changes and precipitation deficit indicate that the three-year mean discharge measured at the site is close to the long-term average discharge. Thus, an estimation of the long-term water balance for the Forsmark area, based on site data presented above, and correlation coefficients between the local SKB stations at Högmasten and Storskäret and nearby SMHI stations was made. The precipitation was estimated to be 560 mm/year, the actual evapotranspiration to be 400–410 mm/year, and the annual runoff to be 150–160 mm/year. The methodology of the calculation of the correlation coefficients and the calculation of the long-term annual precipitation is summarised in /Johansson 2008/.

Numerical modelling results obtained with the HBV model /Johansson 2008/ and the MIKE SHE SDM-Site model /Bosson et al. 2008/ confirm the overall water balance presented above. The mean HBV-calculated actual evapotranspiration, based on data from the four discharge stations in the area, is 404 mm/year. The overall water balance from the MIKE SHE model is presented in Figure 4-18. The calculated water balance is based on modelling results for the period from September 1, 2003, to August 31, 2006; the numbers are presented in mm/year.

The precipitation for the three year period is 533 mm/year, the actual evapotranspiration 405 mm/year (calculated as the sum 122+169+28+56+30 of the various evapotranspiration components in the figure) and the runoff that leaves the model volume via the brooks in the area is 144 mm/year (74+70 in the figure). The total amount of water leaving the model area via the streams and direct runoff over the model boundaries is 152 mm/y (74+70+20–12). Figure 4-18 also shows that the storage changes (the Δ-terms in the figure) are relatively large. The reason for this is that the model period was preceded by a wet period and ended with a very dry summer.

Recharge and discharge patterns

In general, lakes, stream valleys and topographical low points function as discharge areas, whereas groundwater recharge occurs at higher elevations. The small-scale topography and the conductivity profile of the till create many small catchments with local and shallow groundwater flow systems, which overlie the larger-scale groundwater flow system in the bedrock. The shallow groundwater levels in the area cause a strong interaction between evaporation, soil moisture and groundwater. The annual variation in the groundwater level is mostly less than one metre in discharge areas and about 1.5 m in typical recharge areas. In Figure 4-19, the average daily groundwater levels for wells in till located in recharge and discharge areas are illustrated /Johansson 2008/.

Data from many groundwater wells in QD show that the diurnal fluctuation of the groundwater levels in the area is driven by the evapotranspiration cycle. Due to the interaction between the evapotranspiration and groundwater levels in the area, some lakes may act as recharge areas during the summer months. Otherwise, precipitation is the dominating source of groundwater recharge. A field classification of local geomorphology and groundwater recharge-discharge conditions in /Werner et al. 2007/ shows that the groundwater depths in typical recharge areas are more variable and in general larger than the groundwater depths in typical discharge areas. Also, the depth to the groundwater varies in areas considered as typical recharge areas, whereas the variation is small and the groundwater levels are close to ground surface in areas classified as typical discharge areas.

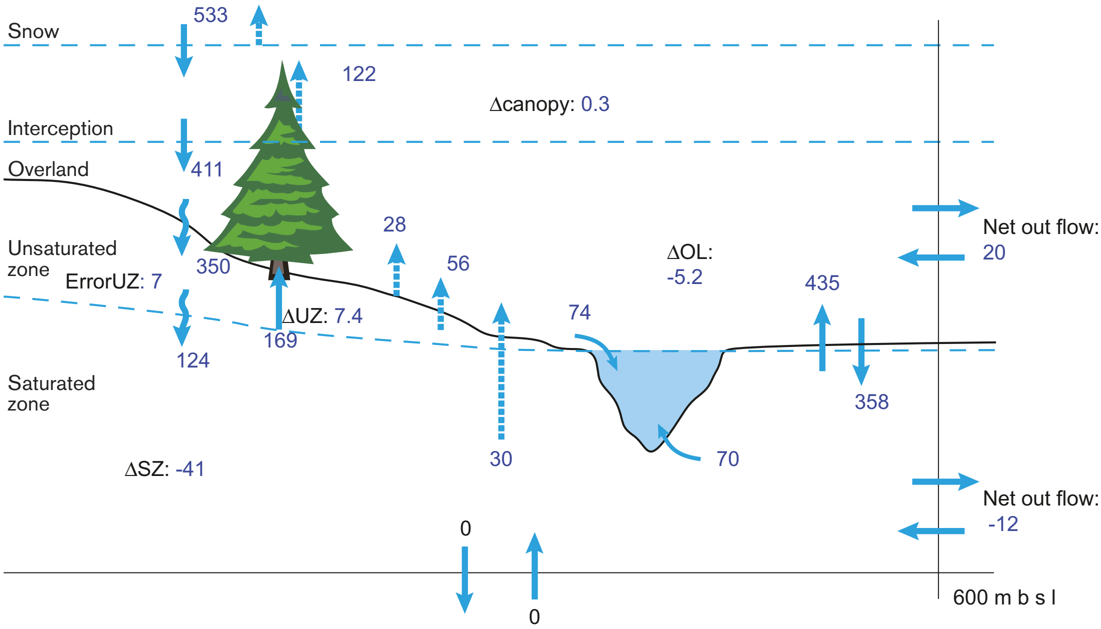


Figure 4-18. *Calculated water balance in mm/year, showing the annual values for the three-year period from September 1, 2003, to August 31, 2006 /Bosson et al. 2008/.*

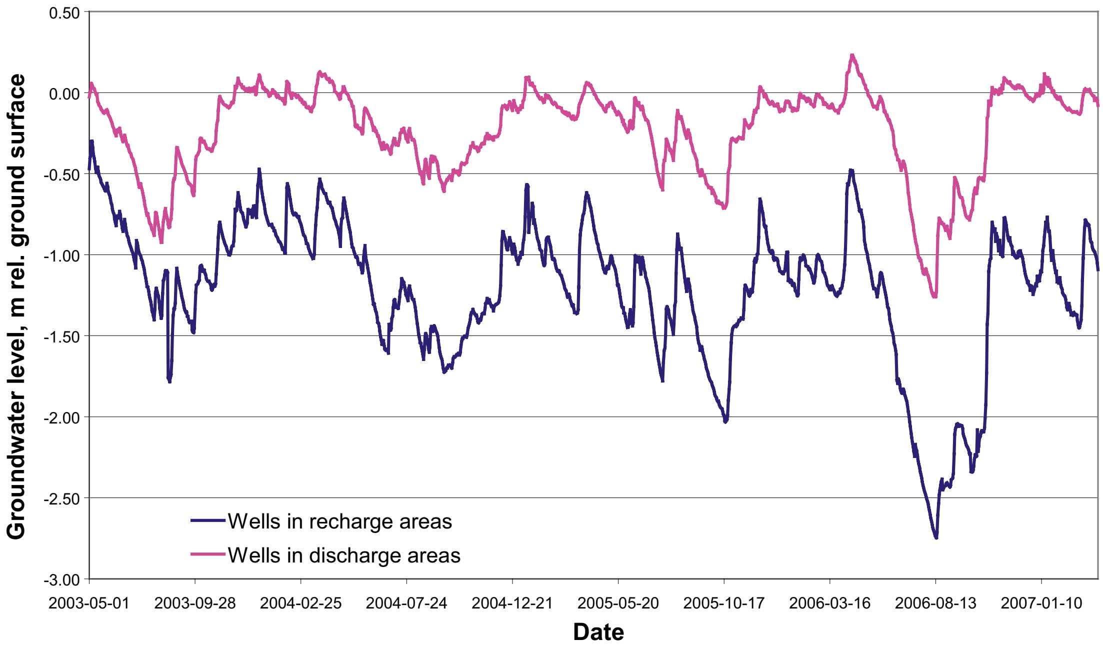


Figure 4-19. *Average daily groundwater levels in relation to ground surface in wells in recharge and discharge areas in till.*

During the site investigation, an extensive programme for chemical characterisation of different water types was conducted. /Tröjbom et al. 2007/ describes the chemistry of the surface water and the near-surface groundwater in the Forsmark area. The chemical composition of the water has been used to support the conceptual hydrological and hydrogeological models. Chemical signatures of deep groundwater were used to detect the influence of deep groundwater discharge in the near-surface groundwater. In general, the results support the conceptual model describing a very shallow groundwater flow system in the QD. However, the high chloride concentrations found below Lake Bolundsfjärden, Lake Gällsboträsket and Lake Fiskarfjärden, together with the isotopic composition of the water, indicate very low flow rates, and that the leakage from the lake water through the bottom sediments is very low.

The pattern of a small-scale groundwater flow system with many local recharge and discharge areas in QD is also shown in the results from the numerical modelling with MIKE SHE /Bosson et al. 2008/. The sea, stream valleys and lakes in the model area are areas of upward flow both in the QD and in the bedrock. Due to the effects of the local topography, the pattern of recharge and discharge areas in the QD is more diffuse than the flow pattern in the rock. In /Bosson et al. 2008/, the recharge and discharge areas are defined as the head difference between two neighbouring calculation layers, areas with an upward gradient are defined as discharge areas and areas with a downward gradient are defined as recharge areas.

The flat topography and the shallow groundwater table in the area imply that the pattern of recharge and discharge areas varies during the year. Results from the numerical modelling show that the spatial extent of the discharge areas in QD increases by almost 45% under dry conditions /Bosson et al. 2008/. The brooks are considered as permanent discharge areas although they are dry during parts of the year. The wetlands, which are frequent in the Forsmark area, can either be in contact with the groundwater zone and constitute typical discharge areas or be separate hydrological systems with low permeable bottom sediments with little or no contact with the underlying aquifer /Johansson 2008/.

4.3.4 Processes driving succession

This section summarises the processes driving the succession of the landscape and how they are implemented in the numerical models. It is assumed that only natural processes influence the new land areas, i.e. anthropogenic influences in new land areas have not been taken into consideration. Changes in hydraulic properties in the QD due to soil forming processes have been neglected, also the hydraulic properties of the bedrock are assumed to be constant in time. The model describing the present bedrock hydraulic properties is used in all representations of future bedrock conditions, and the properties for each QD-type under present conditions have been applied to each QD-type in the models describing the future. The main processes described in this section are:

- shoreline displacement,
- development of Quaternary deposits,
- development of land-use,
- development of the surface water system,
- climate.

Shoreline displacement

The shoreline displacement is crucial when simulating future hydrological conditions. Today the land is rising at approximately 6 mm per year relative to the mean sea water level. The shoreline equation reported in /Brydsten and Strömgren 2010/ has been applied to the hydrological models. Three different shorelines have been studied: 2000 AD, 5000 AD and 10,000 AD. The corresponding shoreline elevations are at –0.17 m.a.s.l. –14.96 m.a.s.l. and –31.42 m.a.s.l. (Figure 4-20).

To describe the shoreline displacement in the numerical modelling, the sea level has been lowered to the level of the shoreline at each time period. In the hydrological modelling, no time period when the shoreline is above the present level has been studied; all the studied time periods have a sea level below the present one. The shoreline displacement causes a development of the landscape in the area. In particular, it influences the succession of lakes and wetlands, the vegetation cover and the QD.

Development of Quaternary geology and vegetation

The spatial distribution and the stratigraphy of the QD change when the land is rising. Erosion and sedimentation processes result in a redistribution of the QD in the area. The QD map representing the spatial distribution of the future QD has been divided into the following groups: postglacial clay, glacial clay, thin postglacial clay, till and bedrock. In the numerical hydrological modelling, the QD maps at 5000 AD and 10,000 AD provided in /Brydsten and Strömgren 2010/ have been used as input. For a detailed description of the modelling of future QD-layers the reader is referred to /Brydsten and Strömgren 2010/.

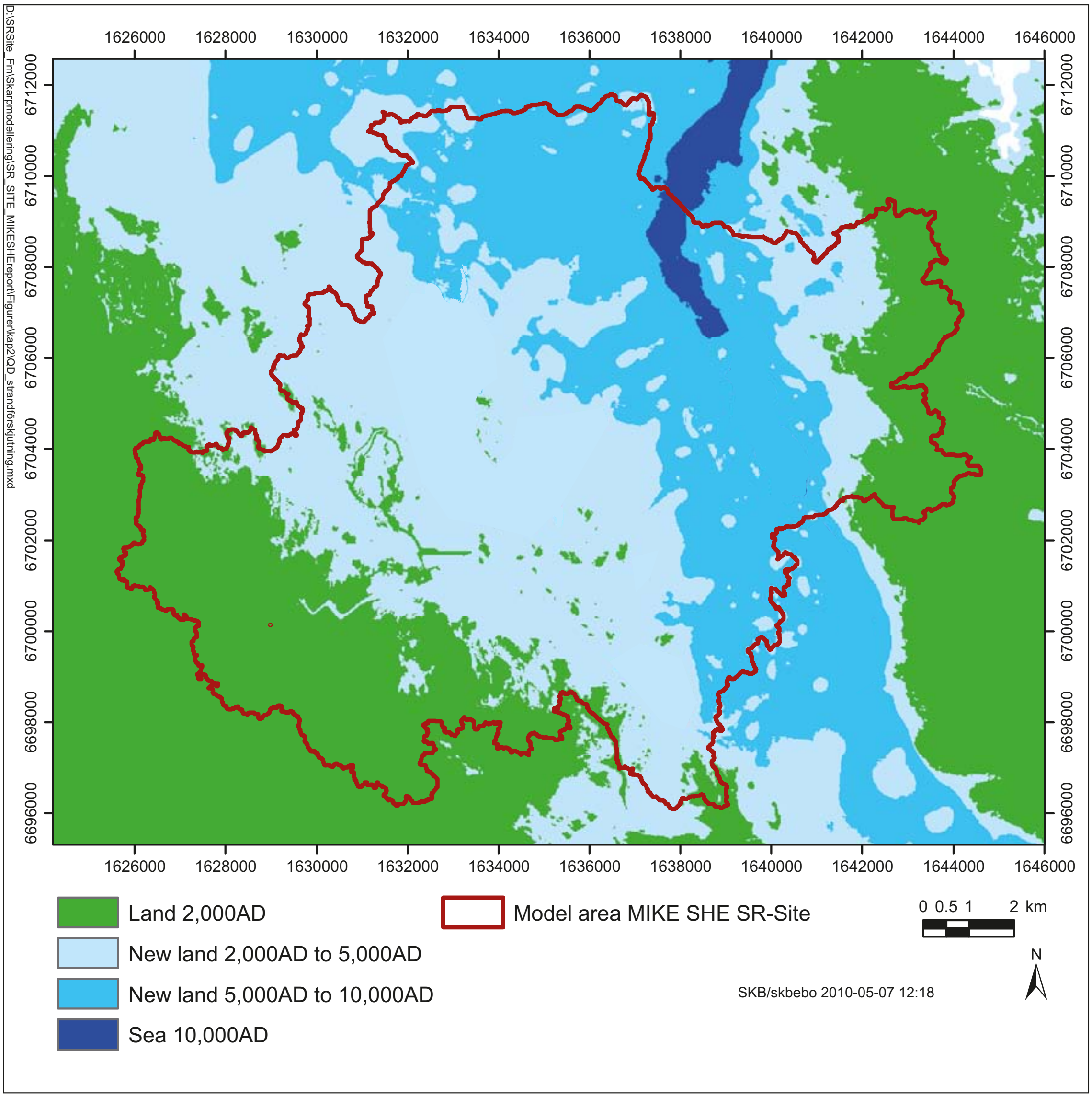


Figure 4-20. *The location of the shoreline at 2000 AD, 5000 AD and 10,000 AD, as applied in the MIKE SHE model.*

By analysing the present distribution of vegetation on the different QD categories, the dominating vegetation on the present QD category was assigned to the corresponding future QD category. Vegetation maps have been constructed for each time period by using the QD map for that specific time period as input. The vegetation type assigned to each future QD is listed in Table 4-4. A detailed description of future vegetation and the vegetation under different climate conditions is found in /Löfgren 2010/.

In the numerical hydrological modelling, it is assumed that future vegetation types have the same properties as the present ones. The leaf area index (LAI) and the root zone depth have been characterised according to the present conditions. Detailed information about the vegetation distribution and the vegetation properties used in the numerical modelling is found in /Bosson et al. 2008/ and /Bosson et al. 2010/.

Table 4-4. The future Quaternary deposits and the associated resulting vegetation types in the future vegetation map.

Future QD	Resulting vegetation type
Post glacial clay	Arable land
Glacial clay	Arable land
Thin postglacial clay	Wetland
Till	Neddle-leaved forest
Bedrock	Scots pine-dominated forest

Development of the surface water system

The future lake and surface water system has been modelled by using the digital elevation models for each time period and the GIS-hydrology extension /Brydsten and Strömgren 2010/. The stream network is created by searching for the points with the largest numbers of upstream cells. In the numerical modelling, it is assumed that the shape of the streams is fixed in time, i.e. no sedimentation or erosion processes are taken into account. The stream channels are assumed to be 2 m wide and 1 metre deep, except in areas downstream the point where the present rivers Forsmarksån and Olandsån are connecting to each other. All streams downstream this point have a width of 8 m and a depth of 1 m. Due to land rise and sedimentation processes, some lakes turn into wetlands. It is assumed that there is always a small stream flowing through the terrestrialised lake. In the MIKE SHE models, the streams follow the deepest trench of the former lake.

Future catchment areas and lakes have been calculated by using ArcGIS. The digital elevation model for each time period has been used as input and the different catchment areas are delineated with the ArcGIS hydrology extension. Due to erosion and sedimentation processes, future lake thresholds are difficult to determine and thus this is an uncertainty in the calculation of future catchment areas and lakes.

Development of climate

Different climatic conditions affect the hydrology at the site. The climate is the driving force in the hydrological system and the climate conditions have an influence on the water balance, the vegetation, the hydraulic properties and the water flow paths in the area. Within the numerical modelling, two climate cases have been studied: a cold climate with permafrost conditions and a warm climate with a high precipitation. A permafrost layer affects the water balance and water flow paths in the area, since the ground is frozen and the hydraulic conductivity in both the QD and the bedrock is strongly reduced. A wet and warm climate was studied to evaluate the effects on the water balance and water flow paths of a long period of high precipitation.

The climate conditions in Sweden in a 100,000-year perspective are described in /Kjellström et al. 2009/. Climate data from this report has been used when defining the different climate cases in the numerical modelling. The mean annual precipitation for the period describing wet and warm climate is approximately 1,280 mm/year, compared to approximately 560 mm/year at present. The annual precipitation for the case describing a cold climate under permafrost conditions is 411 mm/year.

4.3.5 Modelling of future hydrological conditions

In this section, the numerical modelling performed with the modelling tool MIKE SHE within the SR-Site modelling is described. Input data, simulation cases and the modelling results are presented and discussed. For a detailed description of input data, methodology, model domains and grids, different simulation cases, and model results, the reader is referred to /Bosson et al. 2010/.

Brief description of numerical models

Three different models were defined, a regional model covering the main part of the Forsmark regional model area situated on land, and two local models within the regional model area. The regional model covers an area of 180 km^2 and the local models (referred to as model A and model B) have an area of approximately 15 km^2 each (Figure 4-21). The calibrated SDM-Site MIKE SHE model /Bosson et al.

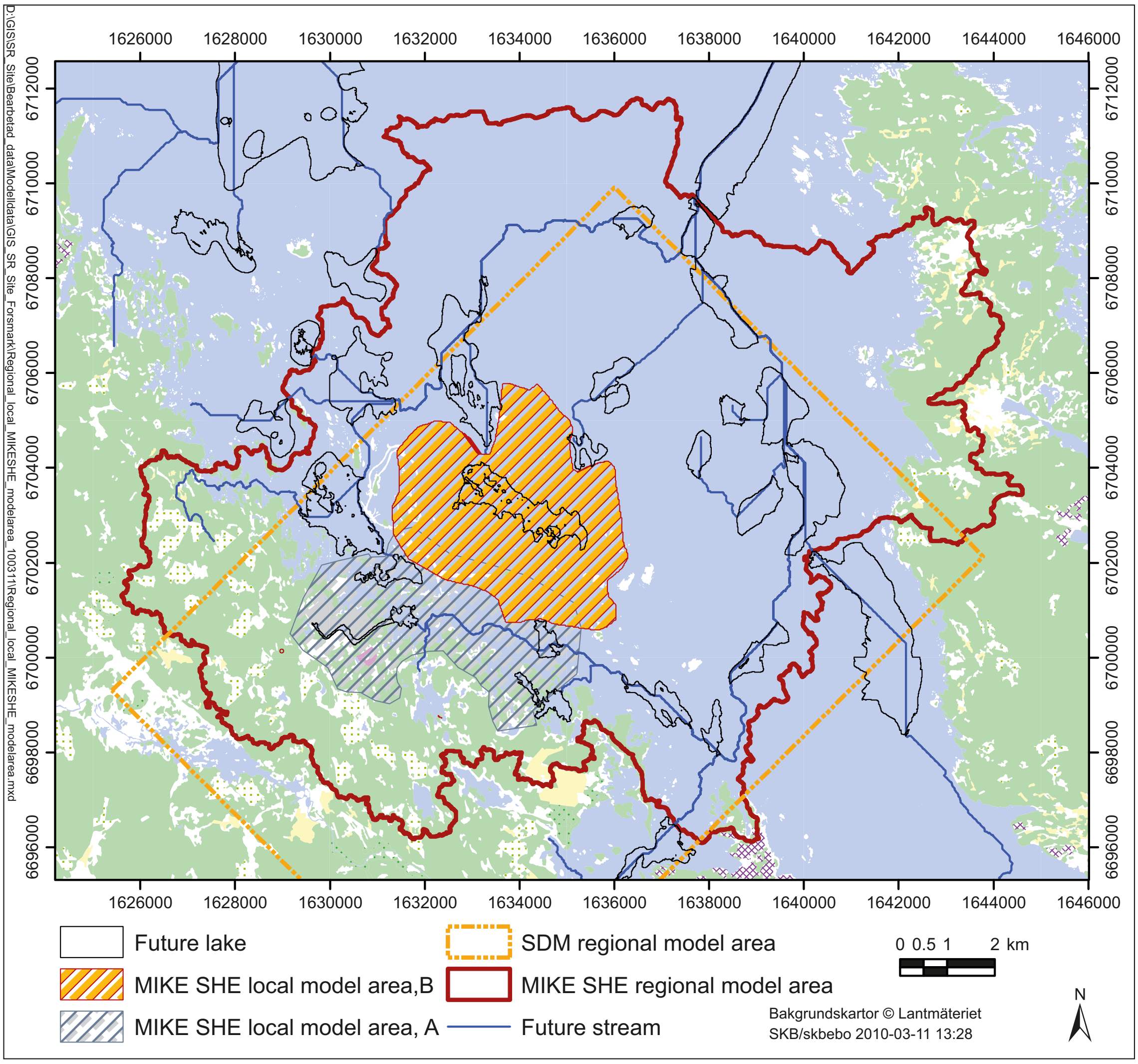


__Figure 4-21.__ The regional and local MIKE SHE model areas /Bosson et al. 2010/. In the figure, the SDM regional model area and the future lakes and streams are also marked.

2008/ was used as a starting point when setting up the SR-Site MIKE SHE models. The properties of the QD from the SDM-modelling have been used directly and no further sensitivity analyses relating to the hydraulic properties have been performed within the SR-Site modelling. Different time periods and climate conditions have been simulated with the regional model. Specifically, a selected year with a normal temperate climate, defined from present long-term weather conditions, a wet temperate climate, and a cold climate with permafrost conditions have been simulated /Bosson et al. 2010/.

The simulations performed with the local models have been applied to the model describing the shoreline, QD model and vegetation cover at 10,000 AD. In Table 4-5, all the different simulation cases are listed, both for the regional and the local MIKE SHE models. In the presentation of results, each model case is named after the time defining the shoreline position and the applied QD model. For example, the simulation case 10000AD_10000QD denotes the MIKE SHE model with the shoreline of 10,000 AD and the QD model representing the conditions at 10,000 AD, whereas 10000AD_2000QD is the model with the 10,000 AD shoreline and the QD model describing present conditions.

The grid resolution of the regional model is 80·80 m and the grid resolution of the local models is 20·20 m. Also the vertical resolution is finer in the local models. The main purpose of the local models was to perform transport calculations. Flow modelling and particle tracking results from the regional model are presented in this section, whereas the results from the local models are presented in Chapter 6.

When simulating future conditions in MIKE SHE, the shoreline, the QD model and the vegetation cover change between the different simulated time periods. The sea has been lowered to the level at that specific time. The periglacial hydrology has been simulated with the model describing the conditions at 10,000 AD as a starting point. Different permafrost depths and associated different numbers and locations of through taliks have been implemented in the model. In addition to the climate input data, the hydraulic properties, both of the unsaturated and saturated zones and those of the surface water system, have been changed in order to describe a permafrost landscape.

The uppermost part of the model is an active layer where the ground surface is affected by meteorological processes and the layer has a frozen, a thawing, an active and a freezing period each year. This means that the hydraulic properties in the active layer are changed during the year. In the permafrost layer, the ground is continuously frozen and the hydraulic conductivities are low to imitate a frozen ground with a high flow resistance. A number of through taliks (Chapter 3) have been defined within the model area. The presence of taliks depends on the prevailing temperature, the presence and properties of lakes and streams as well as on other surface conditions (e.g. vegetation and snow cover).

When modelling wet temperate conditions, no changes in the methodology or the numerical grid were made compared to the normal temperate case; only the meteorological input data were changed. The meteorological data for the wet temperate case are based on data for a wet period of 50 years presented in /Kjellström et al. 2009/.

Results from regional model with temperate climate

Water balance

The water balances of the different simulation cases listed in Table 4-5 have been evaluated for different areas depending on the time being simulated. For all cases, the areas constituting land at the studied time (2000 AD, 5000 AD, 10,000 AD) were studied. Also the water balance of the area constituting land at 2000 AD was studied in all cases to see how the present land area is affected by the shoreline displacement and development of the vegetation and QD-layers. The water balances of the catchment areas of Lake Bolundsfjärden and a future lake outside the present shoreline (referred to as object 116 in the landscape modelling) were evaluated separately to analyse how the water balance of a delineated catchment area is affected by the shoreline displacement and the QD and vegetation development.

Table 4-5. Simulation cases for the MIKE SHE SR-Site modelling. The table also gives information about the QD-model and climate applied in each simulation case.

		QD-model			Transport modelling	
Shore level	**Climate**	**QD_2000**	**QD_5000**	**QD_10000**	**AD****	**PT****
Regional model						
2000 AD	SDM-data*	X				
10,000 AD	Temperate	X		X		X
5000 AD	Temperate	X	X			X
2000 AD	Temperate	X				X
10,000 AD	Periglacial			X		X
10,000 AD	Wet			X		
Local model						
10,000 AD	Temperate			X	X	X

*The same climate data series and simulation period as in the SDM-Site MIKE SHE modelling. This simulation was performed to analyse the results in order to compare measured and simulated groundwater levels and heads and surface water discharges and levels.

**AD = Advection-dispersion, PT = Particle tracking

Studying the water balance for the five models for the area constituting land at 2000 AD there are small changes in evaporation and runoff, less than 10%. The calculated mean annual runoff is approximately 180 mm/year in all cases and the total evapotranspiration is c. 400 mm/year. The annual precipitation is 583 mm/year for all cases since the same meteorological input data is used in all the models. The main changes in the future water balances for the area constituting land today, relative to present conditions, are illustrated and described in Figure 4-22. The largest changes in the flow between different model compartments occur when changing the QD model.

Also when studying the area constituting land at each time period the changes between the total calculated runoff and evapotranspiration are small. Different vegetation covers, lake percentages and properties of the unsaturated zone in the areas result in a varying interception, transpiration and evaporation from overland waters, but the variation of the total calculated evapotranspiration is less than 10% for all the cases. The water balances for the areas constituting land at each time period are shown in /Bosson et al. 2010/.

Groundwater table

The groundwater table in the Forsmark area is very shallow under present conditions. In the major part of the model area the depth to the groundwater table is less than 1 m. Within the present land area, there is a slight increase of the depth to the groundwater table for all simulation cases compared to the 2000AD_2000QD model. This is due to the more distant shoreline in the models describing future conditions.

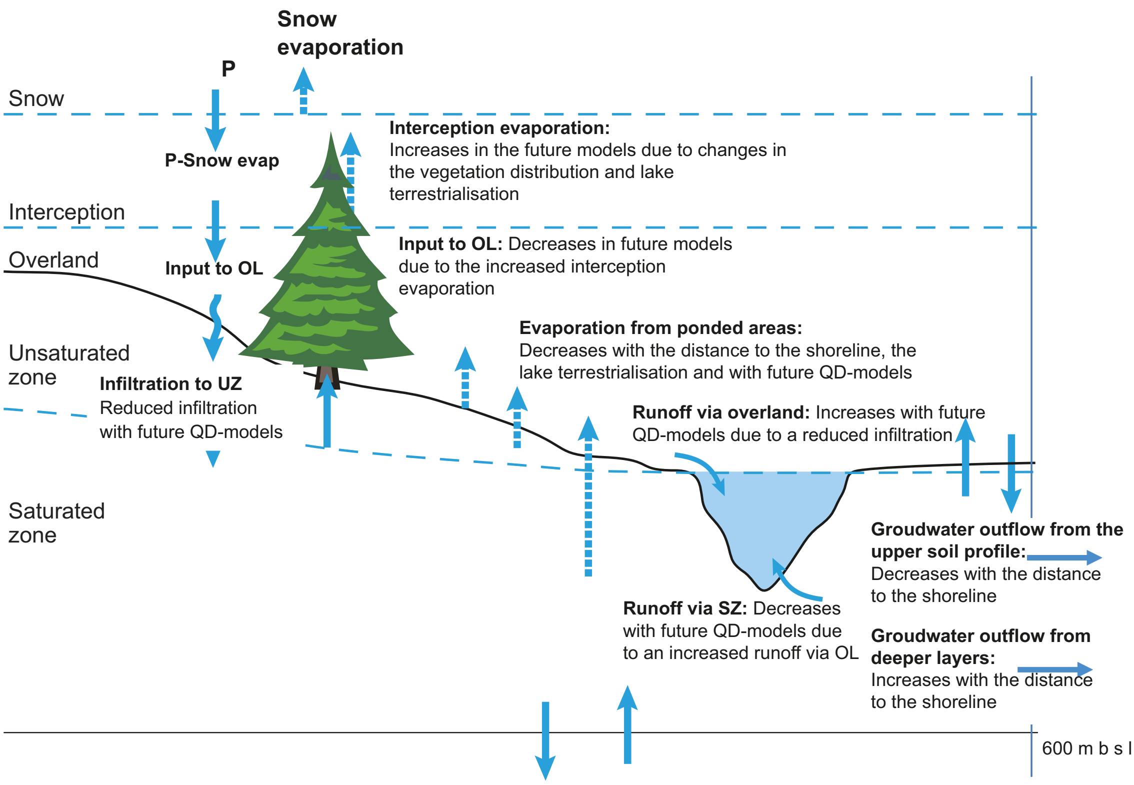


***Figure 4-22.** Main changes in the water balances relative the water balance from the 2000AD_2000QD-model. The comparisons with the future models are made for the area constituting land at 2000 AD.*

Recharge and discharge areas

The model results indicate that, as expected, lakes and stream valleys are discharge areas and the high altitude areas are recharge areas independent of the studied time period. The distribution of recharge and discharge areas changes somewhat with the shoreline displacement, but the overall patterns are the same for all shorelines positions and QD models. The mean situation, as evaluated from the 10000AD_10000QD model, is presented in Figure 4-23. The figure shows the head difference between layer 1 and 2, i.e. the local recharge and discharge areas in the Quaternary deposits.

The scattered pattern of recharge and discharge areas in the QD, governed by the local topography, seems to predominate independently of the shoreline displacement. The majority of the terrestrialised lakes in the future models still act as discharge areas even if the lake itself has dried out. A comparison with a similar representation of results for the upper part of the bedrock (not shown) indicates that the sea, stream valleys and lakes in the model area are discharge areas both in the QD and in the upper bedrock. In the bedrock, the discharge areas are concentrated to the areas close to and under the lakes. Also, the depressions around the streams are reflected as discharge areas in the bedrock.

In all model cases, Lake Bolundsfjärden deviates from the other lakes. The mean situation during the year in the QD-layers of the 2000QD_2000AD-model is that the lake acts as a discharge area. However, during summer periods the lake may act as recharge area due to the transpiration of the plants in the catchment area /Johansson 2008, Bosson et al. 2008/. In the upper bedrock, some parts of the area under the lake have a downward hydraulic gradient. The sheet joints in the upper rock appear to short-circuit the vertical flow, and water is transported towards the sea.

Figures 4-24 and 4-25 illustrate particle tracking and head profile results from the 2000AD_2000QD and 10000AD_10000QD-models. One particle was released in each cell at –150 m.a.s.l. Figure 4-24 shows the flow paths of the particles released under Lake Bolundsfjärden. In the 2000AD_2000QD model the majority of the particles move up towards the south-eastern shoreline of the lake. Some particles cross the sheet joints and move towards the sea and some are moving downwards. The simulation was run for 1,000 years; many of the particles have not reached the surface at the end of the simulation.

Studying the head profile in Figure 4-25, which shows the upper 50 m of the model, it is seen that the main flow direction is towards the lake. Furthermore, the horizontal view shows that the main part of the lake has an upward gradient both in QD and in the bedrock. In the 10000AD_10000QD model, only a few particles move towards the former lake. The rest of the particles are transported in the sheet joints towards the sea and end up in the future lakes further north in the model. The head profile of the upper 50 m of the former lake area shows that most of the area has a downward gradient.

Results from regional models with wet temperate or cold climates

The water balance for the wet temperate climate is shown in Figure 4-26. The figure illustrates the water balance for the area constituting land at 2000 AD. The precipitation is 1,568 mm/year and the potential evapotranspiration (PET) is 1,784 mm/year. This means that the precipitation is three times the precipitation applied in the cases simulating normal temperate conditions. The actual evapotranspiration is calculated to 1,223 mm/year, whereas the runoff is 360 mm/year. The distribution of the precipitated water is approximately 20% runoff and 80% evapotranspiration, which could be compared to 30% runoff and 70% evapotranspiration for normal temperate conditions. There is a large increase in the transpiration from plants; the total transpiration from plants under wet conditions is 572 mm/year (475+97), as compared to 182 mm/year (142+40) for the temperate climate.

Studying the water balance for the permafrost simulation (Figure 4-27), it is seen that the results deviate from the other simulations. The distribution of the precipitated water is almost 50% evapotranspiration and 50% runoff. The decreased evapotranspiration is due to a much lower transpiration from plants. The plants themselves have a lower water demand, but the results are also affected by the fact that the period when the water uptake is active is very short due to the cold climate. However, the runoff to the river system is almost the same as for the wet temperate conditions. Since the ground is frozen most of the year, the infiltration capacity of the soil is lower than for temperate weather conditions. This means that both the infiltration and percolation of water to the saturated zone is lower. A detailed description of the water balances for the different periods of the year is given in /Bosson et al. 2010/.

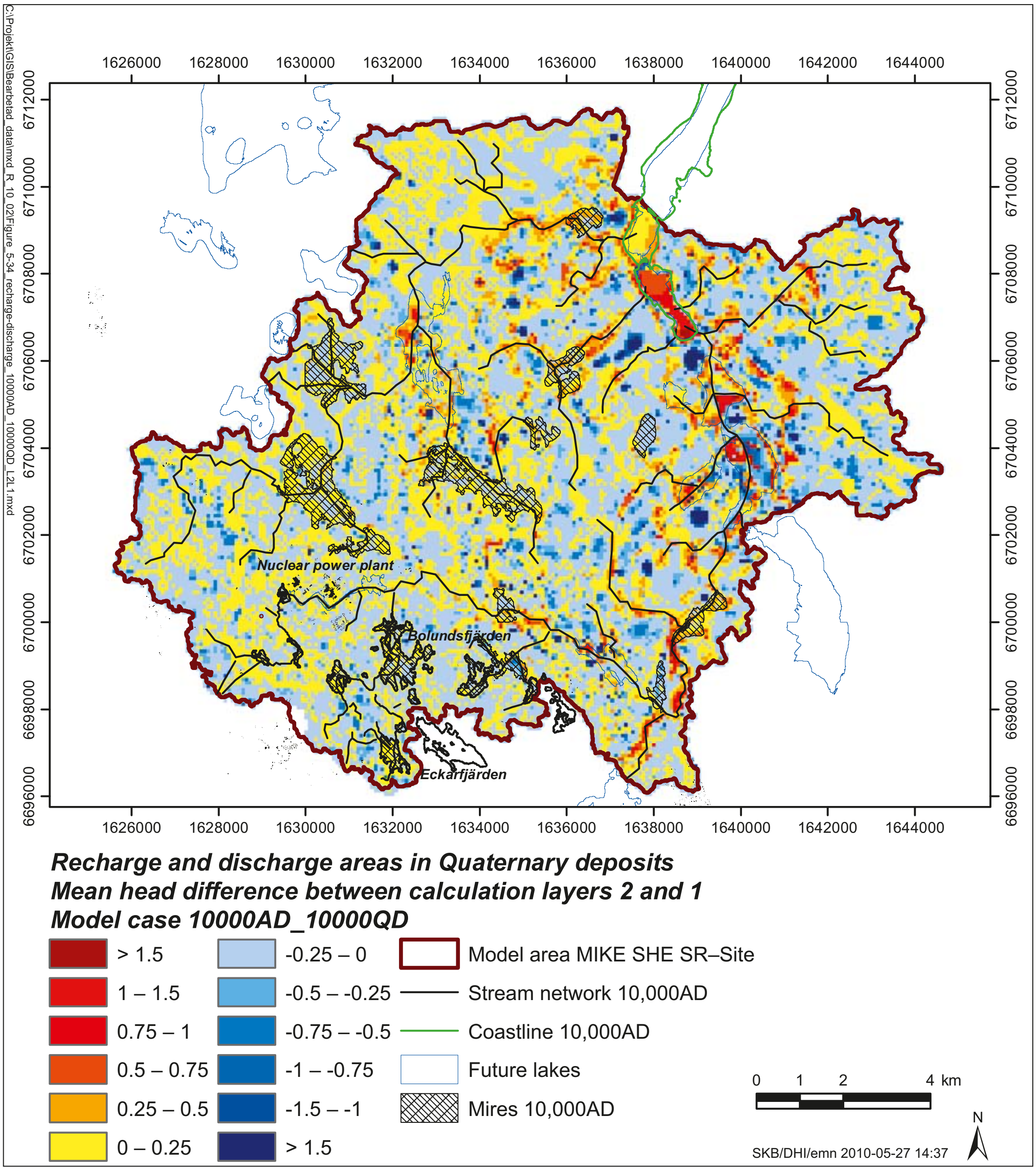


Figure 4-23. *The recharge (negative values) and discharge (positive values) areas in the Quaternary deposits from the 10000AD_10000QD-model, calculated as the head difference between the two QD-layers of the model.*

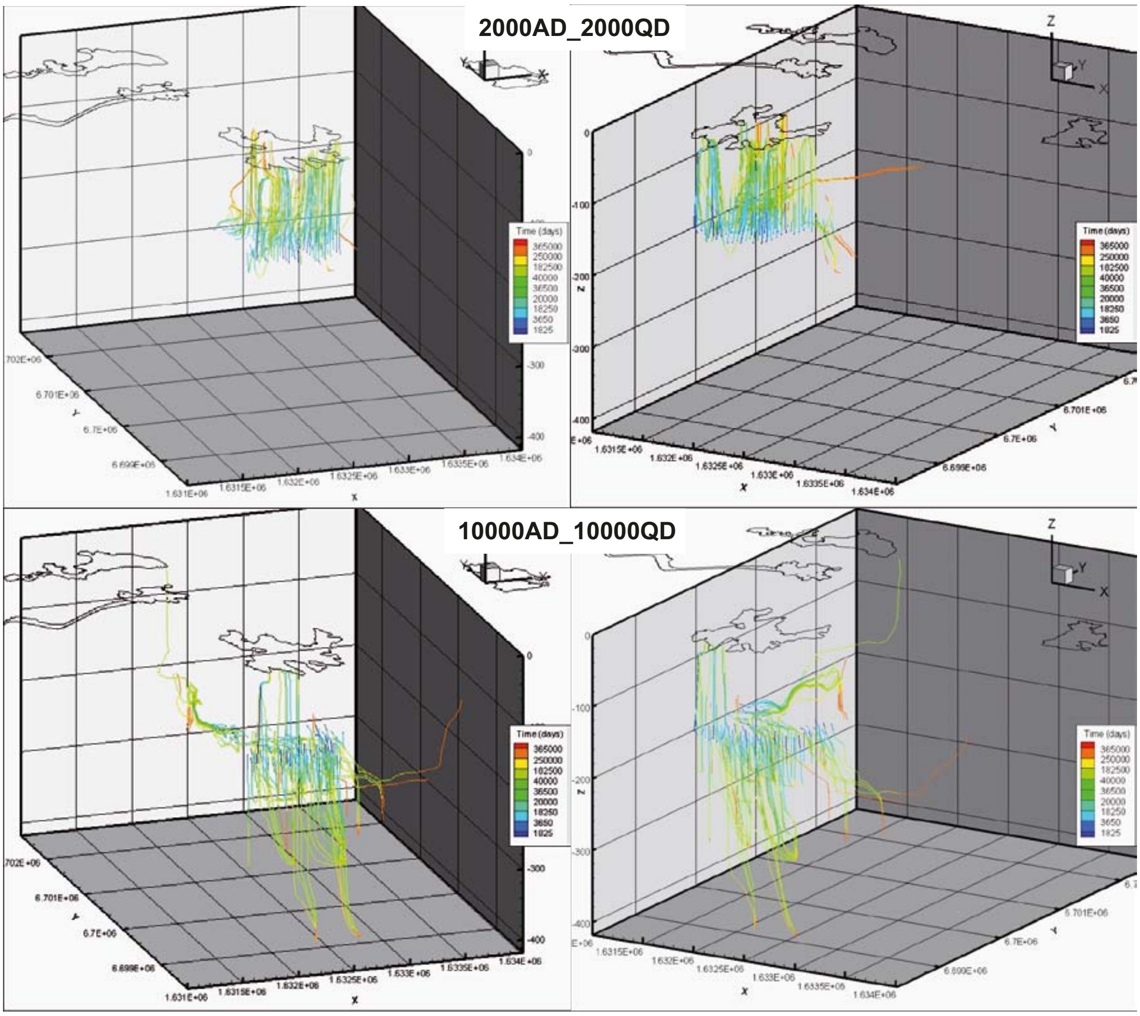


Figure 4-24. *Flow paths traced by particles (colours indicate cumulative travel times), one particle released in each cell at 150 m.b.s.l. Only particles released under Lake Bolundsfjärden are shown. The upper two figures are from the 2000AD_2000QD-model and the two lower figures from the 10000AD_10000QD-model. Two different views are shown for each time period. Lake Bolundsfjärden, the inlet canal and some future lakes are shown as orientation.*

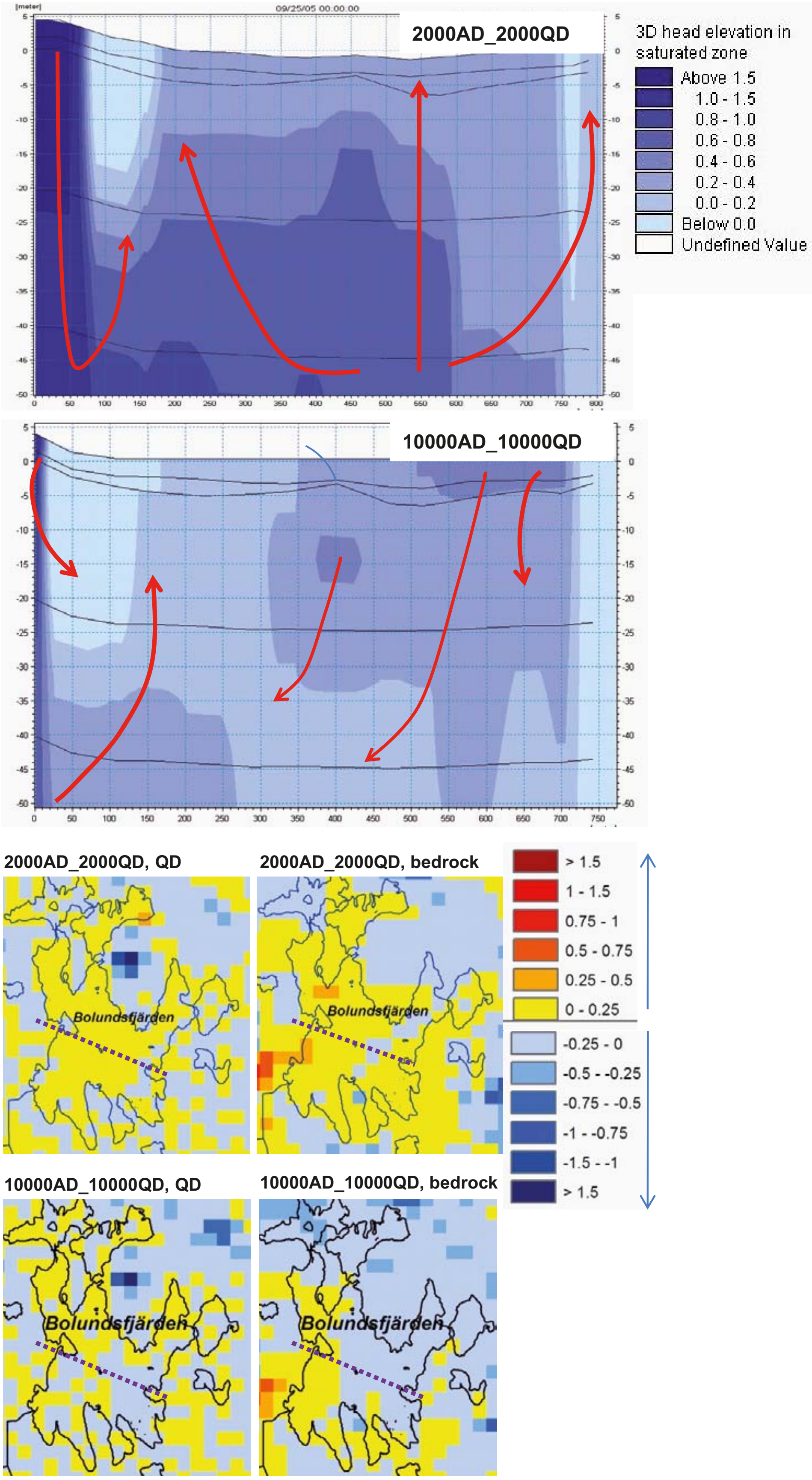


Figure 4-25. *Head profiles in upper 50 m of the models. The upper profile shows results from the 2000AD_2000QD model and the lower one results from the 10000AD_10000QD model. Also, the head differences in QD and the upper bedrock are shown in horizontal views. The location of the profile is shown as a purple dotted line.*

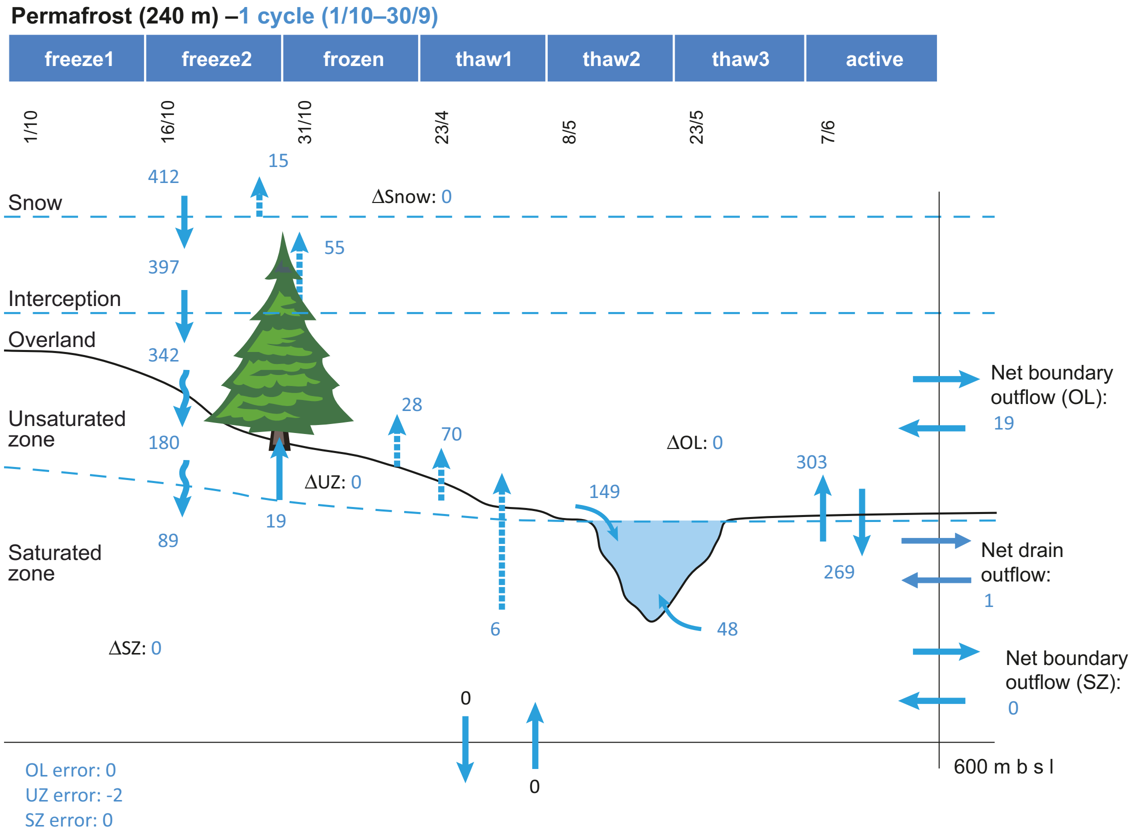


Figure 4-26. *Water balance from the simulation with a wet climate; the water balance is calculated for the area constituting land at 2000 AD.*

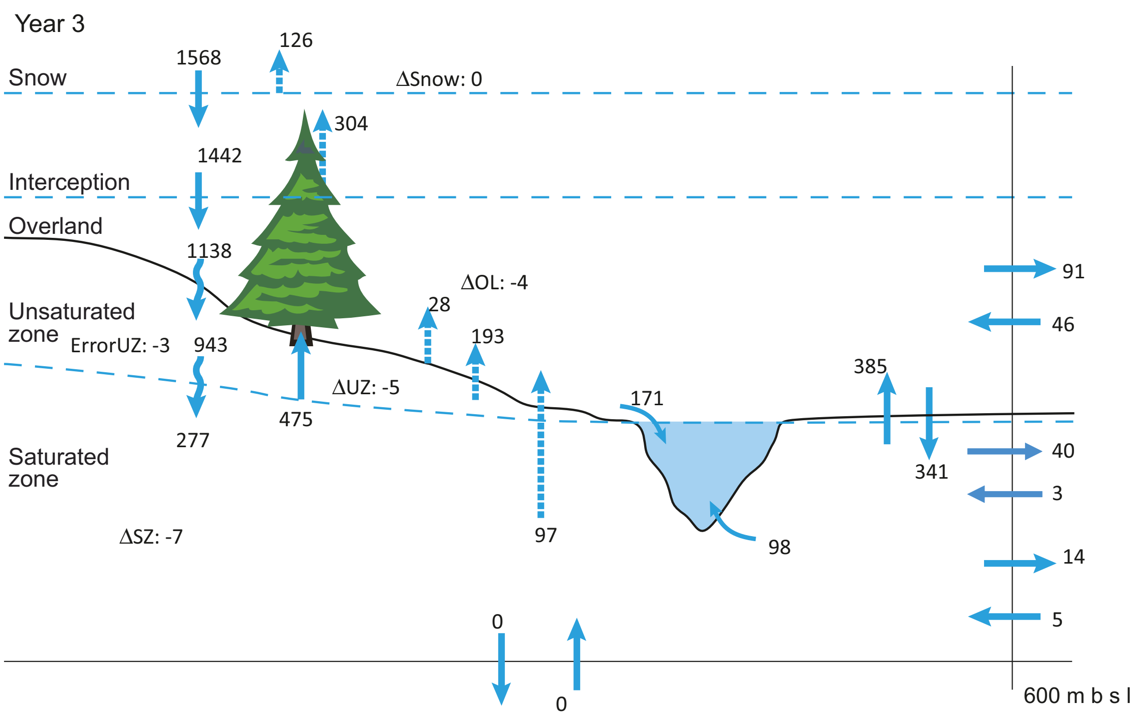


Figure 4-27. *Water balance from the simulation with a cold climate under permafrost conditions; the water balance is calculated for the area constituting land at 10,000 AD.*

When studying the recharge and discharge areas under permafrost conditions, there is a distinct difference in the flow patterns compared with the results from the simulations with temperate climates. For the periglacial system, simulations were performed with two different thicknesses of the permafrost layer, 100 m and 240 m. Figure 4-28 shows the taliks in these two systems. There is a much larger number of taliks in the system with thinner permafrost. All the discharge areas are concentrated to the taliks. Some taliks acts as recharge areas, but the majority are discharge areas.

The recharge and discharge patterns during permafrost conditions are illustrated by particle tracking results in Figure 4-29 and Figure 4-30. Results are shown for the simulation with a 240 m thick layer of permafrost, which has seven taliks within the model area (Figure 4-28). Two different types of particle tracking simulations were performed, one with particle release in the active layer (i.e. the top layer) and one with particle release in the layer just below the permafrost. Figure 4-29 illustrates the flow paths of the particles moving between taliks. There is downward transport in some parts of taliks 7, 6, 5 and 3. Particles travel from talik 7 down through the permafrost, and are then transported horizontally under the permafrost until they reach a discharge area where they are transported upwards (in talik number 6). Similar transport paths can be seen from talik 6 to 4, from 5 to 2 and from 3 to 2.

When particles are introduced in the layer below the permafrost, almost all the particles move towards the taliks. There is horizontal transport in the unfrozen bedrock towards the taliks and when the particles reach the taliks there is a strong upward gradient transporting them up towards the ground surface. The main upward transport is found in taliks 1, 2, 4 and 6. The other taliks act as recharge areas.

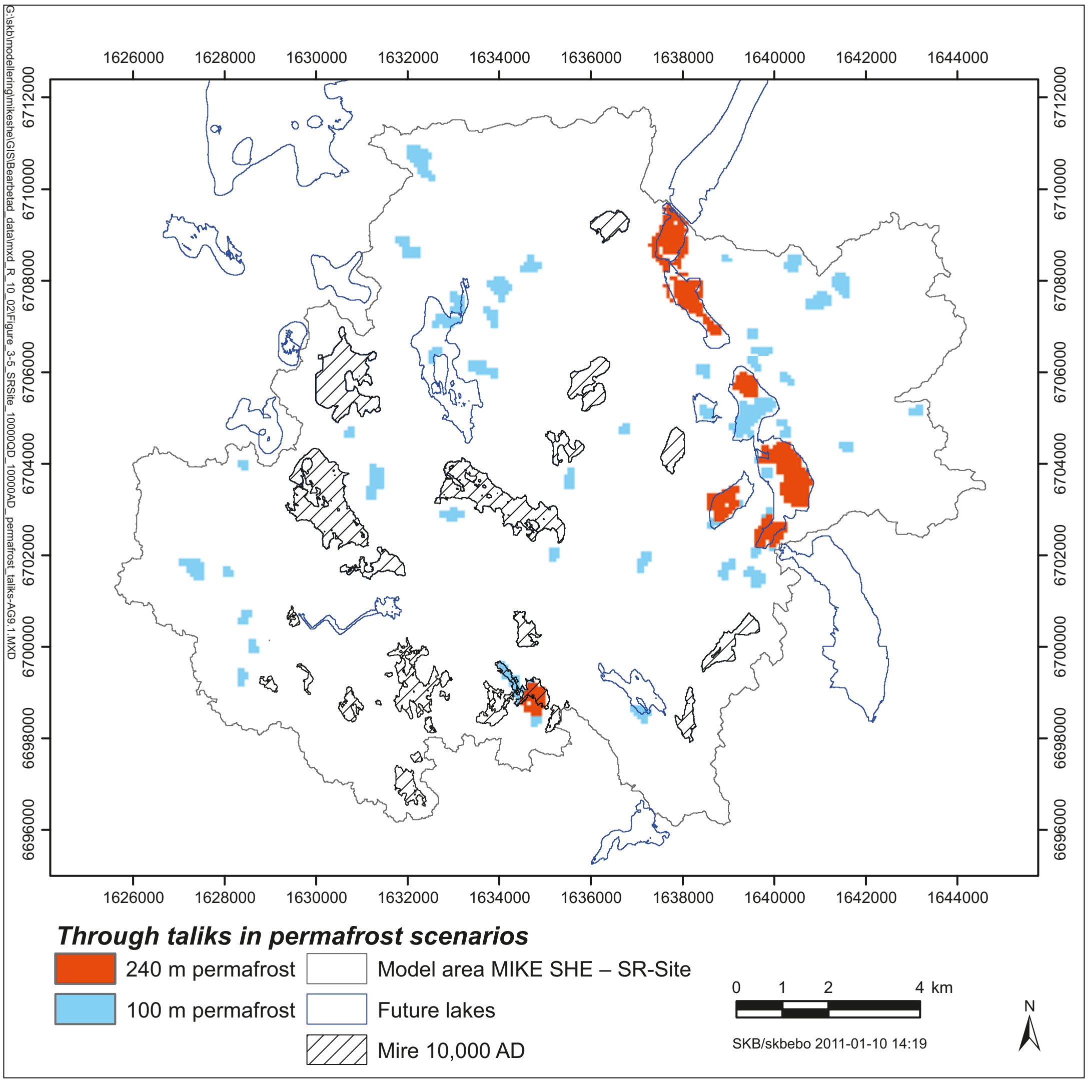


Figure 4-28. *Locations of taliks for two different permafrost depths, 240 m and 100 m, in the modelled periglacial systems at Forsmark.*

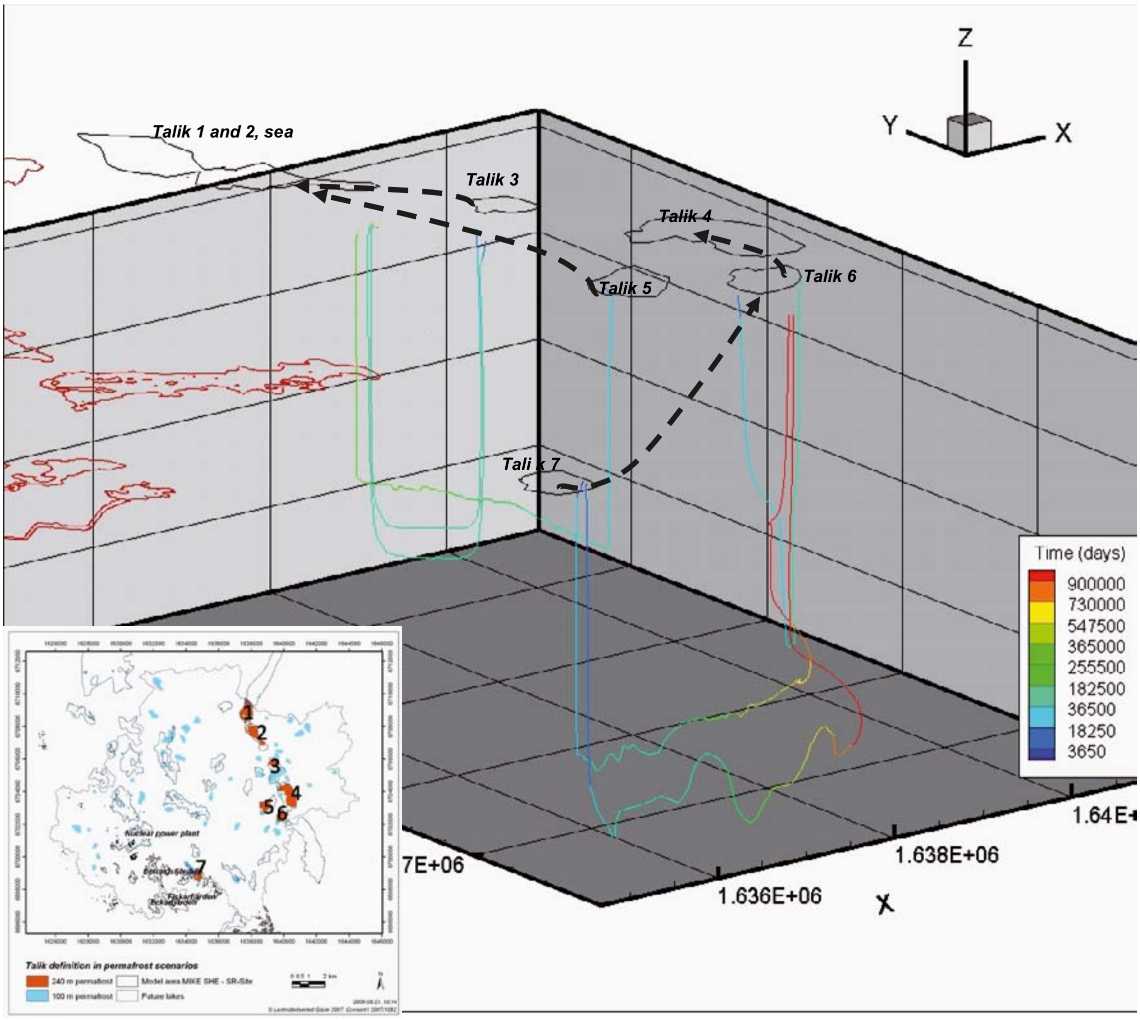


***Figure 4-29.** Transport between different taliks. Particles are introduced in the active (top) layer, and the transport from one talik to another is illustrated in the figure. Colours indicate cumulative travel times.*

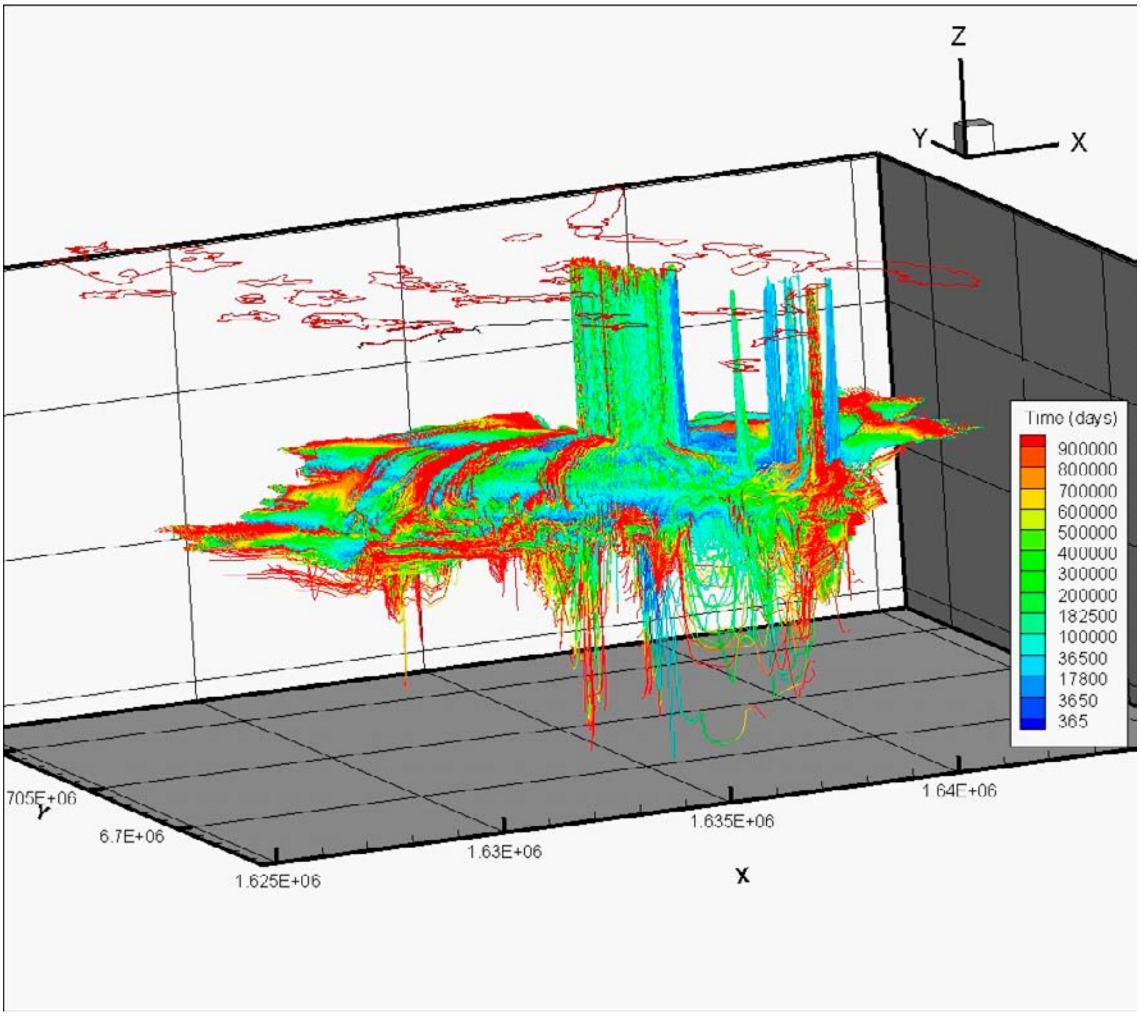


Figure 4-30. *Particle flow paths from a permafrost simulation. Particles are released in the layer below the permafrost at 240 m depth. Colours indicate cumulative travel times.*

4.3.6 Discussion and conclusions

The landscape succession in a hydrological perspective has been analysed by studying the effects of shoreline displacement, development of the QD-layers and the vegetation cover, and the effects of different climates. Present conditions regarding meteorological conditions, surface water levels and discharges, groundwater levels in QD and bedrock, and locations of recharge and discharge areas have been studied during the site investigations at Forsmark. Site investigation data have been used when calibrating and testing the numerical models describing the present hydrological situation at the Forsmark site. By using the knowledge gained during the site investigations, possible future hydrological situations have been described. The present calibrated and tested models have been used as a basis for modelling future conditions.

The present water balance in the area, as estimated from long-term regional measurements and local measurements at the site and also calculated in the numerical modelling, with a precipitation of approximately 560 mm/year, an actual evapotranspiration of c. 400–410 mm/year and a runoff of 150–160 mm/year, seems to change very little with time. The water balances calculated in the numerical modelling with future shorelines do not differ significantly from the measured or calculated water balances for present conditions. The largest change in the internal flows within the temperate period system appears when changing the QD model as the land is rising, thereby including both the effects of the shoreline displacement and the development of the QD-layers. Still, the changes in the amount of water infiltrating the soil in the different studied temperate cases are less than 10% and the internal distribution of the precipitated water is approximately 70% evapotranspiration and 30% runoff independently of the applied QD model.

When applying a wet temperate climate to the model, the internal distribution of the precipitated water changes somewhat. For a wet climate the run-off is approximately 20% of the applied precipitation and the evapotranspiration is 80%. Due to the high evapotranspiration, the runoff during a wet climate is relatively lower than for normal temperate climate conditions. However, there is an absolute increase in the yearly runoff from c. 180 mm to c. 360 mm. The transpiration increases from approximately 145 mm/year for a normal temperate climate to approximately 475 mm/year under wet conditions. However, in both cases the transpiration is about 40% of the precipitation.

The largest change in the overall water balance is found for permanent cold conditions with a permafrost layer affecting the flow conditions. The internal distribution of the precipitated water is then 50% runoff and 50% evapotranspiration. The water demand from the vegetation is very low, due to a poor vegetation cover but also because the active period is short. Even during the active period the temperature is quite low, which means there is no driving force for effective evapotranspiration. The yearly precipitation in the simulation of cold conditions is somewhat lower than that for normal temperate weather conditions (412 mm compared to 533 mm). Since the evapotranspiration is very low, the runoff leaving the system via the surface water streams is slightly larger than under temperate climate conditions. The infiltration capacity under permafrost conditions is low resulting in a higher amount of direct runoff from the surface to the streams.

The increased runoff under wet temperate climate conditions affects the turnover of water in lakes and streams, which influences the transport of matter within and between the different ecosystems in the landscape. The dilution effect on a hypothetical release from the repository to the surface might therefore be higher under wet climate conditions due to the larger amount of water circulating in the surface system. Studying the discharge in the streams and the depth of overland water in the area, it is likely that the streams have enough capacity to transport the water further downstream. If the stream channels did not have sufficient capacity, the increased water flows would be expected to result in net erosion and changes in the stream channel dimensions to accommodate the increased flows. Thus, increased flooding would tend to be a transient phenomenon during the period when the stream channel network was adapting to the enhanced flow regime. No larger flooded areas have been seen in the model results when applying a wet climate. This implies that radionuclides that have reached the surface stream network will follow the same flow paths as under temperate climate conditions.

In summary, no major changes of the water balance will occur, as long as a temperate climate governs the hydrology at the Forsmark site. The internal distribution of the precipitated water might change somewhat. The available models indicate that there will be minor changes, all of them within 10% of the present water balance at the site. If a different climate is considered, larger changes in the overall water balance will occur. Under wet conditions, a larger amount of water will contribute to the runoff with a faster water turnover as a result. Under permanently cold climate conditions with permafrost formation, the infiltration will be strongly reduced; also the annual variation in and dynamics of the hydrology deviate from temperate conditions. In the permafrost landscape, the main part of the turnover of water takes place during the relatively short active period of the year. During the frozen period, all precipitation is accumulated on the ground surface, and almost no water infiltrates due to the frozen soil. Only the talik areas are unfrozen and an exchange of water through the taliks may occur.

For normal temperate conditions, the overall patterns of recharge and discharge areas are the same for the different time periods and catchment areas studied. Changing the QD model from the present QD model to the models describing future conditions does not have a strong influence on the pattern of recharge and discharge areas. There are some exceptions, but in general the overall pattern seems to be governed by the topography and not the stratigraphy, thickness or type of QD. However, the distribution of recharge and discharge areas under some specific objects might change when a lake changes into a wetland. This is the case with Lake Bolundsfjärden where some parts of the lake function as discharge areas at 2000 AD, whereas the whole area under the lake turns into a recharge area at 10,000 AD.

The same pattern as described above is found when a wet temperate climate is applied to the model. Under cold conditions with continuous permafrost, the pattern of recharge and discharge areas changes dramatically. During the present temperate period, the local topography has a strong influence on the location of recharge and discharge areas, whereas the recharge and discharge areas are concentrated to the through taliks under permafrost conditions. The taliks are the only pathways for the water to be transported up or down through the permafrost. Some taliks act as recharge areas and others as discharge areas. Thus, the periglacial flow paths from the repository towards the surface will deviate from the flow paths developed under present climate conditions. Many of the areas defined as taliks are discharge areas also under present conditions.

The shallow groundwater table at present prevails also under future conditions. However, a lowering of the water table within the candidate area, i.e. the area above the planned repository, can be noticed when taking the shoreline displacement and the development of the QD into consideration. At present, the main part of the area has a groundwater table less than 1 m below ground. Under future conditions with a more distant shoreline, the depth to the groundwater will increase somewhat; in particular, the model results indicate that the part of the model area having groundwater depths between 1 and 3 m below ground surface will increase.

With a lower groundwater table, the amount of water transported in the upper part of the profile, which has high transport capacity, will decrease. This means that the fast transport of water to the surface stream network after a rain event might be reduced. A larger portion of the water will infiltrate to the deeper part of the QD profile and the water will be transported in the saturated zone towards the streams. This phenomenon can be seen when studying the future water balances discussed above, where the contribution from the subsurface saturated zone to the runoff increases as the land rises whereas the contribution from the overland part of the model decreases.

The processes and changes in the landscape identified as important for the description of the future hydrology at the Forsmark site can be summarised as follows.

- Climate variations are important to describe. The estimation of the potential evapotranspiration (PET) associated with each climate case is also of great importance for the numerical modelling, since the PET has a large influence on the actual calculated evapotranspiration. The PET used in the model cases describing the future is associated with uncertainty. The estimated PET is also of importance because the groundwater table in the Forsmark area is close to the ground surface and a lot of water is available for evapotranspiration. The overall water balance is affected by climate changes even though the internal distribution of the incoming precipitation is less sensitive to the applied climate. Especially the occurrence of permafrost has a strong influence on the temporal variations and the internal distribution of the water exchange in the area. The locations of recharge and discharge areas are not affected by the climate, except for the case of a permafrost landscape. The spatial distribution of recharge and discharge areas in the permafrost landscape deviates from the distributions under wet and normal temperate conditions.
- The locations of future streams and lake thresholds are important and also a large uncertainty in the description of the future hydrology. The establishment of appropriate locations of the streams is important, in order to estimate a reasonable value for runoff and to avoid formation of extensive flooded areas in the model. The lake thresholds are difficult to determine due to erosion and sedimentation processes. The locations and elevations of the thresholds could have a large influence on the local recharge and discharge pattern.
- The description of the future topography is important. The topography and the climate are the most important driving forces for the hydrology. In comparison, the QD model is less important for the overall water balance and the pattern of regional recharge and discharge areas. However, the stratigraphy and thickness of the QD have some influence on the local distribution of recharge and discharge areas in the near-surface system. Since most of the recharge areas of deep groundwater are concentrated to present or future lakes and/or wetlands, the distribution of the QD close to these areas could have a large impact on the transport of radionuclides in case of a release from the repository. The transport in the regolith is further discussed in Chapter 6.
- Vegetation development has an influence on the hydrology when large changes in the vegetation occur, for example, due to changes in the climate. Small changes in the internal distributions of different vegetation types do not have a large impact on the hydrology in the area. During a period with cold climate, very poor vegetation is developed with a small amount of transpiration as a result. This affects the internal distribution of the different evapotranspiration components in the area. However, “climate induced vegetation changes” generally have small effects on the hydrology compared with changes in the climate itself.

4.4 Chemistry

4.4.1 Available chemical data from the surface system

Chemistry data from the site investigations have been evaluated, described and modelled in three different SDM versions, version 1.1 (F1.1) /SKB 2004/, version 1.2 (F1.2) /SKB 2005/ and version 2.3 (F2.3), the final version of the site descriptive model, SDM-Site Forsmark /SKB 2008/. Major evaluations of chemical data from the surface system are reported in /Sonesten 2005, Tröjbom and Söderbäck 2006, Tröjbom et al. 2007, Hedenström and Sohlenius 2008, Andersson 2010, Löfgren 2010, Aquilonius 2010, Tröjbom and Nordén 2010, Tröjbom and Grolander 2010/. Detailed descriptions of sampling sites, data handling and analysis methods are given in a large number of sub reports (P-reports) referenced in the above mentioned reports.

4.4.2 Present chemical conditions in the surface system

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

Relict and ongoing marine influences probably have a minor effect on the structure of the ecosystems in the area and are mainly manifested as slightly elevated concentrations of marine ions. Ongoing flushing of the Quaternary deposits due to the present hydrological meteoric recharge-discharge patterns develops groundwater types ranging from mainly marine under stagnant conditions in the deposits beneath lakes to mostly fresh Ca-HCO_3^--types at higher locations in the landscape.

The strong influence from calcite has had a profound effect on the development of the terrestrial and limnic ecosystems in the Forsmark area. Secondary precipitation of calcium as calcite and co-precipitation of phosphorus mediates the development of the nutrient-poor oligotrophic hard water lake type typical of this region. In a Swedish context, lakes in the Forsmark area are characterised by low concentrations of phosphorus, and high concentrations of nitrogen and dissolved organic carbon /Tröjbom and Söderbäck 2006, Brunberg and Blomqvist 2003, Andersson 2010/. The rich supply of calcium also influences the development and structure of the terrestrial ecosystems and soil formation /Löfgren 2010/.

4.4.3 Chemical development since the last deglaciation

The chemical conditions observed in the Forsmark area today are a consequence of past landscape development, present and historic land-use, and anthropogenic inputs. The ongoing shoreline regression creates a spatial gradient from the coast in an inland direction, which represents a timeline in landscape development. This means that the spatial gradient of today may be extrapolated and translated into a succession of landscape development for the future. The present chemical conditions found in the modelled area in Forsmark therefore represent a historic time span of about 10,000 years since the last deglaciation. In Figure 4-31, this is illustrated as a box moving over time from the sea-bottom environment to the terrestrial environment, although the illustration is somewhat limited by the fact that climate, vegetation cover and anthropogenic influence via e.g. atmospheric deposition and land-use have varied during the period.

The historical development of the chemistry in the surface system at Forsmark can be divided into four stages based on differing hydrological conditions /Tröjbom et al. 2007/:

(1) Deglaciation of exposed glacial sediments, submerged by the freshwater Baltic Ice Lake. These deposits contained large amounts of limestone originating from the sea floor of Gävlebukten, 100 km north of the Forsmark area /Ingmar and Moreborg 1976, Hedenström and Sohlenius 2008/.

(2) Freshwater conditions were replaced by the brackish Littorina Sea, with increasing salinity, where density turnover infiltrated sea water through the underlying sediments /Laaksoharju et al. 2008/.

(3) Close to the emerging coast when a shallow sea still covered the area, the topographical discharge gradient may have transported traces of deep groundwater into glacial and post-glacial deposits. This flow pattern is still present close to the coast line /Bosson et al. 2010/.

(4) As soon as land emerged, precipitation and recharge of meteoric water created new hydrological flow patterns recharging through the regolith and discharging in streams and lakes. At this stage, aeration by meteoric recharge, in combination with a supply of organic carbon, altered redox conditions in the shallow groundwater. Increased supply of H^+ ions, mainly supplied through decomposition of organic matter, is the ultimate driving force for weathering reactions that take place in the regolith and bedrock /Tröjbom et al. 2007/.

4.4.4 Baltic Sea salinity development

The past salinity in the Baltic Sea since the onset of the Littorina period has been reviewed by /Westman et al. 1999/ and /Gustafsson 2004/. From proxy data, they estimated a range within which the past 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 2004/. Based on these studies, an estimated range for the salinity in the open Bothnian Sea offshore from Forsmark during the past c. 9,000 years was presented in /Söderbäck 2008/.

The future salinity the Baltic Sea is sensitive to changes in the freshwater supply, as well as to changes in the water exchange with the ocean. This was modelled by /Gustafsson 2004/ in a sensitivity analysis of the Baltic Sea salinity to climate changes. A conclusion from that study was that the possible range of future salinity in the southern Baltic Sea is between freshwater conditions and a salinity of 15 psu (practical salinity unit), depending on the combination of climate conditions and sea level. Accordingly, any long-term forecast of the future salinity will be utterly uncertain, since long term climate development is most uncertain. For a discussion on salinity and an illustration of the modelled development, see Chapter 8.

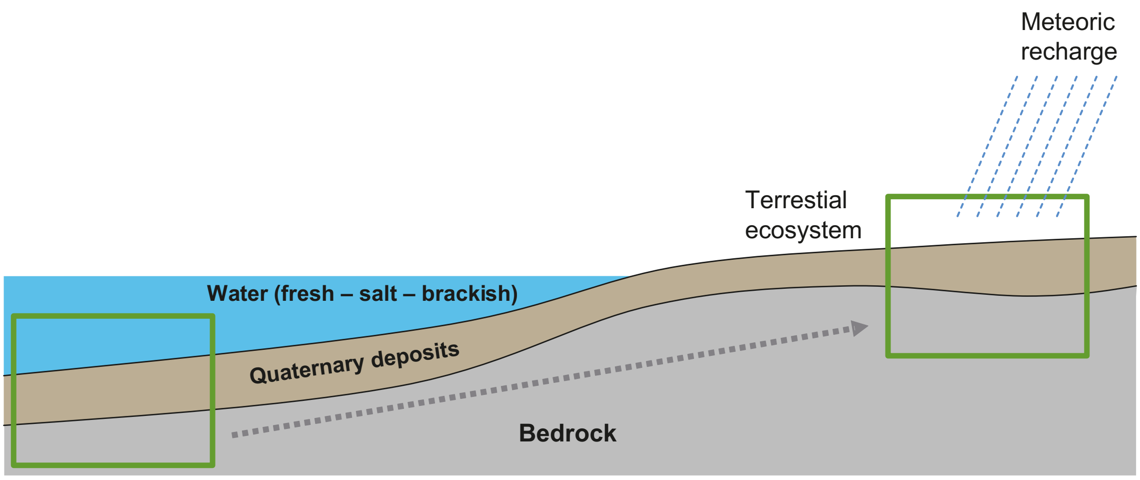


Figure 4-31. *A hypothetical cross-section of the Forsmark area today, illustrating the spatial gradient that can be extrapolated and translated into a succession representing landscape development for the future. The left box represents the conditions soon after the deglaciation (8800 BC), whereas the right box represents conditions in the most elevated parts of the area which have been exposed to precipitation and chemical weathering for several thousands of years. Figure from /Tröjbom and Grolander 2010/.*

4.4.5 Evaluation of the chemistry at landscape level

Chemical conditions in the Forsmark area were evaluated at landscape level by estimating pools and fluxes of stable elements in the terrestrial and limnic ecosystems. The distribution of elements between different biotic and abiotic pools, together with estimations of element fluxes in and out of the pools give an overall picture of major sources and sinks in the landscape. General patterns among elements and element groups can reveal common processes in the landscape and can also indicate if elements show analogous behaviour in the ecosystems (cf. /Tröjbom and Grolander 2010/ for a description of the model and assumptions).

In Figure 4-32, the relative sizes of sources and sinks are shown for a large number of elements. In this figure, the exchange with the atmosphere is always a source, i.e. atmospheric deposition. Major sinks are accumulation in lakes and export via watercourses. The mass balance term, i.e. the difference between known sources and sinks in the mass balance, may either be positive or negative. A positive mass balance term means that the known sinks exceed the known sources and in this case this term represents an additional supply from e.g. weathering reactions in the terrestrial system. A negative mass balance term means conversely that the known sources exceed the known sinks and in this case this term represent net accumulation in the terrestrial system (e.g. elements supplied via atmospheric deposition are accumulated in the terrestrial system). From Figure 4-32, it can be concluded that the relative distribution of sources and sinks differs significantly among elements and element groups.

For elements in the upper half of Figure 4-32 (Pb to Mn), input from the atmosphere is equal to or exceeds the known sinks (export via surface water and accumulation in lake sediments). This implies that a significant fraction of these elements is retained in the terrestrial system. In case of e.g. Pb, Zn, Cd, Cu and Hg only c. 10% of the atmospheric deposition input reaches the Baltic Sea via discharge or is accumulated in the lake sediments. This general pattern also applies to metals as Ni, Nb, V, Ga, Cr, Be, W, Co, Th, Rb, Mn as well as metalloids and non metals as in the cases of Se, Ga, P, Be, I, Sb, N and As.

For elements in the lowest part of Figure 4-32 (Fe to K), the sinks exceed the estimated input from the atmosphere which implies that there is a net contribution of these elements from a source within the terrestrial ecosystem. Weathering of minerals and ongoing flushing of marine remnants are possible terrestrial sources for these elements, but there is still a significant portion originating from atmospheric deposition. Metals such as Fe, Y, Sc, Zr, Mo, Sr, Ba belong to this group as well as several elements of marine origin, e.g. Cl, Na, Li, S, Br and K.

For six elements in the lower part of Figure 4-32 (Mg to C), atmospheric deposition only balances a minor fraction of the known sinks. This means that weathering reactions and other processes in the terrestrial system are the main sources of these elements. Once released into surface water, these elements could be accumulated in lake sediments or further exported to the Baltic Sea. The main constituents of minerals in rocks and regolith as Al, Si, Ca and Mg, as well as U belong to this group.

The broad range of elements studied shows that there are general patterns for the distribution and behaviour in the landscape of different groups of elements. Deviations from these general patterns either reflect unique properties of specific elements important for the understanding of their behaviour in the Forsmark area, or specific uncertainties related to the elements. In the mass balances, atmospheric deposition seems to be one of the major uncertainties. This is not exclusively a question of choosing the best method for estimating dry and wet deposition, but to correctly interpret what these measures represent.

Compared to estimations of deposition, emissions to the atmosphere are much harder to estimate. If not negligible, the omission of the emissions might influence the mass balances significantly by exaggerating the net input from the atmosphere and underestimate e.g. weathering input. If the deposition measurements include significant amounts of matter originating locally from the sub-catchment, the actual net deposition is further overestimated. This might be applicable to geogenic elements (e.g. Fe, Mn, Zr, Sc, Y, and REE) as well as nutrients (e.g. P) transported via for example pollen.

It should be emphasised that the relative distribution patterns in Figure 4-32 are strongly dependent on the uncertainties associated with the flux estimations. The major conclusion from this exercise is that the overall patterns very probably reflect the range in behaviour in the landscape for different elements,

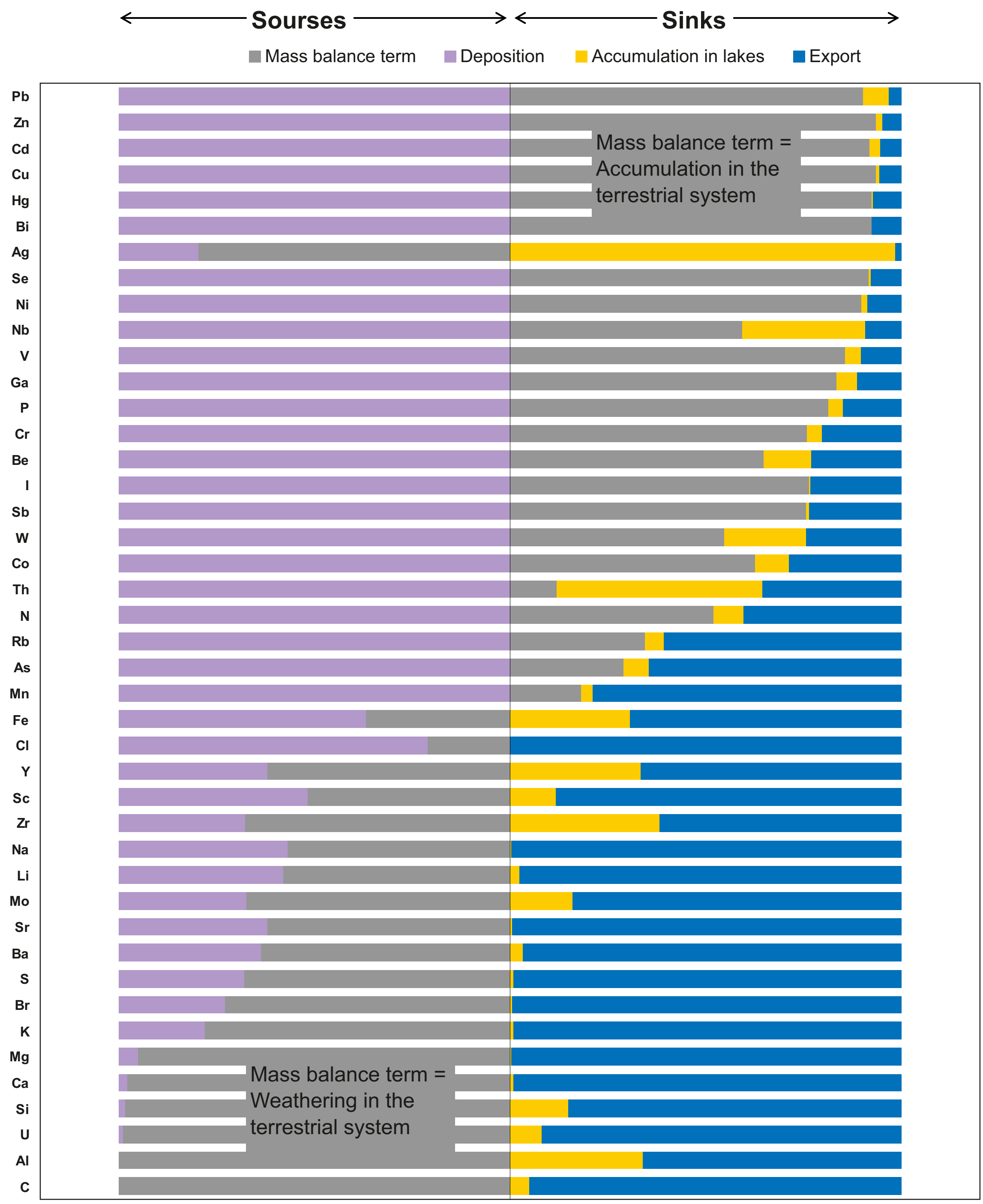


Figure 4-32. *Relative comparisons of element fluxes at landscape level in the Forsmark area. Exchange with the atmosphere is always treated as a source, e.g. atmospheric deposition (lilac colour). Major sinks are accumulation in lakes (yellow) and export via watercourses (blue). The mass balance term (grey), corresponding to the difference between the above mentioned fluxes, either represents a source on the left side (mainly weathering in the terrestrial system) or a sink on the right side (accumulation in the terrestrial system). Figure from /Tröjbom and Grolander 2010/.*

but that the exact location of a single element on this scale is more uncertain due to uncertainties in background data. The overall trend lining up the elements from Pb at the top to Al close to the bottom reflects the contrasting properties of these elements; Pb is an air borne pollutant bound to particles and organic matter in the terrestrial and limnic ecosystems, whereas Al has a local mineral origin through weathering where a significant portion accumulates in lakes in the form of mineral particles.

Element pools were estimated for the terrestrial and the limnic ecosystems in the Norra Bassängen catchment based on carbon budgets and element concentrations measured in a large number of organisms, soil, sediment and water /Andersson 2010, Löfgren 2010/. In Figure 4-33, the pools of both the terrestrial and limnic ecosystems are compared. The producer and consumer pools are combined in a total biota pool per ecosystem (T_Bio and L_Bio). In the left panel, the upper and lower regolith pools are summed per ecosystem representing the entire regolith layers (T_Rego and L_Rego, respectively). From this figure, it is clear that the regolith pools are dominating and of comparable size within the catchment of Norra Bassängen (note that this relation is dependent on the assumption of the vertical extent of the regolith, cf. below). In the right panel, the lower regolith layers have been excluded and the remaining pools represent the amounts available in the short term.

For most nutrients in the terrestrial system the biota (T_Bio) and organic regolith pools (T_RegoUp) are not negligible compared to the inorganic lower regolith pools. This is especially evident for Cl where a large fraction of the total amount of this element is found within the biota pool (mainly as tree biomass), but also nutrients such as N, P, K, S, Ca, Zn and Cu share this pattern. Some elements, not essential for biota, are also enriched in the terrestrial producer and organic regolith pools compared to most other elements, e.g. Hg and Cd. These elements show distribution patterns similar to essential trace elements such as Cu and Zn.

Some elements seem to accumulate in the terrestrial organic regolith layer (T_RegoUp) but not to any greater extent in the biota pools, e.g. Pb, Sb, As and Ag. These elements, which are not actively taken up by the plants, are probably associated with particulate and/or organic matter. This is well known for Pb and results in limited mobility and accumulation of this metal in terrestrial ecosystems (cf. mass balance above). The metalloid As, on the other hand, is according to the mass balance more mobile compared to Pb and a greater fraction of the atmospheric input seems to reach the surface water system. U is also enriched in the terrestrial organic upper regolith layer (T_RegoUp) compared to geogenic elements as Si and Al, but is not to any greater extent taken up by the biota. The mobility of U seems to be high in the Forsmark area, probably due to the unique hydrochemical environment, and much of the U released by weathering reactions in the terrestrial system reaches the Baltic Sea according to the mass balance.

In the limnic system, the dissolved pools (L_Water) comprise a significant fraction of the total amounts of marine ions (e.g. Cl, Br, Na, Mg, as well as K, Li, Rb, and I, S) according to the right panel of Figure 4-33. In the Forsmark area marine influences either originate from recurring intrusions of Baltic sea water into the lower located lakes, or by flushing of relict marine remnants /Tröjbom et al. 2007/.

These estimations are dependent on the underlying assumptions. In particular, this is valid for the terrestrial lower regolith pool (T_RegoLow), for which the vertical extent was set to 0.5 m in the estimation in /Löfgren 2010/, although the average thickness of the regolith layer on land areas is estimated to 4 metres /Hedenström et al. 2008/. This means that the terrestrial lower regolith pool could be underestimated in Figure 4-33, implying that the dominance of the T_RegoLow pool is even larger. The rationale for including only the upper 0.5 metres in the estimation of the T_RegoLow pool in /Löfgren 2010/ was that this layer is in contact with the root zone and thus potentially participating in the biochemical cycles.

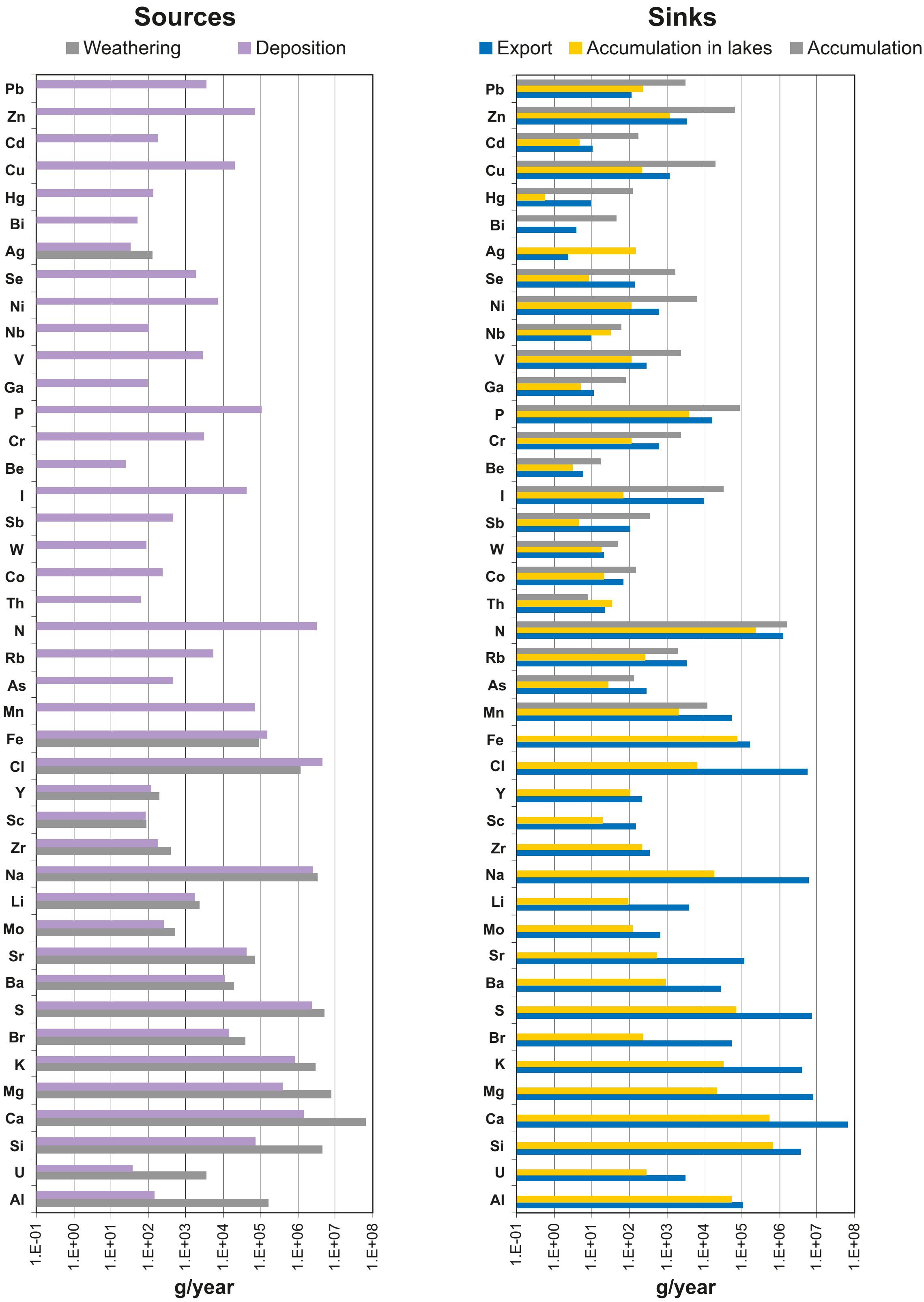


Figure 4-33. *Comparison between terrestrial and limnic element pools in the Forsmark area. In the left panel, the terrestrial and limnic consumer and producer pools are combined in the 'T_Bio' and 'L_Bio' pools, respectively. The upper and lower regolith pools are combined in the 'T_Rego' and 'L_Rego' pools. Particulate and dissolved fractions of the lake water are combined in the pool denoted 'L_ water'. In the right panel the RegoLow pools are excluded and the regolith is represented by 'T_RegoUp' and 'L_RegoUp', respectively. This latter selection represents the pools available for element cycling in a short perspective. Figure from /Tröjbom and Grolander 2010/.*

4.4.6 Factors forming the future chemical environment

Several factors will influence the development of the chemical environment of the Forsmark landscape in the future. External abiotic factors, such as land uplift, climate and atmospheric deposition, set the limits, whereas internal factors, such as primary production and land-use, may have profound influence via feedback mechanisms.

The ongoing land rise and the withdrawal of the Baltic Sea will continue in the future and new land and new lakes will emerge. As this process proceeds, land-use and vegetation cover will change, new lakes will be transformed into mires and further into potential arable land. The land rise process creates a gradient from young soils close to the coast to more mature soils in the inland. The emerging Forsmark landscape is not a chemical system in steady-state. Instead, a number of processes at different time-scales interact and form variable conditions over time. When the land rises, the groundwater table will be slightly lowered compared to the present conditions. A larger portion of the water will infiltrate to the deeper part of the regolith and the contribution from the subsurface saturated zone to the runoff will increase.

Chemical conditions in lakes and streams reflect the geometry, size and composition of the terrestrial parts of the catchments as well as the morphology and influence from lakes and wetlands within the hydrological network upstream. Most hydrochemical measurements from the Forsmark area represent small catchments with little influence from older, more mature parts of the landscape. The typical ontogeny of the lakes in this area is a short oligotrophic hardwater stage (that may or may not occur) lasting about 1,000 years followed by the development of brown-water lakes and finally wetland formation. The deeper parts of Öregrundsgrepen will in the future possibly develop into a number of relatively large and deep eutrophic lakes with a hydrochemistry more resembling larger lakes further south along the coast. In the long term, all lakes could be regarded as temporary since they will eventually be filled up and transformed to either wetland or drier land areas (cf. /Andersson 2010/).

Climate changes, either anthropogenic or natural, could change the prerequisites forming the chemical conditions in either a shorter or longer perspective by altered temperatures, precipitation patterns and water balance. During a warm and wet climate (i.e. the global warming case), there will be only minor differences in the relative water balance compared to the present temperate climate, although the absolute runoff will increase significantly due to higher precipitation. The increased runoff under wet climate conditions affects the turnover and residence times of water in lakes and streams, which influences the transport of matter within and between the different ecosystems in the landscape.

Under permafrost conditions the water balance will be significantly altered. Since the evapotranspiration is very low, the runoff leaving the system via the surface water streams is larger for the cold climate than under temperate climate conditions, even though the applied precipitation is lower. The infiltration capacity under permafrost conditions is low resulting in a larger amount of direct runoff from the surface to the streams. Changing temperatures and hydrological patterns according to the cases described above may influence properties such as primary production and weathering rates, which in the longer term could lead to more or less altered chemical conditions in the surface system.

The formation of a vegetation cover on emerging land has profound effects on the development of the chemical conditions of the surface system. Decomposition of organic matter generates H^+, which is the driving force for weathering reactions in the deposits, as well as a source of organic carbon and other nutrients in the surface water /Tröjbom et al. 2007/. In the young Forsmark area these processes are still not in steady state and equilibrium has not been established between accumulation and decomposition of organic matter. This will occur after a further 2,500 to 6,000 years from land rise according to /Löfgren 2010/. As primary production in the terrestrial system is the ultimate driving force for weathering reactions in the regolith, a warmer and wetter climate leading to increasing primary production will also lead to increasing weathering rates in the regolith. Conversely, a cold (and dry) climate with reduced primary production capacity would probably lead to decreasing weathering rates in the surface system.

It is also plausible that atmospheric deposition patterns will change due to altered anthropogenic emissions in the (relatively near) future. Deposition of some elements will most probably increase in the future whereas anthropogenic emissions and deposition of other elements, e.g. heavy metals such as Pb, Cd, Hg, Cu and Zn perhaps will decrease. When the Baltic coast moves further east due to the land rise process, marine influences via atmospheric deposition will be reduced in the present Forsmark area.

Over time, land-use has had profound effects on the terrestrial and limnic ecosystems and on the chemistry observed in the surface system. Cultivation, breeding livestock, fertilization, forest management, draining of wetlands and lowering of lakes are all factors that potentially affect weathering rates, leakage of nutrients and conditions for retention in the limnic ecosystem. The part of the Forsmark area currently submerged by the sea contains larger areas of clay than the currently emerged part, which is dominated by till /Hedenström and Sohlenius 2008/. Depending on future land-use, hydrochemistry could therefore be considerably altered.

4.4.7 The chemical development in a 10,000-year perspective

If the factors and driving forces described in previous section change, or if for example limited resources are depleted by ongoing processes, chemical conditions in the surface system will be altered in the future. In this section, probable responses and potentially changing conditions are outlined.

Calcite-bearing till deposited during the last glaciation has had profound effects on the hydrochemistry in the Forsmark area. Weathering of calcite releases Ca^{2+} ions and increases alkalinity in the shallow groundwater and in fresh surface water. The ample supply of Ca^{2+} ions and the high alkalinity gives conditions conducive to precipitation of calcite in wetlands and lakes forming calcareous sediments /Hedenström and Sohlenius 2008/.

During precipitation, other elements co-precipitate and accumulate in the sediments as well. This is the case for the essential nutrient P, which is withdrawn from the water phase leading to reduced primary production and development of the oligotrophic hard water lake type found close to the calcite-influenced coast of northern Uppland /Andersson 2010, Ingmar and Moreborg 1976/. The limnic ecosystems in the Forsmark area are hence heavily affected by these specific hydrochemical conditions. In the terrestrial ecosystem, the effects of the calcite are perhaps less pronounced compared to the limnic ecosystems and mainly manifested by the occurrence of some lime-favouring species and the formation of some specific soil types /Löfgren 2010/. At smaller scale, the rich supply of the essential nutrient Ca could potentially affect primary production by the formation of fertile soils as well as influencing the biochemical characteristics of the plants /Tröjbom and Nordén 2010/.

Estimates based on pool quantities and present weathering rates suggest that the calcite in the regolith layers might be consumed by weathering reactions in a relatively near future, perhaps within a time span of some 1,000 years depending on the assumptions /Tröjbom and Grolander 2010/. Studies of /Ingmar and Moreborg 1976/ showed that the calcite in the soil horizon has been consumed down to considerable depths further inland from Forsmark and that there is a clear gradient of this depth towards the coast. The observation that the oligotrophic hardwater stage usually persists a few thousand years perhaps supports the diminishing calcite influence, although other factors in the catchment could have influence on the presence of this lake type /Andersson 2010/.

These estimates imply that the calcite influence will diminish in a relatively near future, at least in a 10,000 year perspective. The present deviating conditions of the Forsmark area will therefore change towards the hydrochemical environment seen in most other parts of Sweden. In the long term, this has implications on the magnitude of processes as co-precipitation and primary production in the limnic ecosystem. Dissolved Ca and P, as well as pH and alkalinity will drop. The surface water quality in the Forsmark area will approach the conditions found in the brown-water lakes and streams further inland today. This probably means higher concentrations of total organic carbon (TOC) as well as increased concentrations of total P.

Chemical weathering of minerals more resistant than calcite is also driven by the supply of H^+ mainly generated during decomposition of organic matter. Strong acids dissolved in the precipitation or formed by oxidation of sulphides also contribute with H^+. The maximum weathering potential is limited by the total amounts of H^+ available. Different minerals are resistent to weathering to a varying degree and if there are more easily weathered minerals present, the dissolution of these minerals consumes H^+ at the expense of the dissolution of less readily weathered minerals.

This means that weathering rates of e.g. silicates are expected to be lower in the regolith in the Forsmark area today compared to similar sites with no calcite present in the regolith. It could therefore be presumed that weathering rates of less readily weathered minerals as silicates will increase in the future when the calcite in the regolith is depleted. Also the release of other major constituents originating from weathering of these types of minerals, e.g. Al and Na, Mg, Ca, are assumed to be enhanced in the future chemical environment, as well as release of trace elements incorporated in the bulk minerals, e.g. U, Th, as well as e.g. Zr and rare earth elements.

Surface water in the Forsmark area is characterised by relatively high concentrations of marine ions such as Cl, Na and Mg. The recent regression of the Baltic Sea has left marine remnants in the bedrock as well as in the regolith in the Forsmark area. These relicts that are generally present below the highest coast line along the Baltic coast will consequently be flushed by recharging meteoric water. In the lower located areas at Forsmark, this process is ongoing, whereas it has almost been completed in the higher parts.

In fact, there are still marine intrusions directly influencing the lakes close to the sea level (e.g. Lake Bolundsfjärden) /Tröjbom et al. 2007/. Within approximately 100 years, the relict marine Cl-pool might be flushed according to current export rates and estimated pools in the regolith. At this time, the concentrations of e.g. Cl will be mainly determined by the atmospheric deposition rate. Despite large uncertainties, this estimation shows that the relict marine influences will decrease in a relatively short time perspective (cf. /Johansson 2008/). When the Baltic coast moves further east due to the land rise process, the atmospheric deposition of elements originating from sea water will further decrease.

The global warming climate case could, however, counteract or reverse the development towards reduced marine influences by rising sea water levels. Lowered levels of sulphate in shallow groundwater and fresh surface waters might also have effect on Ba as well as Ra, leading to higher mobility of these elements in the future chemical environment /Sena et al. 2008/.

Mass balances show that many metals in the surface system mainly seem to originate from atmospheric deposition and that a significant fraction of these metals are accumulated in the terrestrial system /Tröjbom and Grolander 2010/. There is consequently a potential for increasing area-specific discharge of some metals in the future Forsmark area, either when the system has reached steady state or due to the advance of the metal front in the soil horizon /Klaminder et al. 2006/. The potential decrease in pH, alkalinity and Ca concentrations due to the depletion of the calcite in the regolith will alter the hydrochemical environment in a direction that might affect metal complexion and metal mobility.

As the mobility of many metals increases when pH is lowered, retention of these metals will potentially decrease in the future chemical environment. The mobility of other metals seems to be enhanced under present hydrochemical conditions and the presumed future changes could lead to reduced mobility of e.g. U. In addition to these factors, altered organic matter contents and the form of particulate matter could also significantly govern metal mobility in different directions depending on the element.

The land rise process will, in combination with the morphology of the future landscape, create new catchments and new lakes in the land emerging from the Baltic Sea. These catchments will contain larger areas of more fine-grained sediments compared to the present Forsmark area /Hedenström and Sohlenius 2008/. Weathering rates and area specific mass discharge of some elements from these areas could be significantly higher compared to the present Forsmark land area which is dominated by till. This is especially evident if these soils are drained and cultivated similar to comparable arable soils further inland. Area-specific losses of e.g. phosphorus are at least an order of magnitude higher for arable land compared to forest land /Tröjbom et al. 2007/, and a greater proportion of arable land compared with the present land-use distribution could significantly increase the nutrient status and primary production in the fresh water recipients.

Some future lakes will receive water from larger catchments, e.g. Forsmarksån and Olandsån compared to the small drainage area in the present Forsmark area. This might have great effects on the lake ontogeny and the oligotrophic hardwater stage will probably be omitted due to the input of nutrients and coloured substances from upstream catchments. The chemical characteristics of these future lakes will probably more resemble the present lakes of Forsmarksån, e.g. the lakes "Norra Åsjön" and "Södra Åsjön".

In a few thousand years, a number of relatively large and deep lakes will be formed in the deeper parts of Öregrundsgrepen. These lakes will possibly develop into the eutrophic lake type with a hydrochemistry more resembling larger lakes further south along the coast. This type of lake is characterised by nutrient-rich conditions, high primary production and a great potential for retention due to the large depth and long residence time (cf. /Andersson 2010/). Increasing primary production in future lakes due to higher availability of phosphorus together with longer residence times in the large and deep lakes might enhance the accumulation and retention in the limnic ecosystem. Also transport and retention of metals associated with organic matter could be expected to change when the surface water becomes more nutrient rich.

4.4.8 General effects of alternative climate cases

The above described development of the future chemical environment in the Forsmark area and the potential effects assumes climate conditions not significantly deviating from the present conditions, i.e. temperate climate. During the next 10,000 years alternative climate cases are also possible: the global warming case leading to a warmer and wetter climate with rising sea levels, and the permafrost case characterised by cold and dry conditions.

The global warming case implies higher temperatures, increased discharge and higher sea level. These factors will change the structures of the ecosystems as well as the magnitude of primary production and weathering rates, but if the underlying processes are unchanged compared to the temperate case the parameter values that describe the behaviour of elements in the ecosystems are not necessarily changed.

The permafrost case implies a significantly colder and drier climate compared to the present temperate conditions. During permafrost, discharge of groundwater is directed to vertical structures in the landscape called "taliks", which probably coincide with the present lakes and other depressions in the landscape /Hartikainen et al. 2010/. Under these conditions, characterised by less mobile water and lower temperatures, reaction rates could be presumed to be lower, leading to e.g. lower weathering rates. Primary production is probably also reduced implicating less influence from biota, e.g. uptake of nutrients, retention and presence and decomposition of organic matter, which all are factors that might affect the behaviour of radionuclides in the landscape.

Beyond the time perspective of 10,000 years, the conditions at the surface will change radically when a new glacial cycle starts and the area is again covered by thick ice. When the ice cover retreats, the again submerged Forsmark area will be covered by fresh glacial deposits. These are exposed during the following land rise, and the cycle will start all over again. Chemical signs of previous glacial periods and interglacials are mainly left in the bedrock as relict marine traces or isotopic signatures of the water reflecting other climates /Söderbäck 2008/.

5 Present state and succession of ecosystems and land-use

This chapter covers the present state and succession of ecosystems and land-use at Forsmark. Long-term ecosystem development in near-coastal areas of Fennoscandia is driven mainly by two different factors: shoreline displacement and climate change. In addition, human activities and land-use have strongly influenced both terrestrial and aquatic ecosystems, especially during the last centuries.

The SR-Site safety assessment treats a period of 120,000 years (and beyond) and will therefore include periods with a climate very different from today (see Chapter 3). In this section, some typical characteristics of the major ecosystems are described for the climate conditions considered in the safety assessment. The ecosystem characteristics in a temperate domain are represented by the present conditions (Section 5.1). The ecosystem characteristics during colder or warmer climate conditions, i.e. during the periglacial domain and the global warming case, are predicted by substituting "time for space " using knowledge of ecosystem characteristics in regions with colder or warmer climate today (Sections 5.2 and 5.3).

Generally, the glacial domain will assume an ice sheet of considerable thickness /SKB 2010a/ and, consequently, this means that terrestrial and limnic surface processes are restricted to a minimum. For the marine ecosystem, periglacial ecosystem characteristics are assumed for the glacial domain when the ice edge is located within the model. The ecosystem characteristics of the glacial domain are therefore not further treated in this context.

In the description of ecosystems, characteristics such as biomass, net primary production, sedimentation and peat accumulation, are in focus since they are considered to be of interest in a safety assessment perspective because of their direct implications for food web transfer and long-term accumulation in the landscape. The ecosystems are also presented in a context of successional trajectories (i.e. landscape development), in order to support the assumptions concerning spatial delimitation and distribution of ecosystems, and ecosystem succession in a long-term perspective in the radionuclide modelling.

Land-use is of particular interest in radionuclide modelling, since agricultural utilisation of the landscape gives rise to exposure of humans. Present and historical land-use (Section 5.5) may be used to predict and model future land-use in the Forsmark area (Section 5.6). Four variants of land-use are modelled for the future landscape at Forsmark: three variants with temperate conditions but with varying degrees of utilisation of land, and one variant with periglacial conditions. Particular attention is put on the potential for using organic deposits (peat) for cultivation. The hydrological models (Chapters 4 and 6) show that radionuclides may reach the surface system in wetlands covered by organic deposits. The potential land-uses of wetlands are therefore of special interest.

5.1 Ecosystems in Forsmark during a temperate climate domain

The site descriptions have provided large amount of information describing the ecosystems of today and this information is presented separately for marine systems /Aquilonius 2010/, limnic systems /Andersson 2010/ and terrestrial systems /Löfgren 2010/. Mainly, six different ecosystems have been used to characterise the landscape, emphasising differences in transport and accumulation of matter, land-use and the ability to identify these vegetation types by remote sensing. These ecosystems are: sea, lake, stream, wetland, agricultural land and forest (Figure 5-1). Below follows a brief description of these ecosystems at the present time and how they are interconnected over time by successional and developmental processes.

The present conditions are assumed to represent ecosystem characteristics in a temperate climate domain. However, in addition to climate, future ecosystems may differ from the present ones due to landscape development. Differences in expected ecosystem characteristics under future temperate conditions compared to present conditions are discussed in the section covering landscape development below. The climatological boundaries for the temperate domain are further elaborated within Chapter 3 and a comprehensive description in provided in /SKB 2010a/.

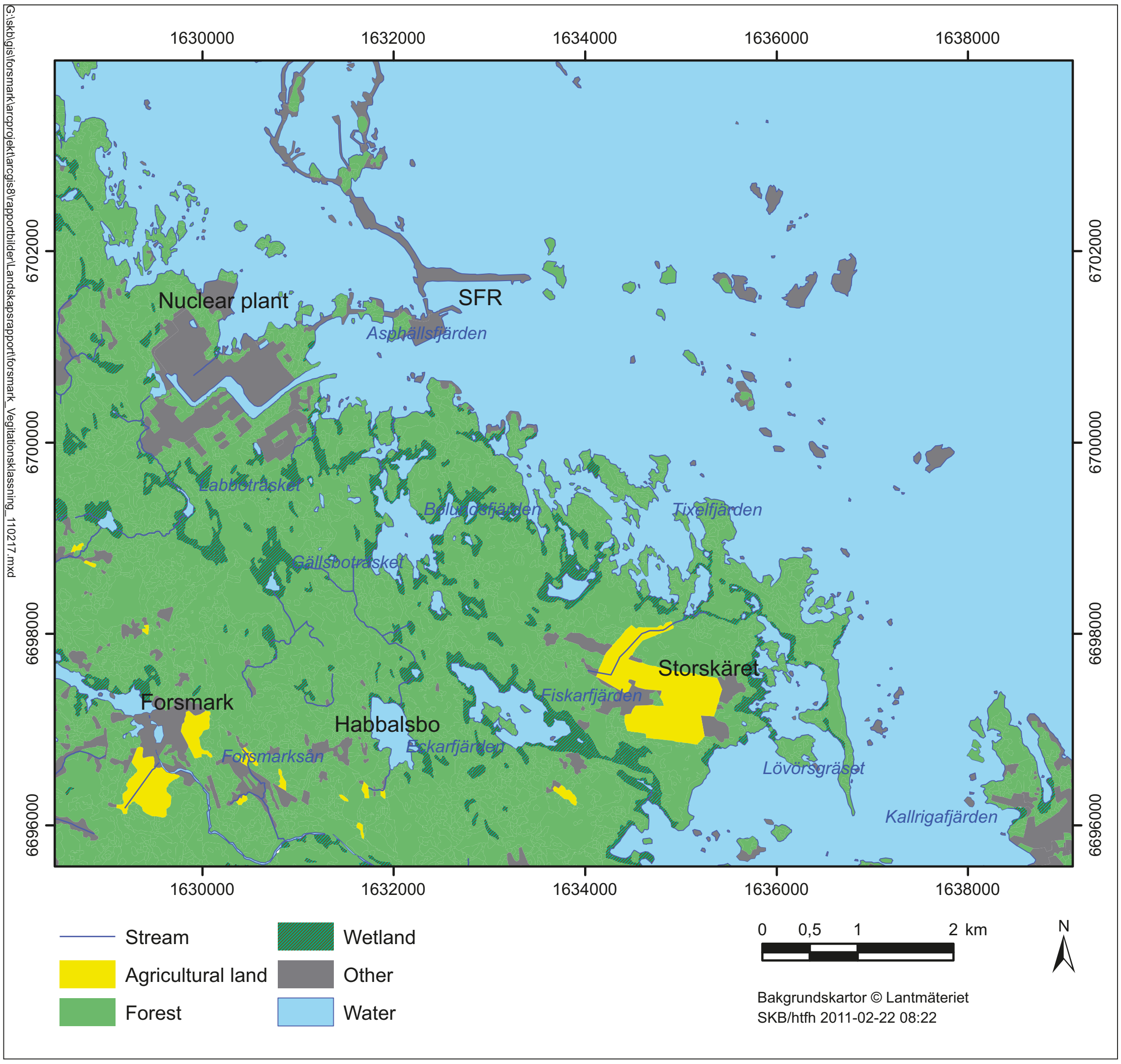


***Figure 5-1.** Distribution of ecosystems at Forsmark. The surface systems are divided into six ecosystem types, three terrestrial (agricultural land, wetland and forest) and three aquatic (lakes, streams and marine ecosystems). The areas marked as "other" include buildings, hard surfaces, and other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

5.1.1 Present ecosystem characteristics

Marine ecosystems

The marine environment can be categorised into several ecosystems (e.g. hard- and soft-bottom ecosystems, deep and shallow etc.), due to external drivers acting on the environmental boundaries generating ecosystems of varying structure and composition. However, in Forsmark the general functional groups and the ecosystem processes are assumed to be similar in the whole marine area despite varying environmental boundaries, though the magnitude, distribution and composition of the functional groups and food-web transfers may vary. Therefore, in the descriptions of the present landscape the marine ecosystem is considered as one ecosystem.

Large parts of the Forsmark marine area are open sea and are delimited by the steep sloping island of Gräsö in the east and the gradual slope of the mainland to the south-west. Most of the area consists of shallow exposed hard bottoms (boulders, bedrock) and areas with glacial clay covered by sand interspersed with deeper valleys with soft bottoms. Postglacial clays and mud deposits (accumulation bottoms) are found only in sheltered inshore settings, i.e. flads and gloes (lagoonal and bay areas). These environments may comprise pelagic, and benthic soft- and hard-bottom habitats to a varying degree. The exchange of water is very rapid in the area; the hydraulic residence time is less than a day on average.

The primary producers in the pelagic habitat, the phytoplankton, vary throughout the year with regard to species composition as well as biomass. After a spring bloom of diatoms, dinoflagellates and other smaller flagellates become more important, later to be followed by maximum densities of the cyanobacteria and zooplankton. The zooplankton species in Forsmark are generally the same species as in the rest of the Baltic. The most common zooplankton taxa in the Baltic are the small crustaceans, copepods and cladocerans, but rotifers, ciliates and larvae from other organisms are also present.

The fish fauna is a mixture of freshwater and marine species, where the freshwater species like perch and pike inhabit coastal areas and marine species like herring and sprat dominate offshore areas. Forsmark harbours bird species that feed in the marine habitat as piscivores or herbivores. Most of the bird species migrate between winter grounds and nesting grounds in the spring and summer. Thus, most birds leave Forsmark to winter further south, although some species also stay the winter and breed in the area, like cormorants and the white-tailed eagle. In Forsmark, the grey seal also inhabits the area, although not in high densities /Aquilonius 2010/.

The primary producers in the benthic habitat, the phytobenthos, consist of large photosynthesising algae and vascular plants (macrophytes) and microscopic unicellular organisms (microphytes including cyanobacteria). They are limited to the photic zone, which is roughly between the surface and twice the average water transparency attenuation depth. For the bays and coastal areas the average water transparency depth is not more than 3.4 to 3.6 m and, large areas deeper than 7 m lack vegetation cover. However, in the deeper more off-shore basins, the water transparency depth is larger, and vegetation can be found down to c. 20 m. In shallow soft bottom areas where the salinity often is lower than in more offshore areas, soft bottom-dwelling phanerogams are present (Figure 5-2). In deeper secluded areas the *Xanthophyceae* algae *Vaucheria dichotoma* is found in high densities.

The highest biomass values for benthic fauna in the Forsmark area are found in vegetation-associated soft bottoms. In these communities, the dominating benthic fauna are detrivores, although both taxa and mean biomass are much lower than further south in the Baltic Sea due to the salinity. In deep soft bottom areas (>20 m) the light is generally too sparse to allow any vegetation and the ecosystem is dominated by benthic heterotrophic organisms, i.e. benthic bacteria, baltic clam, Monoporeia,

Figure 5-2. *Soft bottom with Potamogeton pectinatus at Forsmark.*

isopods and amphipods. On hard bottoms, the subsurface zone generally is occupied by the green algae, deeper down followed by the filamentous brown algae and Fucus, and below them the red algae grow. The red algae occupy the largest parts of the vegetated bottom in the area (Figure 5-3). Benthic bacteria, i.e. all heterotrophic bacteria on the sea floor and in the sea bed, in Forsmark show a higher abundance and biomass than generally found in Kattegat and the Baltic Sea.

The present nutrient levels are low to moderately high in Forsmark compared with similar areas in the region. Primary producers (i.e. macrophytes) is the most abundant functional group in the area, especially along the coastline. In offshore areas, benthic fauna tend to dominate. Pelagic fauna is the smallest group in the area. Due to the dominance of the macrophytes, the biomass is unevenly distributed, mainly focused along the coast and in shallow areas. The lowest biomass values are found in the deep areas offshore. Like biomass, net primary production (NPP) is highest along the coast line, but in the offshore areas, higher water transparency and availability of nutrients permit relatively high primary production by phytoplankton.

In general the major part of the marine area is heterotrophic (i.e. primary production is less than the respiration). Nevertheless, due to the high production in the coastal zone, the whole area is on average autotrophic (i.e. primary production exceeds respiration). Hence, the shallow coastal area generally tends to be autotrophic, and supplies the rest of the area and adjacent marine areas with material. The rapid water turnover is due to the shallow exposed archipelago of the area. Mainly because of the rapid water turnover and the large fraction of exposed transport bottoms, burial (sediment accumulation) is today relatively low in Forsmark.

Limnic ecosystems

The limnic system includes both lakes and running water. Most lakes are open and have distinct flow into, through, and out of their basins. These through flows determine the water retention time (the time required to replace all the water in the lake), and the retention time can be used to distinguish between lakes and streams, with lakes having longer retention times than streams where water is replaced much more rapidly. Below follows a brief description of the limnic ecosystem, which is based on /Andersson 2010/.

Figure 5-3. *Hard bottom with red algae at Forsmark.*

The Forsmark area lakes are small (lake areas range from 0.01–0.75 km^2) and very shallow (the "median lake" has an average depth of 0.3 m and a maximum depth of 1 m, see Figure 5-4). The lakes are oligotrophic hard-water lakes, i.e. they contain high calcium levels but low levels of nutrients, as phosphorus is precipitated together with the calcium. The concentrations of dissolved organic carbon are very high (c 20 mg DOC L^{-1}) whereas water colour is relatively low. This kind of lake is common in the region, i.e. along the coast of northern Uppland, but is very uncommon in Sweden in general /Brunberg et al. 2002/.

Due to shallow depths and low water colour, primary producers flourish in the benthic habitat of the lakes. The dominant vegetation is stoneworts (*Chara sp.*). At the top of the bottom sediment, algae and cyanobacteria are often found in unusually thick layers (>5 cm). These groups of primary producers dominate the biomass and primary production, making phytoplankton biomass and production be of less importance /Andersson 2010/. The lakes are surrounded by reed belts, which are extensive around smaller lakes.

The dense stands of *Chara* harbour various kinds of benthic fauna and also function as refuges for smaller fish. Common fish species are perch and roach, as well as tench and crucian carp. This last species survives low oxygen levels and is the only fish species present in the smaller lakes, where oxygen levels can be very low during winter. The present oligotrophic hardwater lakes are net autotrophic, i.e. primary production exceeds respiration. The autotrophy of present-day lakes is, although common in Forsmark, unusual in Sweden and world wide (e.g. /del Giorgio et al. 1997, Sobek et al. 2003/).

The streams in the Forsmark area are very small and mostly resemble man-made ditches, although in some stretches the riverbanks are about two metres deep (Figure 5-5). Long stretches of the streams are dry during summer, but they may function as passages for migrating spawning fish during wetter conditions, especially in the more downstream areas.

Figure 5-4. *Lake Eckarfjärden, one of the larger lakes in the Forsmark area. Eckarfjärden is, like all other lakes in the area, a shallow oligotrophic hardwater lake surrounded by reed.*

Figure 5-5. The streams in Forsmark are small and many are dry during summer. a) The largest stream in the site investigation area in Forsmark, near the inlet to Lake Bolundsfjärden (May 2007). b) One of the streams that dry out during summer (photo from July 2003).

Streams may host a large community of biota and be important for wildlife in terms of passages for fish and transport of nutrients. Deposition and accumulation of matter in streams, on the other hand, are of minor importance and biological processes for long-term accumulation of matter are insignificant. On a short time scale elements may be trapped in streams, but during high discharge events trapped elements are resuspended and transported further downstream. This means that the annual retention is small or non-existent /Meyer and Likens 1979, Cushing et al. 1993, Reddy et al. 1999/.

This is especially valid for very small streams like those in the Forsmark area and streams may principally be regarded as transport routes in modelling of radionuclide transport. However, at high-flow periods flooding of wetlands surrounding the streams may occur, which may result in an accumulation of matter in the wetlands. An investigation conducted in parts of the Forsmark area indicates that the flat topography in the area promotes the occurrence of small floodplains /Carlsson et al. 2005/. The size of flooded areas adjacent to streams in Forsmark today is further described in /Andersson 2010/.

Terrestrial ecosystems

In the descriptions of the present terrestrial ecosystems only the wetlands are considered to be discharge areas of deep groundwater, whereas forests mostly are recharge areas and agricultural land may have properties from both the former categories, but is defined by the land-use. Below follows a brief description of these ecosystems, which is based on /Löfgren 2010/.

A major part of the wetlands in the Forsmark area are coniferous forest wetlands and fens (approximately 25 and 75% of the wetlands within the regional model area, respectively, see Section 4.1 in /Löfgren 2010/). The wetlands are characterised by a high calcareous influence, resulting in the extremely rich to intermediate fen types common in this area /Göthberg and Wahlman 2006, 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*. Forested wetlands may be dominated by conifers, mostly Norway spruce (*Picea abies*) or by birch (*Betula pubescens*) and/or alder (*Alnus glutinosa*). Many wetlands in the Forsmark area show indications of terrestrialisation where a fen replaces a shallow lake. This characterises many younger wetlands that are heavily dominated by dense and high stands of common reed (*Phragmites australis*) (Figure 5-6). In the Forsmark area, large bogs are rare because they have had too little time to develop in the young terrestrial environment (see wetland development below). Bogs or fens with partially bog-like vegetation are, however, found further inland.

The agricultural land is the most intensively managed land in the landscape and is a major provider of food for human consumption, either directly as crop production or as production of fodder for animals. The agricultural land is further divided into semi-natural grasslands and arable land. The use of areas to provide summer fodder for animal husbandry has changed over time, where the use of wood pastures once was common when most of the suitable land areas were cultivated.

Today, a large part of livestock grazing and hay-making takes place in former arable fields with richer soils and higher nutrient content due to fertilisation. According to the land-use data, the agricultural area in the Forsmark area comprises 84 ha, of which 34 ha is arable area and 50 ha is classified as semi-natural grasslands or pastures /Löfgren 2010/. Only around 10% of the total agricultural area (arable area and pasture) is used for production of grain and vegetables.

Forests contain different types of vegetation, all of which have a more or less dense tree cover (>30%). A forest is often regarded as the climax stage under the present conditions in most parts of the landscape and forest trees are quick to colonise areas previously kept open by human land-use. The forests are dominated by Scots pine (*Pinus sylvestris*) and Norway spruce situated mainly on wave-washed till. Spruce becomes more abundant where a deeper soil cover is found along with more mesic-moist conditions. Bare rock is not a widespread substrate in the Forsmark area, making pine forest on acid rocks quite scarce.

Deciduous forests represent 4% of the land area and mixed forests represent 6%. They are dominated by birch (*Betula pendula*), aspen (*Populus tremula*), alder and rowan (*Sorbus acuparia*), but Norway maple (*Acer platanoides*) and ash (*Fraxinus excelsior*) are also fairly common. Especially ash may be

Figure 5-6. *A wetland in Forsmark dominated by reed (Phragmites australis).*

abundant along sheltered seashores. The Forsmark area has a long history of forestry, which is seen today in a fairly high frequency of younger and older clear-cuts in different successional stages in the landscape. Birch is the dominant 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.

5.1.2 Landscape development

In the reference glacial cycle (Chapter 3), Forsmark will exhibit a temperate climate domain during the initial 25,000 years, even though this domain will be interrupted with shorter periglacial climate domains. During a temperate climate domain, the spatial distribution of ecosystems in the area will change due to the shoreline displacement, decreasing the initial extensive marine area (the submerged marine stage, in average a 150–200 m deep offshore area) and extending the areas for limnic and terrestrial ecosystems as a result of the regressive shoreline. In Figure 5-7, present conditions (2020 AD) and the predicted landscape in 9500 AD are presented to illustrate the changed distribution of the ecosystems in the area.

In the present landscape of Forsmark the shoreline displacement has over long periods continuously created inshore bays, lakes and new land areas. The subsequent succession of these emerging areas follows different trajectories depending on local factors such as wave exposure during the marine shore stage, slope and surrounding topography. Succession is a directional change of ecosystem structure and functioning, which may occur over time scales from decades to millennia. A schematic illustration of some of the main trajectories is shown in Figure 5-8, where the sea bottom is the starting point and the end point is an inland bog or a forest locality (or a clear-cut depending on the land-use).

Development of marine ecosystems

Sheltered marine areas and bays accumulate organic and fine-grained inorganic material, whereas the finer fractions are washed out from more wave-exposed shorelines with a large fetch. The shoreline displacement will bring marine basins initially located far out in the open sea, adjacent to the shore, thus increasing the effect of runoff from land, which may influence water chemistry, nutrient load and light penetration. As the area become shallower and more secluded, the water turnover will become slower. The marine ecosystem part of the model area in Forsmark decreases due to the shoreline displacement and around 11,500 AD only limnic and terrestrial ecosystems exist in the area.

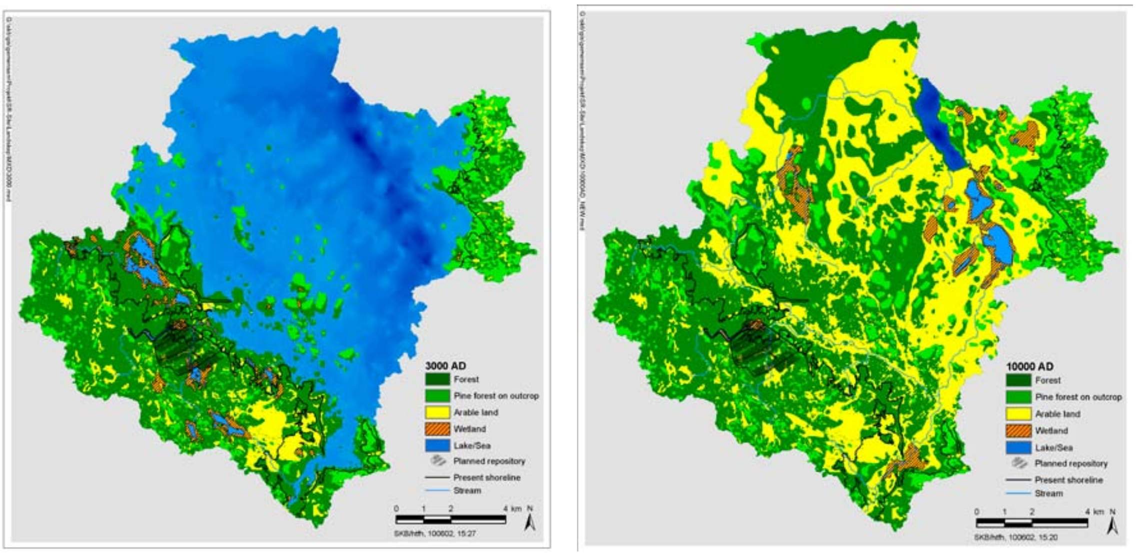


Figure 5-7. *Ecosystem distributions at 3000 AD (left) and 9500 AD (right) according to the landscape development model produced in SR-Site. Note that the displayed version is illustrating the assumption that all possible areas for agriculture are used.*

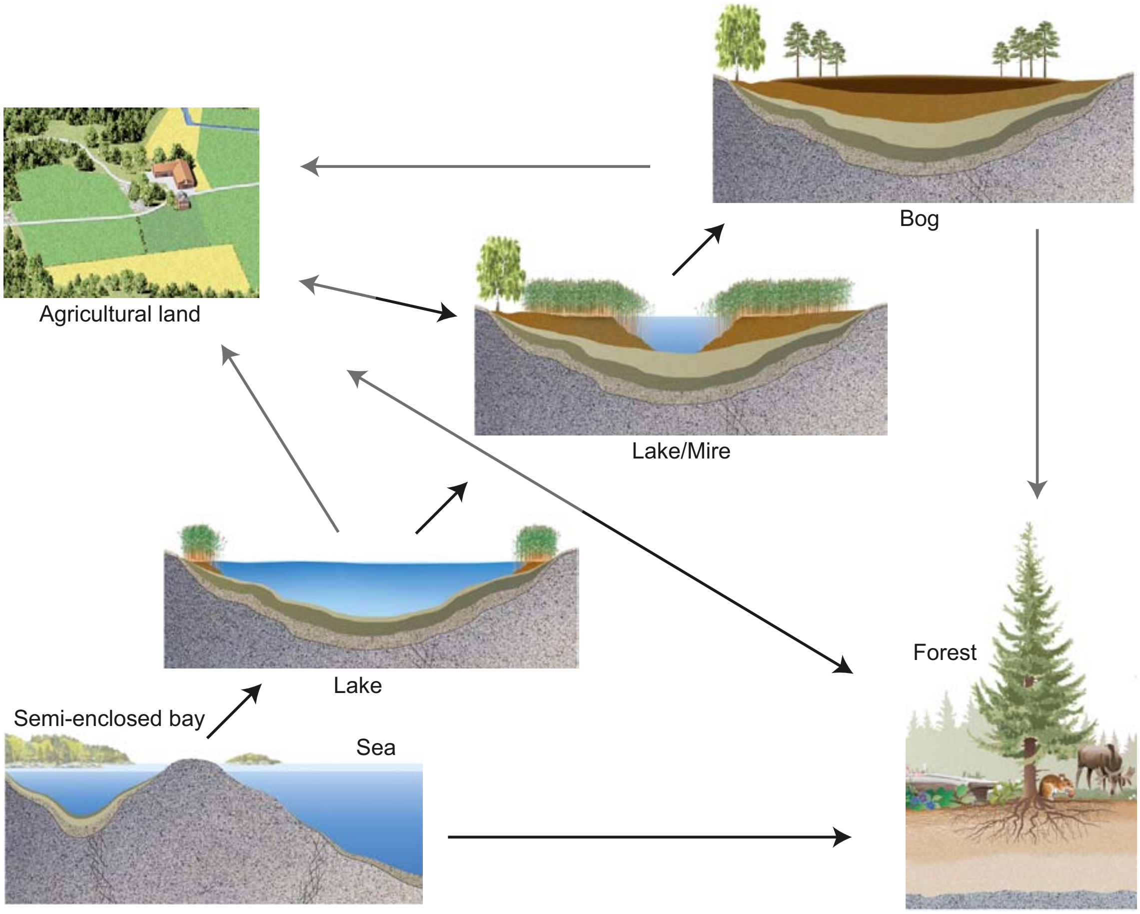


Figure 5-8. *A schematic illustration of the major ecosystems that may be found at certain points during a temporal sequence, where the original sea bottom slowly becomes land due to shoreline displacement. Black arrows indicate natural succession, while grey arrows indicate human-induced changes to provide new agricultural land or improved forestry. Agricultural land may be abandoned and will then develop into forest or, if the hydrological conditions are suitable, into a fen. A forest may be "slashed and burned" and used as agriculture land.*

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

The influence of less saline discharge water from land will lower the salinity and the organisms will shift from being a mix of freshwater and saline species in the Baltic Sea, towards a dominance of more freshwater species. Around 11,000 AD, when the marine area in Forsmark is almost completely gone from the model area, the salinity will have decreased to between 2 to 3 ppm, which is consistent with present Bothnian Bay conditions. The Bothnian Sea will be isolated from the Baltic Proper around 25,000 AD and become a large freshwater lake /Påsse 2001/.

Development of limnic ecosystems

A sea bay may both be isolated from the sea at an early stage and thereafter gradually turn into a lake as the water becomes fresh, or it may remain as a bay until shoreline displacement turns it into a wetland (Figure 5-8 and Figure 5-9). After isolation from the sea, the lake ecosystem gradually matures in an ontogenetic process which includes subsequent sedimentation and deposition of substances originating

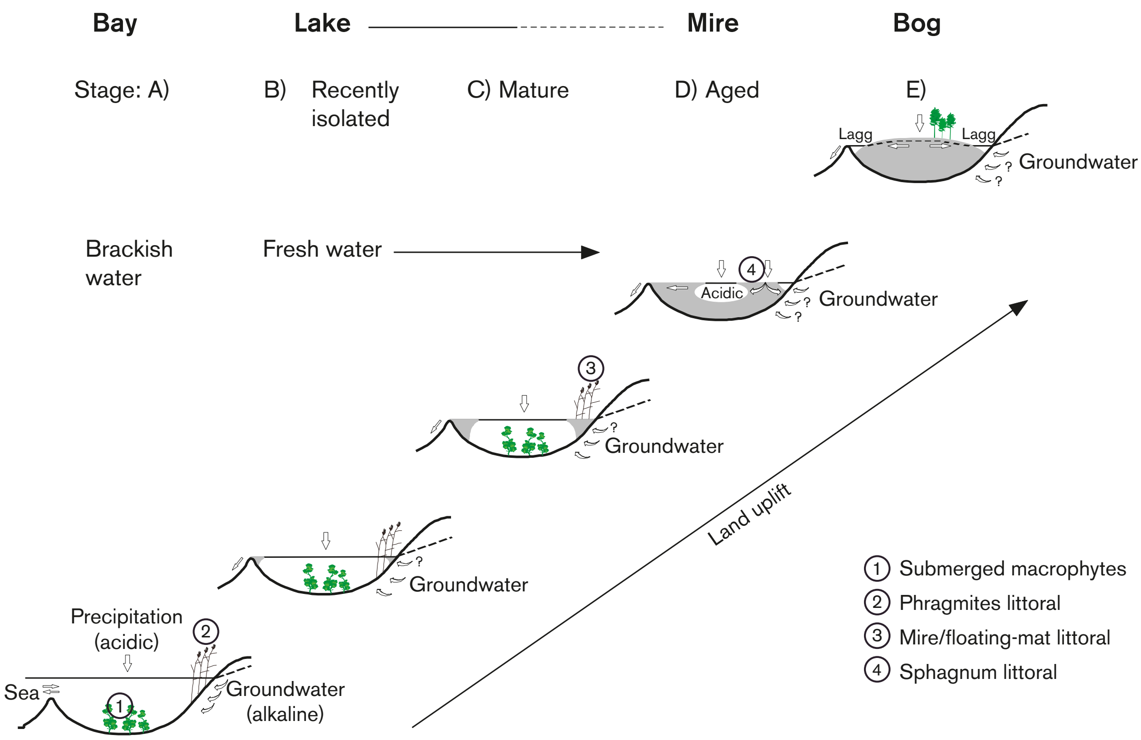


Figure 5-9. *Schematic description of the ontogeny of a closed-off bay of the sea to a bog. The figures represent different important components of the ecosystem. Modified from /Brunberg and Blomqvist 2000/.*

from the surrounding catchment or being produced within the lake. Hence, the long-term ultimate fate for most lakes is an inevitable fill-up and conversion to a wetland (further discussed in Chapter 8 in /Andersson 2010/).

In Forsmark, all present-day lakes have developed into shallow oligotrophic hardwater lakes that are characteristic of the area. In the future, shoreline transgression will isolate deeper marine basins and turn them into freshwater bodies. These deeper lakes can be expected to differ somewhat from the shallow oligotrophic lakes of today. In addition, some of the shallow lakes that will form may turn into dystrophic brown-water lakes. Three of the future lakes will have depths of more than 10 m and these are considered to represent deep lakes. The remaining lakes that form will have depths around 2 metres or less and are considered shallow. Below follows a brief description of the expected functioning of future shallow and deep lakes, and streams in the Forsmark area.

Many of the shallow lakes that will emerge due to land-rise are assumed to closely resemble the present-day oligotrophic hardwater lakes in Forsmark with high primary production on the lake floor. However, it is also possible that they will become dystrophic, i.e. with brown water and dominated by respiration of allochthonous material produced in the surrounding terrestrial catchment. According to /Brunberg and Blomqvist 2000/, the development of brown-water systems is coupled to the retention time and character of upstream lakes. Present lakes that have emerged in the catchments of Forsmark-Olandsån have evolved into dystrophic lakes, mainly due to the inflow of brown water from upstream dystrophic lakes.

In contrast, emerging lakes without large input of brown water are likely to become oligotrophic hardwater lakes. In addition, one could hypothesise that lakes with short retention times should be dystrophic due to turbidity of the water. However, many of the present-day Forsmark lakes have short retention times so it is evident that lakes with short retention times may also become oligotrophic hardwater lakes. The retention time in future lakes spans a wide range but the majority of the shallow lakes in the future are assumed to become oligotrophic hardwater lakes (further discussed in /Andersson 2010/).

The future oligotrophic hardwater lakes are assumed to be similar to the present lakes in the area and most of them are modelled to be net autotrophic /Andersson 2010/. However, immediately upon isolation some of the shallow lakes may be dominated by respiration. Respiration decreases as the lakes become shallower (due to sediment accumulation) and the proportion of photic area increases in the lakes, i.e. with time these lakes also turn autotrophic. On the contrary, if the emerging lakes are dystrophic it is likely that they remain heterotrophic for their entire lake stage.

The deep lakes that will emerge in the Forsmark area differ from the shallow ones in a number of respects and are assumed to more closely resemble other deep lakes in the county. The greater depths of the future lakes result in aphotic areas where benthic photosynthesis does not occur, whereas respiration does occur. This together with a short retention time and thereby large inflow of allochthonous material indicates that the lakes will become net heterotrophic. The lakes will be deep enough to allow for thermal stratification during summer and/or winter. During stratification no mixing of deeper and shallower water occurs and anoxic conditions in the deeper water may release nutrients from the sediment leading to high nutrient concentrations. Higher nutrient concentrations and areas with low light climate indicate that primary production in the pelagic habitat may be much higher in the deep lakes than in the shallow lakes whereas benthic primary production is likely lower.

In the future deep lakes, a large part of pelagic production may be utilised directly in the pelagic habitat by zooplankton, but the losses through the outlet are probably large due to a short retention time. There will most likely be higher habitat diversity in larger than smaller lakes considering both vegetation and animals. For example, is it likely that the future deep lakes will contain more fish species. Biomasses per hectare, on the other hand, are most probably similar to those in the present oligotrophic hardwater lakes.

In the future, larger streams than those currently present will be formed in the area, and are assumed to more closely resemble the River Forsmarksån. These deeper streams are assumed to not host benthic primary producers, but on the other hand, they may contain larger amounts of pelagic producers. The retention time in future streams will be shorter than at present, due to larger water flows, induced by larger drainage areas. This larger flow indicates that these larger streams will also function as transport routes as there will most probably be insignificant sediment accumulation.

Development of terrestrial ecosystems

Mires are formed basically through three different processes: terrestrialisation, paludification and primary mire formation /Rydin and Jeglum 2006, Kellner 2003/. Terrestrialisation is the filling-in of shallow lakes by sedimentation and establishment of vegetation. Paludification, which is the dominant process of mire formation in Sweden, is an ongoing water logging of more or less water-permeable soils, mainly by expanding mires. Primary mire formation is when peat is developed directly on fresh soils after emergence from water or ice. All three processes are likely to occur in the Forsmark area, but terrestrialisation probably represents the largest areas of peatland development in the investigation area today.

This pattern, where reed is the dominating pioneer during terrestrialisation, is also seen in the peat archives of bogs further inland /Fredriksson 2004, Bergström 2001/, although the extent of the historical importance of reed during terrestrilisation is uncertain. Other important stages in peatland development are dominated by sedges (*Carex*) and/or brown mosses (*Bryales*) and *Sphagnum*, respectively /Fredriksson 2004/. Forested wetlands are found in different stages of the wetland ontogeny, where wood-*Carex* peat (Birch and/or Alder) often is found earlier in the succession and wood-*Sphagnum* peat (Scots pine) may be a part of the last successional stage /Fredriksson 2004, Bergström 2001/.

The richer types of mires, which are typical of the Forsmark area, will undergo a natural long-term acidification when turning into more bog-like mires (Figure 5-10). Most wetlands are discharge areas; however, the raised bog, with rain-fed production on the bog plane has a restricted or non-existent connection to the groundwater table, and is of less interest in a safety assessment where the radionuclides enter the ecosystem from below. Moreover, the potential yield after drainage will decrease drastically if *Sphagnum* peat dominates the surface layers (i.e. a bog) and other wetlands would be preferred for agricultural purposes.

Most of the ecosystems have their different characteristic land-uses, which also are presented and discussed in Sections 5-5 and 5-6. But one of the largest impacts on ecosystems are draining activities, which historically have been pursued to create arable land or to improve the forestry yield /Löfgren 2010/. Land suitable for cultivation is often situated in the low-lying parts of the terrain and often occurs in small irregular pockets in the surrounding boulder-rich terrain. In the middle of the 19th century, larger wetland areas in the woodlands were subsequently drained and cultivated as arable land

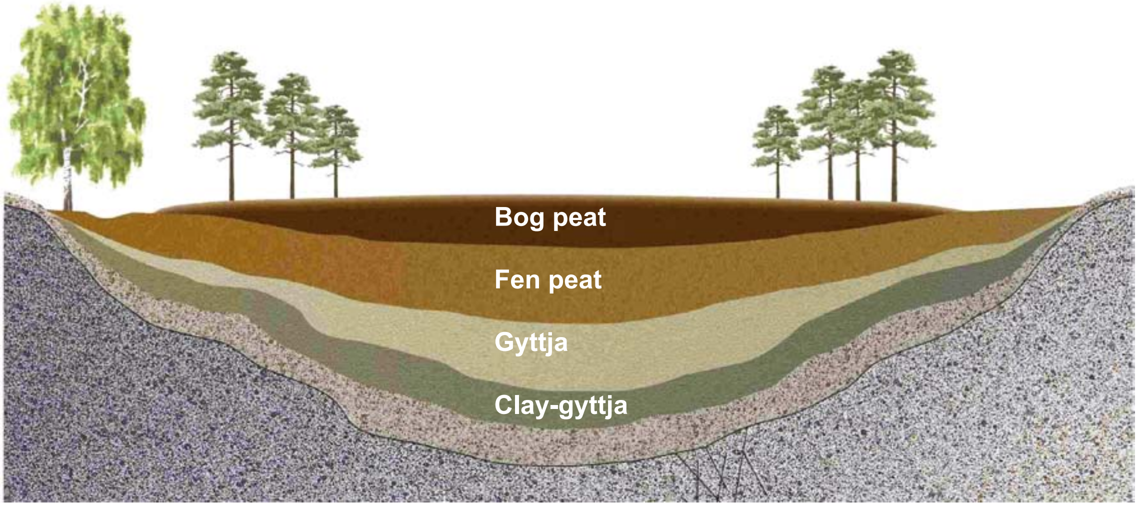


***Figure 5-10.** A schematic bog where the stratigraphy illustrates the different successional stages from the isolated sea bay to the bog.*

(Figure 5-8). Some of these areas are still cultivated whereas others are now abandoned and, in some cases, have become woodlands or wetlands again /Berg et al. 2006/. In the future, large areas of glacial clay will be exposed, which has to be considered as a preferable substrate for cultivation (see Section 5-7).

The largest part of the land area is, however, not defined by the stages described above and is dominated by till and outcrops. 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. Wave-exposed shores will undergo a relocation of previously accumulated sediments, and these shores will emerge as wave-washed till, where the grain size of the remaining sediments is a function of the fetch at the specific shore. Shores with wave-washed till are the most common kinds in the Forsmark area, but rocky shores and shores with fine sediments can also be found.

The emerging rocky and till shores have a sea shore vegetation zonation that is defined by their tolerance to water inundation and salt sprays /Jerling 1999, Jerling et al. 2001/. Bushes and trees create a varied light environment and new habitats. In this way, the flora and vegetation change steadily but with a relatively high degree of determinism e.g. /Svensson and Jeglum 2000/. In most areas with a thicker soil layer, Norway spruce forest has to be regarded as the dominating vegetation type in this area, if the management and land-use were to decrease. Scots pine would probably be more restricted to areas with a shallower, more nutrient poor soil layer if forestry management was to decrease and fire was once again to become a natural disturbance in the landscape /Sjörs 1967, Engelmark and Hytteborn 1999/.

5.2 Ecosystems in Forsmark during a periglacial climate domain

Regional vegetation patterns are mainly determined by climate, soil properties and human land-use. The more specific local characteristics are also a function of local site factors, such as topography, soil moisture and fire resistance in terrestrial ecosystems, while depth, salinity and temperature are of importance in aquatic ecosystems. Consequently, a number of factors could be used to predict ecosystem properties during different climate regimes and during landscape development. This section outlines potential ecosystem properties for ecosystems in Forsmark under a periglacial climate domain.

The periglacial climate domain is defined by the presence of permafrost. A mean annual ground temperature between –5 and –2°C is defined as the boundary for discontinuous permafrost (50–90% of landscape covered by permafrost) and –5°C and colder as the boundary for continuous permafrost (90–100%) /Heginbottom et al. 1995/ (see also Chapter 3). The warmest month has an average temperature between 0°C and 10°C /Peel et al. 2007, Breckle 2002/. The permafrost may be interrupted by unfrozen areas below lakes, so called taliks.

Also, the sea may be underlain by permafrost to a variable extent depending on climate and sea-level history. Polar regions of today may be used to predict conditions in Forsmark under periglacial conditions. Greenland has been suggested as a potential analogue to Forsmark with regard to a permafrost climate, mainly based on similarities in the bedrock (Figure 5-11). Greenland experiences a wide range in temperature and the north of Greenland has perennially ice-covered lakes, whereas lakes in southern Greenland have open water for 6 months of the year. However, in addition to the climate variation, there is a wide range of other factors, such as nutrient and salinity concentrations and regolith characteristics, which also influence differences.

5.2.1 Ecosystem characteristics

Marine ecosystems

In the reference case, the climate is assumed to be temperate until around 9400 AD (see Chapter 3). At that time there is only a small area in the Forsmark landscape which still is sea. The periglacial domain in marine ecosystems is characterised by lower water temperature and a shorter ice-free season. The Baltic Sea is a semi-enclosed sea with a limited exchange of water with adjacent more saline seas and specific mixing and stratification conditions, which implies that it is not entirely appropriate to compare with conditions around Greenland. Still, in combination these two regions give an indication of the characteristics of a marine ecosystem in a periglacial climate domain in Forsmark.

Greenland is located in the high latitude areas of the world with the highest marine primary production, in spite of lower temperatures and a shorter growing season. This is mainly due to the upwelling of nutrient-rich deep water with an origin in nutrient-rich runoff from land /Huston and Wolverton 2009/. The growth period is shorter (60–100 days) in Greenland, but the nutrient-rich upwelling along the ice-edge contributes to the high primary production. Light and nutrient limitations are more important than temperature during ice-free conditions.

Figure 5-11. *A small lake with surrounding wetland close to the edge of the Greenland ice cap near Kangerlussuaq used for comparison as an analogue to the future Forsmark at periglacial conditions.*

Moreover, the melting of sea ice in spring results in a stratification of the upper water column that promotes primary production. The zone seaward of the ice edge is important for plankton production and planktivorous crustaceans and fish. Sea ice and the ice edge are also of major importance as a habitat for marine mammals (large whales, seals and walruses) and seabirds. In addition, sea ice together with snow cover controls the exchange of heat, CO_2 and other properties between the atmosphere and ocean. The marine areas of Greenland are important fishing grounds and are characterised by relatively few dominant species, which interact strongly /Buch et al. 2005/.

In comparison with Forsmark today, the Bothnian Bay has a longer ice-covered season (100–190 days/year), lower annual water temperature and salinity (2–3 ppm), as well as lower species diversity, biomasses and primary production. There is a higher degree of dominance of freshwater species in the Bothnian bay than in Forsmark. In the outer parts of the Bothnian Bay, the ice moves and scrapes away the vegetation (down to 1–2 m depth), causing a higher proportion of annual primary producers than in less ice-affected areas more southwards in the Baltic Sea, where perennial algae occur frequently. The growing season is also significantly shorter (4–5 months compared to 8–9).

In northern and temperate seas, the retrieval of nutrients from the sea floor is especially effective due to the sinking of the heavy colder surface water during winter, inducing the nutrient-rich warmer bottom water to ascend. This is likely to occur in Forsmark during the periglacial domain, although depending on the out- and inflow through the entrance areas (the Danish sills and the sill between the Bothnian Bay and the Baltic proper), river runoff, net precipitation and large-scale atmospheric circulation, it is unpredictable to what degree this will change from present conditions. The primary production could, due to the nutrient conditions, be higher, lower or similar to present conditions. Nevertheless, it is likely that it will be within the range of today's estimates.

In addition, a likely development is that respiration will decrease along with temperature. The growing season will be shorter and the ice will provide an increased habitat for breeding of marine mammals. The bird fauna has been very stable in the Baltic during the recent interglacial /BACC 2008/ and will probably be similar. The sea-bound flora and fauna will probably have a dominance of freshwater species and a higher degree of species able to adapt to colder climates. The colonisation of new marine species will probably be very limited due to the semi-enclosed character of the Baltic Sea, although new freshwater species may colonise. In Table 5-1, marine ecosystem parameters are listed along with potential changes during a periglacial climate domain.

Limnic ecosystems

A large difference between periglacial lakes and present lakes in Forsmark is that there will be no reed surrounding the lakes. The reed belt surrounding lakes may be important for the functioning of lakes by structuring the composition of water entering the lake from the sub-catchment, and the reed belts in the littoral may function as sheltered breeding areas for aquatic organisms. In periglacial regions, instead of reed, lakes may be surrounded by bryophytes or vascular plants (i.e. *Hippuris sp.*) (Figure 5-12).

In addition to existing lakes defined by bedrock depressions, there will be thermokarst lakes (thaw lakes) in periglacial conditions. Thermokarst lakes form in a cyclic pattern where permafrost freezes and thaws, forming temporary water-filled depressions with a life span of a couple of hundred years. Thermokarst lakes are usually small and shallow. From an ecological point of view they may be important for the landscape as they may be hotspots of biological activity in tundra regions with abundant microbial activity, primary production, benthic communities and birds.

At present, thermokarst lakes are the most abundant aquatic ecosystems in the Arctic and for example in Yukon river delta in Alaska the number of thaw lakes and ponds is estimated at 200,000 /Maciolek 1989/. However, thermokarst lakes do not have connection to groundwater flow and are therefore not important in the context of radionuclide transport from a deep repository. Therefore, thermokarst lakes are not further described below, but the focus is on lakes defined by bedrock depressions which may have connection to groundwater below the lake bottoms.

In colder climates, lake ice coverage will be thicker and persist longer during the winter. This leads to less light penetration, affecting the primary producers beneath the ice as well as affecting mixing and transport of nutrients. The magnitude of water runoff will be similar to present-day conditions, but nutrient concentrations may be lower due to a shorter runoff season, altered weathering, production and retention in the ground surrounding the lake, as well as altered internal circulation

Table 5-1. Expected marine parameter values in different climate domains compared to present (temperate). Note that values represent mean values and values in brackets represent ranges of values measured during the site investigations performed by SKB in the marine areas in Forsmark and Laxemar-Simpevarp (see Chapter 3 in /Aquilonius 2010/). Values denoted with an * include other measurements performed in the areas, ** denotes values calculated from measured values in the area (see Chapter 6 in /Aquilonius 2010/).

Parameter	Temperate Forsmark	Global warming Bothnian Sea / Baltic proper	Periglacial
Period with ice coverage (days)	1–4 months	1–2 months shorter or absent	9–10 months
Total nitrogen concentration (mg L^{-1})	0.5 (0.2–2.8)	Probably higher	Probably lower
Total phosphorus concentrations (mg L^{-1})	0.02 (0.007–0.06)	Probably higher	Probably lower
DOC concentrations (mg L^{-1})	5 (1–21)	Similar to present, higher or lower	Probably lower
DIC concentrations (mg L^{-1})	11 (0.3–27)	Similar to present, higher or lower	Probably lower
Particulate matter (kg dw/m^3)	0.4 (0.08–2.2)	Similar to present or higher	Probably lower
Oxygen-free bottoms		More	~present
Salinity (‰)	4.4 (0.2–5.4)	< present / 0–15	< present / 0–15
Light penetration (m)	2.7 (0.3–6.4)		
Biotic parameters	**Temperate**	**Global warming**	**Periglacial**
Phytoplankton biomass (g C m^{-3})	0.2 (0.02–0.5)	Similar to present, higher or lower	Similar to present, higher or lower
Chlorophyll (ug L^{-1})	1–4		
Microphytobenthos biomass (g C m^{-2})	2 (0.5–5)	Similar to present, higher or lower	Similar to present or lower
Benthic macroalage and macrophytes (g C m^{-2})	8 (0.3–93)	Similar to present, higher or lower	Similar to present or lower
Bacterioplankton biomass (g C m^{-3})	0.3 (0.04–0.5)	Similar to present, higher or lower	Similar to present, higher or lower
Benthic bacterial biomass (g C m^{-2})	1 (0.4–4)	Similar to present, higher or lower	Similar to present, higher or lower
Zooplankton biomass (g C m^{-2})*	0.08 (0.01–0.2)	Similar to present, higher or lower	Similar to present, higher or lower
Fish biomass(g C m^{-2})*	0.3 (0.06–1)	Similar to present, higher or lower	Similar to present, higher or lower
Seal biomass(g C m^{-2})*		Similar to present, higher or lower	Similar to present or higher
Bird biomass(g C m^{-2})*		Similar to present	Similar to present
Benthic fauna biomass (g C m^{-2})*	6 (0–12)	Similar to present, higher or lower	Similar to present or lower
Pelagic Primary production (g C m^{-2} y^{-1})**	17 (2–46)	Similar to present, higher or lower	Similar to present, higher or lower
Benthic primary production by macroalgae (g C m^{-2} y^{-1})**	69 (1–228)	Similar to present, higher or lower	Similar to present or lower
Benthic primary production by microphytobenthos (g C m^{-2} y^{-1})**	29 (5–60)	Similar to present, higher or lower	Similar to present or lower
Pelagic respiration (g C m^{-2} y^{-1})**	33 (7–66)	Similar to present, higher or lower	Similar to present, higher or lower
Benthic respiration(g C m^{-2} y^{-1})**	40 (25–73)	Similar to present, higher or lower	Similar to present, higher or lower
Net ecosystem productivity (g C m^{-2} y^{-1})**	46 (–38–225)	Similar to present, higher or lower	Similar to present, higher or lower

***Figure 5-12.** A Greenland lake surrounded by heathland vegetation. This is as an example of possible lake surroundings in Forsmark under periglacial conditions.*

of nutrients /Warwick et al. 2008/. There is an increased risk of oxygen depletion during the winter due to longer periods with ice cover. The very shallow lakes in Forsmark show signs of anoxia today, and lake depth is probably important for the occurrence of anoxia under periglacial conditions as well.

Despite a shorter growing season, biomasses of primary producers are not necessarily lower in periglacial conditions than in temperate regions. In periglacial lakes there are often large biomasses of macrophytes and microbial mats or moss mats cover the benthic habitats in some lakes in polar regions (Figure 5-13). Thus, species composition may change but it is likely that biomasses and production of benthic primary producers in periglacial conditions will closely resemble the biomasses and production in temperate conditions where the lake bottoms are covered by the macroalgae *Chara* and a microbial mat of cyanobacteria. Phytoplankton biomasses are relatively low in present-day Forsmark lakes and it is likely that the biomasses will be similar in aperiglacial climate (for further details see /Andersson 2010/).

Even if primary production remains similar between periglacial and temperate climate domains, fish biomass and production will probably decrease in periglacial conditions. Fish have to adapt to the colder climate and fish diversity is lower in a colder climate. If anoxia occurs in winter below ice, fish will be absent from the lakes. The expected effects of periglacial conditions compared to temperate conditions on abiotic and biotic parameters in lakes are summarised in Table 5-2.

Terrestrial ecosystems

The biome representing tundra (e.g. group E subgroup Tundra ET /Peel et al. 2007/), has a vegetation that is dominated by the field and bottom layer. Under periglacial conditions in Forsmark the same Quaternary deposits may be assumed to be present as under temperate conditions and potential functional vegetation types characteristic for this biome can be suggested and associated with these Quaternary deposits. A shrub layer (e.g. *Betula nana* and *Salix* sp.) may be dominating in a transition zone between the tree line and the tundra, and also be present in the tundra environment under more wet/moist conditions, e.g. on minerogenic soils close to mires or along rivers (*Salix* sp).

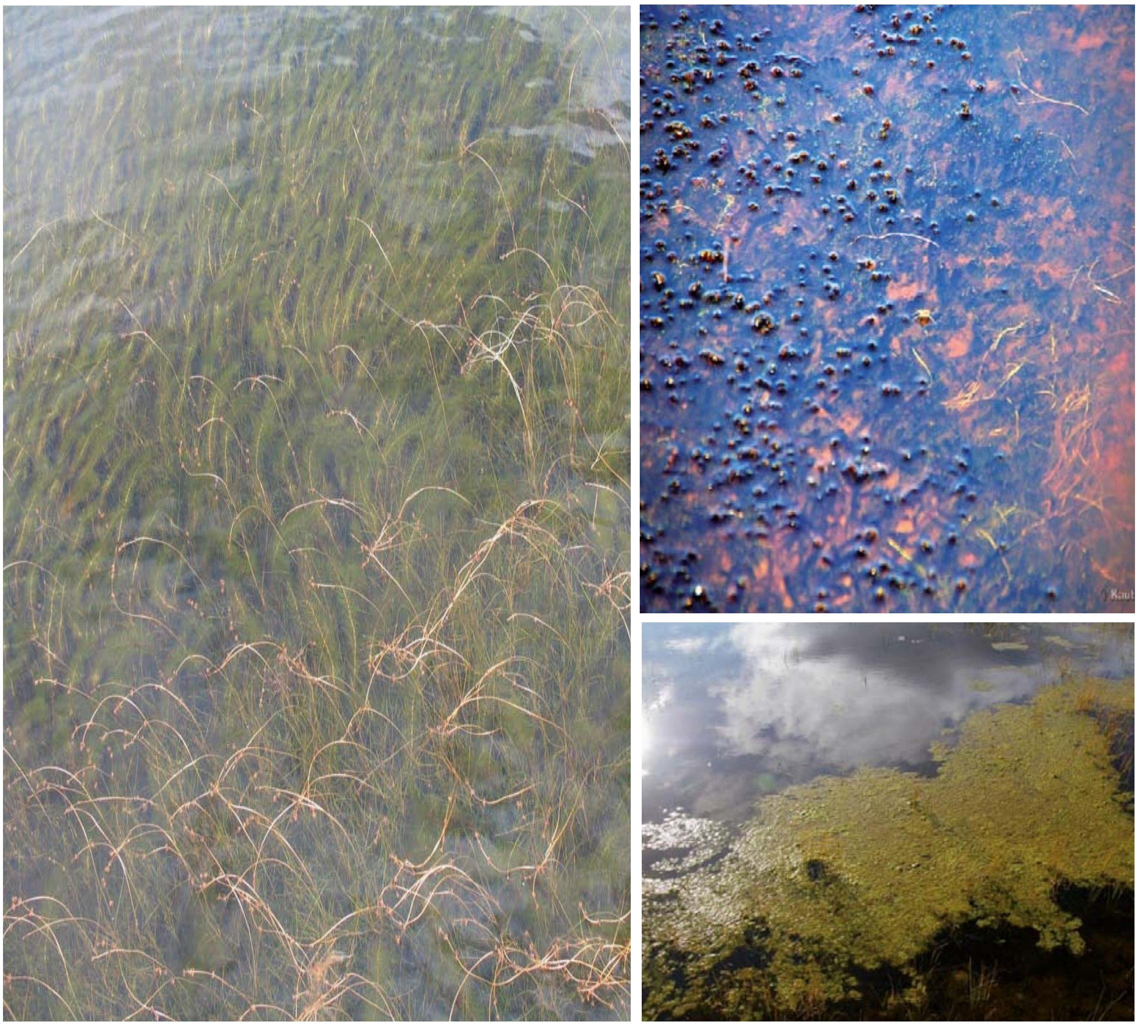


Figure 5-13. Vegetation found in Greenland lakes as examples of vegetation found in lakes in periglacial conditions. Myriophyllum sp. forms thick vegetation on the bottom of a Greenland lake (left) similar to the Chara beds in present Forsmark lakes. Thick mats of brown mosses cover some of the Greeenland lakes (upper right) and in calm areas floating vegetation may form (bottom right). Photos from lakes near Kangerlussuaq, Greenland.

Similarly, sheltered low points (which in most cases also have a deeper soil layer) would be colonised early during an advancing tree-line or will contain the last fragments of trees when the tree-line is regressing. These sheltered areas are less exposed to wind and have a warmer and moister microclimate. Heathland, dominated by dwarf shrubs, grasses, bryophytes and lichens is often found on more coarse-grained deposits on slopes and other more or less well-drained localities. Wind exposed localities on bedrock or bouldery ground under arctic/alpine conditions often have very sparse vegetation, such as epilitic lichens and some cushion-forming herbs, due to cryoturbation and wind erosion, and such areas are termed “barrens”.

The same areas that have been classified as wetlands during temperate conditions will also be wetlands in a periglacial landscape and will be dominated by sedges and bryophytes. This general vegetation description should be regarded as a rough suggestion and a number of factors such as north- and south-facing slopes or prevailing wind directions are important structuring components in regard to where these or similar vegetation types are found in a subarctic or arctic landscape /Breckle 2002, Sieg et al. 2006/. Moreover, a prevailing permafrost regime together with a lower evapotranspiration would suggest larger areas being partially or periodically water-inundated than expected from the patterns of the current landscape.

Table 5-2. Expected limnic parameter values in different climate domains compared to present (temperate). * represents a median value in present day lakes, values in brackets represent range of values measured in the present lakes, ** ranges are taken from values in the literature, * Lakes Bolundsfjärden and Eckarfjärden in Forsmark. Values are further discussed in /Andersson 2010/.**

Parameter	Temperate	Global warming	Periglacial
Abiotic parameters			
Period with ice coverage (days)	141* (98–143)	1–2 months shorter	Several months longer
Nitrogen concentrations (mg L^{-1})	0.99* (0.33–3.7)	Probably higher	Probably lower
Phosphorus concentrations (mg L^{-1})	0.01 * (0.004–0.04)	Probably higher	Probably lower
DOC concentrations*	17* (4.2–33)	Similar to present, higher or lower	Probably lower
Particulate matter (kg dw/m^3)		Similar to present or higher	Probably lower
Periods with anoxia	Only in very shallow lakes	Lower risk of anoxia in winter, higher risk in summer	Probably in winter in shallow lakes
Biotic parameters			
Phytoplankton biomass (g C m^{-3})	0.04* (0.02–0.06)	Similar to present, higher or lower	Similar to present
Microphytobenthos biomass (g C m^{-2})	3.8 * (2.8–5.8)	Similar to present, higher or lower	Similar to present
Benthic macroalage and macrophytes (g C m^{-2})	22 * (11–134**)	Similar to present, higher or lower	Similar to present
Bacterioplankton biomass (g C m^{-3})*	0.05 *	Similar to present, higher or lower	Similar to present
Benthic bacterial biomass (g C m^{-2})	3.7 * (3.0–4.2)	Similar to present, higher or lower	Similar to present
Zooplankton biomass (g C m^{-3})	0.06 * (0.02–2.3**)	Similar to present, higher or lower	Similar to present
Fish biomass(g C m^{-2})	1.0 * (0.5– 1.6)	Similar to present, higher or lower	Lower
Benthic fauna biomass g C m^{-2}	1.6 * (0.24–5.0)	Similar to present, higher or lower	Similar to present
Pelagic Primary production (g C m^{-2} y^{-1})	16 * (10–19)	Similar to present, higher or lower	Lower
Benthic primary production by macroalgae (g C m^{-2} y^{-1})	87 *	Similar to present, higher or lower	Similar to present or lower
Benthic primary production by microphytobenthos (g C m^{-2} y^{-1})	56* (34–77)	Similar to present, higher or lower	Similar to present or lower
Pelagic respiration (at 1 m depth) g C m^{-2} y^{-1}	74	Higher	Lower
Benthic respiration	73	Higher	Lower
Net ecosystem productivity *** (at 1 m depth) g C m^{-2} y^{-1}	11–15	Similar to present or lower	Similar to present

A sufficiently reduced temperature will eventually change a temperate or boreal environment to a more tundra-like environment. This will lead to lower biomasses and NPPs in both forested taiga and tundra peatlands /Gower et al. 2001, Wielgolaski et al. 1981/. Such a change might also increase relative carbon storage in relation to NPP, whereas the actual amount that is stored, e.g. as peat, will be lower than under present conditions. /Vardy et al. 2000/ compared long-term apparent rates of carbon accumulation for the boreal and arctic mires and these data suggest that permafrost mires have no more than half the carbon accumulation rate as those in the boreal region (see /Löfgren 2010/ for a review).

A lower mean annual temperature will reduce the yield of crop production, and the specific conditions found in a permafrost landscape will dramatically change the potential for cultivation. There are examples of agricultural production in tundra areas where the vegetation period is about 24 days (>+5˚C), with a mean annual temperature of around –5.9°C /Khudyakov et al. 1999/. In this area, a mixture of the perennial grasses *Poa pratensis* and *Alopecurus pratensis* was sown in artificial meadows for fodder production, but large quantities of fertilizers were used to sustain growth. Expected effects of periglacial conditions compared to temperate conditions on abiotic and biotic parameters in wetlands and arable land are summarised in Table 5-3.

Table 5-3. Examples of changes for a number of properties in wetlands and arable land in relation to the prevailing situation in Forsmark today, which represents a temperate climate in the radionuclide modelling. For further description of the changes and references see /Löfgren 2010/.

Property	Periglacial	Global warming	Comment
Abiotic			
Growing season	–	+	
Precipitation	–	–/+	In the south, it may be drier and warmer /BACC 2008/
Temperature	–	+	
Evapotranspiration	–	+	/BACC 2008/
Biotic			
Biomass	–	+	
NPP	–	+	
Soil respiration	–	+	
Soil organic matter accumulation	–	–/+	
Vegetation height	–	–/+	
Berry yield	–/+	–/+	
Fungi yield	–/?	+	
Potential game	–/?	–/+	Herbivores will migrate in the winter season in a periglacial environment
Domestic animal meat production	–	–/+	
Crop production	–	–/+	To a certain extent it will increase until it gets too dry

5.2.2 Ecosystems and landscape development

The general successional trajectories for a periglacial domain resemble the description for the temperate domain in regard to the main ecosystems, but lack human induced conversions of ecosystems such as draining of wetlands for agricultural use (Figure 5-14). There are many examples of how small and irregular human disturbances such as road building and wheel tracks may cause irreversible changes in the landscape. /Breckle 2002/ suggested that small disturbances easily can alter the natural dynamics. The landscape development may be affected by either transgressive or regressive shoreline displacement, as a potential ice sheet retreats or advances. A regressive displacement would reverse the trajectories and eventually terrestrial and limnic reservoirs would end up in a marine environment. These could either be preserved or dispersed, but would from a safety assessment perspective be of minor importance.

The ecosystems in Figure 5-14 have more or less different species composition than during a temperate climate domain, but basically the same processes in regard to accumulation of sediments and organic matter will be present. The accumulation of sediments in lakes will probably be lower, whereas in marine basins it can be similar, lower or higher than during temperate conditions. If the marine primary production is high and the grazers mismatch with the blooms, an increase in accumulation in the area or in adjacent basins will be the result. The accumulation of organic matter in fens and bogs will be slower than during a temperate domain and the transitions will consequently be slower (see /Brydsten and Strömgren 2010, Löfgren 2010/ for reviews). For example, reed will not be a part of the infilling of lakes, but the peat stratigraphy will be rather similar to periglacial peat stratigraphies, where brown mosses dominate in the bottom followed by *Carex* peat and *Sphagnum* peat. These stages are reversible depending on mire ontogeny and regional factors such as local climate.

The largest part of the land area would be dominated by till and outcrops and a similar situation as today would prevail, where rocky shores, shores with wave-washed till, sandy shores and shores with fine sediments would be found as a function of the wave exposure. These areas would be dominated by different types of heathland depending on the grain size of the underlying regolith. Possibly the more fine-grained sediments would be more wetland-like compared to the situation found today, due to the poor drainage caused by the permafrost.

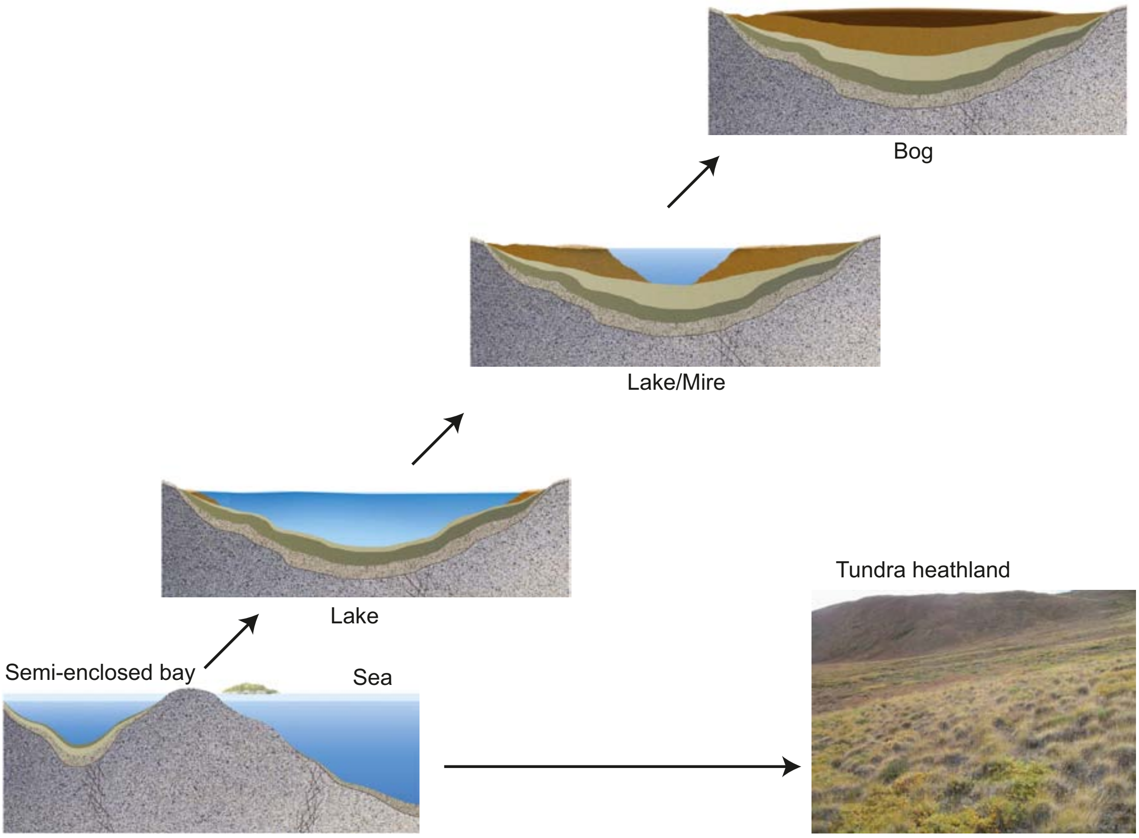


Figure 5-14. *A schematic illustration of the major ecosystems that may be found at certain points during a temporal sequence in the periglacial climate domain, where the original sea bottom slowly becomes land due to shoreline displacement. Generally, human land-use is restricted under these conditions and no large draining projects are assumed to be of importance for the large-scale structure of the landscape.*

5.3 Ecosystems in Forsmark in a global warming case

The global warming case suggests a future where anthropogenic emissions cause the present temperature to increase and the temperate conditions could be extended. /Kjellström et al. 2009/ generated data to describe the vegetation under the modelled global warming climate conditions, where the temperature increase was +3.6°C. This temperature increase is in similar range to that predicted by /Meehl et al. 2007/ for the boreal and subarctic zone, which is 1–3°C by 2029 and 5–6°C by the end of the century.

The sea level in Forsmark will be affected only marginally even if a full collapse of the Greenland ice sheet was to occur in a warming climate /Milne et al. 2009/. However, large uncertainties remain regarding the effect of a potential melting of the West Antarctic ice sheet and the amount of sea level rise due to thermal expansion of the oceans (see /SKB 2010a/). This uncertainty means that, contrary to what is seen is the modelled development of the shoreline for the global warming case, there may be a transgression in parts of the Forsmark area during the first thousands of years of the evolution.

However, in the long run the remaining isostatic uplift will result in that the Forsmark site is situated above the Baltic Sea level in the global warming case. Thus, the description of ecosystem succession for present climate conditions that is presented above (Figures 5-8 and 5-9) will, in principle, be valid also for a somewhat warmer climate. For a detailed discussion of future climate conditions, including uncertainties, see /SKB 2010a/. Ecosystem characteristics, on the other hand, may be altered due to warmer conditions. This section outlines potential ecosystem properties for ecosystems in Forsmark under the warmer conditions related to the global warming case.

5.3.1 Ecosystem characteristics

Marine ecosystems

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

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

It is likely that the thermocline in most coastal areas will move further out during the summer. As a result, the warm water species will extend their habitats at the expense of the cold water species. A similar spread of freshwater species at the expense of species with higher salinity optima is also likely to occur due to the decrease in salinity. The range of marine species will be shifted further south and may decrease, at the same time as the range and biomass of freshwater species will increase.

In the case of marine mammals, a reduction in the extent of ice cover during the winter will lead to reduced reproduction, since they need ice to breed their cubs /BACC 2008/. At present, the marine mammals only have a small impact on the structure and function of the marine ecosystems at the site. A potential decrease in abundance will only generate a very small change in the properties of the marine ecosystem, and is assumed not to have any effect on the general transfer and accumulation of radionuclides.

Considering the bird fauna of the Baltic, studies of the historical bird fauna indicate a surprisingly stable situation, i.e. practically all species currently breeding in the Baltic were present already during the Littorina stage /BACC 2008/. Some, if not most or even all, recent changes are reinvasions and reflect the climate-dependent variability of distribution range. On this basis, there seems to be no major species turnover to be expected, but the population sizes, regional distribution patterns and community structures are likely to change /BACC 2008/.

The effects of a global warming domain on the marine ecosystem are very complex and hard to predict. Although many factors may lead to increased primary production, other possible outcomes are that net ecosystem production remains the same or can be encompassed in the variation in present-day temperate conditions, i.e. the predicted change in ecosystem properties of relevance for dose modelling may span from present conditions to increases and to decreases, depending on a complex set of factors and interactions (see Figure 5-15 and Table 5-1).

At present, ecosystem changes due to climate change are preoccupying a large part of the environmental science society /BACC 2008, HELCOM 2007, MacKenzie et al. 2007, Geider et al. 2001/, and yet it is not possible to make confident predictions of development. The composition of the ecosystems may be altered due to global warming conditions although the magnitude and direction of the processes occurring will be similar to those under present conditions. For a more comprehensive discussion on possible effects on the marine ecosystem in Forsmark readers are referred to /Aquilonius 2010/.

Limnic ecosystems

Lakes are affected by global warming and lakes are proposed to serve as sentinels of climate change due to their rapid and observable responses to climate change (e.g. /Adrian 2009/). However, the response of lakes to global warming is individual and affected by catchment characteristics, lake morphometry and food web interactions, and the response of lakes to global warming is less clear than effects on terrestrial ecosystems /Blenckner 2005, Smith et al. 2008/. The effect on abiotic parameters is relatively easily foreseen whereas effects on biotic parameters are difficult to determine (Figure 5-15).

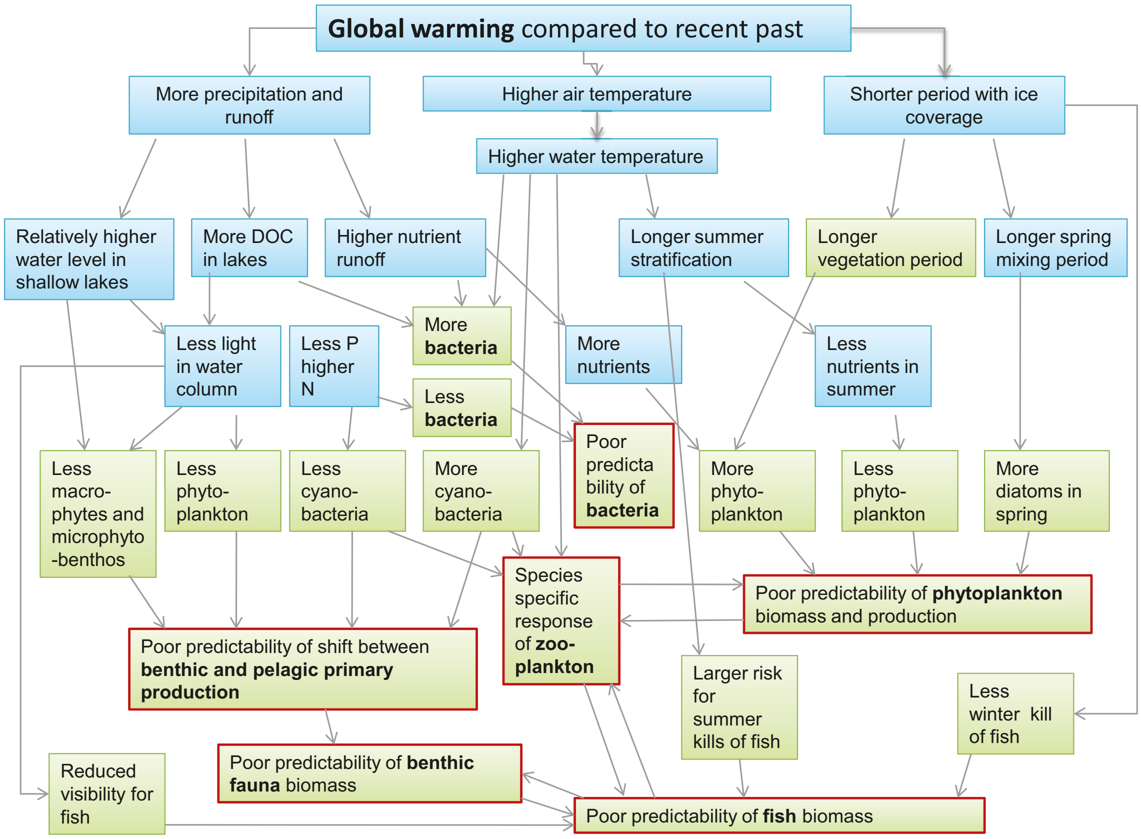


Figure 5-15. *Major effects of global warming on aquatic ecosystems compared to present situation in temperate regions. Note that although effects on abiotic factors (blue boxes) are determined with relatively high confidence, the effects on biotic parameters (green boxes) are less confident due to many interactions in the ecosystem between abiotic and biotic parameters as well as between different biotic components. Boxes marked with red borders are the expected net result on different functional groups of biota. Modified after /Smith et al. 2008/. The effects of global warming on the aquatic ecosystems are further discussed in /Andersson 2010/ and /Aquilonius 2010/.*

An increased air temperature will lead to a longer stratification period in summer and shorter periods with ice coverage, e.g. /Weyhenmeyer et al. 1999, Smith et al. 2008, Livingstone and Adrian 2009/. Since the temperature in winter in the global warming scenario will range between 0 and 6°C, there will likely be at most short periods of ice coverage interrupted by open water periods. This of course also has implications for other abiotic and biotic parameters in the lakes, such as mixing, light conditions, biomass and production.

Runoff is modelled to increase, which will influence nutrient concentrations by altered input, but also by altered retention time in lakes. Processes within the lake, such as mixing and anoxia, may influence the future nutrient concentrations in the water column and although many studies indicates higher nutrient concentrations there are also examples of reduced phosphorus concentrations due to global warming /Blenckner 2005 and references therein/. Likewise, in most lakes dissolved organic carbon (DOC) is expected to increase due to global warming. However, the effects of climate factors on DOC are complex and include combined effect of temperature, precipitation, decomposition, solubility, hydrological transport, land-use and acid depositions. Depending on climate scenario and catchment characteristics, DOC concentrations could remain similar to present /Sobek et al. 2007, Smith et al. 2008, Jennings et al. 2010, Naden et al. 2010/.

At present, DOC concentrations are very high in the Forsmark lakes which may be caused by internal release of DOC from primary producers. Therefore, if DOC input from the catchment were to increase there would likely be a decrease in internal DOC production (due to shading of primary producers by humic substances thereby reducing DOC production by primary production) and the DOC concentrations would probably remain similar to those at present under global warming conditions.

The amounts of particles in water are likely to increase in the global warming period. There are two reasons for this. Firstly, increased runoff from the catchments may increase the quantities of particles reaching the streams and lakes. Secondly, increased temperature may lead to a shift from a benthic to a pelagic food web leading to higher amounts of phytoplankton and bacteria in the water column (further discussed below).

There may be a shift in occurrence of anoxia from winter to summer. At present, anoxia occurs in the very shallow lakes in Forsmark during winter. A shortened period with ice coverage reduces the risk of anoxia in winter. On the other hand, increased production in summer can lead to increased amounts of degradable matter, resulting in increased respiration and increased anoxia during summer stratification (when the water column is divided into an upper and a lower layer that are not mixed with each other). An example of the latter situation is the German Lake Müggellsee where anoxia increased during summers with increased temperatures /Wilhelm and Adrian 2008/.

As stated above, the effect on biotic components in lakes are difficult to foresee and there may be an increase or decrease in phytoplankton biomass. There may be a shift in species composition towards more cyanobacteria which may cause nuisance to animals and humans. There may also be a shift from benthic to pelagic primary production or the production may remain in the benthic habitat. Fish biomass may increase or decrease due to global warming. However, the fish biomass is already relatively high in Forsmark, so the biomass will probably remain similar to present or decrease. Possible effects on abiotic and biotic parameters in a global warming conditions compared to the recent past are summarised in Table 5-2. For a more comprehensive discussion on possible effects on the Forsmark lakes, readers are referred to /Andersson 2010/.

Terrestrial ecosystems

A warmer climate usually means potentially more biomass and NPP, as well as reduced carbon storage in the short term depending on the magnitude of the climate change /Chapin et al. 2002, BACC 2008/. /Craft et al. 2008/ showed that C sequestration was negatively correlated to the mean annual air temperature for temperate freshwater peat lands in the U.S. A similar pattern has also been described from the former Soviet Union, where a lower accumulation of peat was found under more temperate conditions compared to boreal conditions /Gorham 1991/. Peat production in peat lands is also a function of precipitation, and a higher temperature combined with more precipitation may result in periods of unchanged peat accumulation under warmer conditions.

Modelling of the vegetation with the dynamic vegetation model LPJ-GUESS (e.g. /Sitch et al. 2003/) generated data to describe the vegetation under the modelled global warming climate conditions, where the temperature increase was +3.6°C /Kjellström et al. 2009/. Boreal coniferous forests shifted northward relative to their present-day distribution due to warm winters that preclude regeneration in southern parts of their current range /Sykes and Prentice 1995/, while dry summers with enhanced evapotranspiration relative to recent past conditions limit tree growth in Mediterranean areas.

The modelling result suggests that Forsmark would be dominated by broadleaved trees with larger biomasses but almost similar NPP as today. Other modelling approaches, e.g. /BACC 2008/, suggest a climate response where forest productivity and biomass increase. They also highlight the uncertainties concerning the carbon dynamics in wetlands. An increased temperature, with an increased evpotranspiration, will likely lower the groundwater table and increase heterotrophic respiration. This can initially be balanced by an increased plant production in the mire, which is enhanced by drying. /Strack et al. 2008/ suggested that dry peatland areas such as bog hummocks and ridges will act as smaller sinks or sources of CO_2, whereas wet zones will likely become greater sinks.

5.4 Transitions between climate domains

Transitions between different vegetation types due to a changing climate may lead to other responses that are difficult to predict. The recent debate concerning effects of global warming has generated literature describing mostly short-term responses to temperature increases spanning over a few degrees. Reviews, e.g. for temperate and boreal forests /Hyvönen et al. 2007/ and peatlands /Limpens et al. 2008/, have shown that single-factor responses can be misleading due to the large number of interactions between different factors and feedbacks.

From the perspective of a safety assessment, the most critical scenario is if large pools of organic matter/biomass were suddenly released during a short time span as a consequence of a transition between two climate domains. This release could then again be accumulated and reach even higher concentrations compared to the original situation. If no secondary accumulation occurs, the release would eventually only lead to dispersal and dilution of the radionuclides. Transitions between climate domains (as defined above) are generally slow processes spanning thousands of years, but there may be cases where sudden changes could occur as a response to long-term changes reaching a threshold. However, the extent and magnitude of such potential sudden changes as an effect of climate change must still be regarded as poorly known.

5.4.1 Transition from a colder to a warmer climate

Generally, it has been suggested that an increased temperature has a negative effect on the water table and a positive effect on decomposition and causes a general decline in carbon sequestration in wetlands in the long term (e.g. /Limpens et al. 2008/). This is probably true for a positive temperature change in the case of temperate and boreal peatlands (the case of Forsmark today). The effects of such a change for frozen peatlands, causing the permafrost to thaw, will, however, be more uncertain /Limpens et al. 2008/. The water released by the melting of the ice may increase the water residence time, promoting peat formation and thus local carbon accumulation but increasing CH_4 emission. However, if the permafrost layer is impermeable, the thawing will lead to drainage, stimulating decomposition processes /Hilbert et al. 2000/.

The C sequestration rate of collapse scars in thawing peat lands may be high /Myers-Smith et al. 2008/ and a future climate warming could lead to increased collapse and thereby peat expansion and greater carbon storage /Camill and Clark 1998, Robinson and Moore 2000/. In peatlands with discontinuous permafrost, severe fire events may contribute to permafrost thawing, leading to more permanent vegetation changes and potentially increasing carbon accumulation in the long term /Kuhry 1994, Schuur et al. 2008/.

5.4.2 Transition between a warmer and a colder climate

A transition from the climate prevailing today to a colder climate has been investigated and discussed to a lesser extent. Generally, the opposite pattern compared to a transition to a colder climate, would be suggested from patterns across different climates. More temperate fens/peatlands would be able to accumulate more peat, whereas northern peat lands would have a slower accumulation rate, but preserve the peat accumulated previously.

5.5 Historical and present land-use

In this section, the historical development of human land-use is discussed. The agricultural land is the most intensively managed land in the landscape and is a major provider of food for human consumption, either directly as crop production or as production of fodder and other types of feed for animals. The agricultural land is further divided into semi-natural grasslands and arable land.

Present and historical land-use can be used to predict future land-use. The focus of the description of historical land-use is those aspects that are of importance for radionuclide modelling. For a number of radionuclides, cultivation is the land-use that generates the doses to human. The focus of the land-use model is consequently on areas that may be used for cultivation. To be able to model future land-use it is important to know which current Quaternary deposits are used as arable land in Forsmark and surrounding areas. It is also important to know to what extent current and former wetlands (peat) are used for cultivation, since these areas are assumed to receive radionuclide releases. Special attention is paid to agriculture on peat, since peat is formed in wetlands and may be utilised for agriculture.

5.5.1 Historical land-use

A major part of the Forsmark model area was completely covered by water until c. 1500 BC. The known development of human land-use is therefore based on information gained outside the Forsmark area. After the deglaciation of the last glacial, forests of mainly *Betula* (birch) and *Pinus* (pine) covered Sweden for several thousands of years. In the Holocene, temperatures reached a thermal maximum between 5500 and 2000 BC, the summer temperature in southern Sweden was then c. 2° warmer than at present /Antonsson and Seppä 2007/. Forests with *Tilia* (lime), *Quercus* (oak) and *Ulmus* (elm) then covered large parts of southern Sweden. The temperature decreased after this warm period, and the forests became increasingly dominated by coniferous trees.

Before the Younger Stone Age (4000–1800 BC), the impact of human activities on the natural landscape was small and almost all terrestrial areas in South- and Mid-Sweden were consequently covered by forest. In southern Sweden during the first phase of the Younger Stone Age, the dense forests were cleared /Hyenstrand 1994/, often by the use of fire, and the open areas created were first cultivated for some years and then used as grazing land. When the available soil nutrients were consumed, the area was left and became overgrown. After 30–40 years it was possible to clear and use the area again. The extensive farming, in combination with a growing population, meant that large areas were utilised. Within c. 1,000 years, human land-use had brought about large changes of the landscape in southern Sweden. /Söderbäck 2008/.

During the Bronze Age (1800–300 BC) and Iron Age (300 BC–1100 AD) the areas with cultivated soils gradually increased. Tar and lumber also became commercially important. In the past, there were no sharp borders between forest and agricultural land, as forests were grazed and areas were mowed or cultivated in non-permanent fields. Extensive grazing of livestock in the forests is believed to have been an important factor affecting the plant communities around villages in the more densely populated parts of Sweden. Iron mining has had an important role in the Forsmark region since the Iron Age. As the iron industry became more organised in the 16th century, forests were cut down to feed furnaces and mines with wood and charcoal. The region around Lake Mälaren was almost depleted of trees at the end of this period /Welinder et al. 1998/.

The use of areas to provide summer fodder for animal husbandry has changed over time, where the use of wood pastures once was common when most of the suitable land areas were cultivated. Today, a large part of livestock grazing and hay-making takes place in former arable fields with richer soils and higher nutrient content due to fertilisation.

Before the modernisation of agriculture, 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 were used for cultivation close to the villages in the 17th and 18th centuries /Cousins 2001/. Areas with clay or peat are often characterised by a high groundwater table and were instead used for mowing. As management intensity and population increased, more of the medium-fertile soils were used for agriculture, whereas the poorest soils were set aside for grazing /Rosén and Borgegård 1999/. The modernisation of agriculture made it possible to drain areas with peat and clay for cultivation. Mires, especially fens, have been converted to arable land from the mid 19th century. This has been done by lowering the groundwater table in mires and lakes by ditches.

During the 18th to 20th centuries there was a demand for increased food production since the population was growing. This resulted in extensive ditching of wetlands and lowering of lake surfaces which considerably changed the landscape. The proportion of open landscape was largest in the late 19th century. However, this trend came to an end as management was rationalised by the use of fertilisers and better equipment in the early 20th century. Sweden has subsequently experienced a nationwide regression in agricultural activities. During the late 1900s, farmers have been encouraged to plant coniferous trees on arable land, thereby accelerating the succession into forest.

One example showing how the proportion of QD used as arable land has changed through time comes from Valö close to Forsmark. /Berg et al. 2006/ shows that during the beginning of the 19th century most arable land was situated in areas with glacial clay and till (Figure 5-16). These deposits could be cultivated relatively easily without any extensive ditching. Many areas with clay and peat were wetlands and meadows where the groundwater table then was too high for cultivation. The available technique at that time probably did not allow ditching and cultivation of these areas. A large proportion of these former wetlands is today used for cultivation (Figure 5-17). It is possible that these areas have been covered by a peat layer which has oxidised during the usage as arable land (see below).

The usage of peat as arable land is a rather recent phenomenon. Extensive draining of wetlands started a bit more than hundred years ago and peaked in the 1930s in Sweden /Eliasson 1992/. The proportion of peat used as arable land was largest during the mid-part of the 20th century and has thereafter decreased. Many mires in Sweden have been be drained and in some areas in the south of Sweden as much as 90% of the wetlands have been drained /Svanberg and Vilborg 2001/.

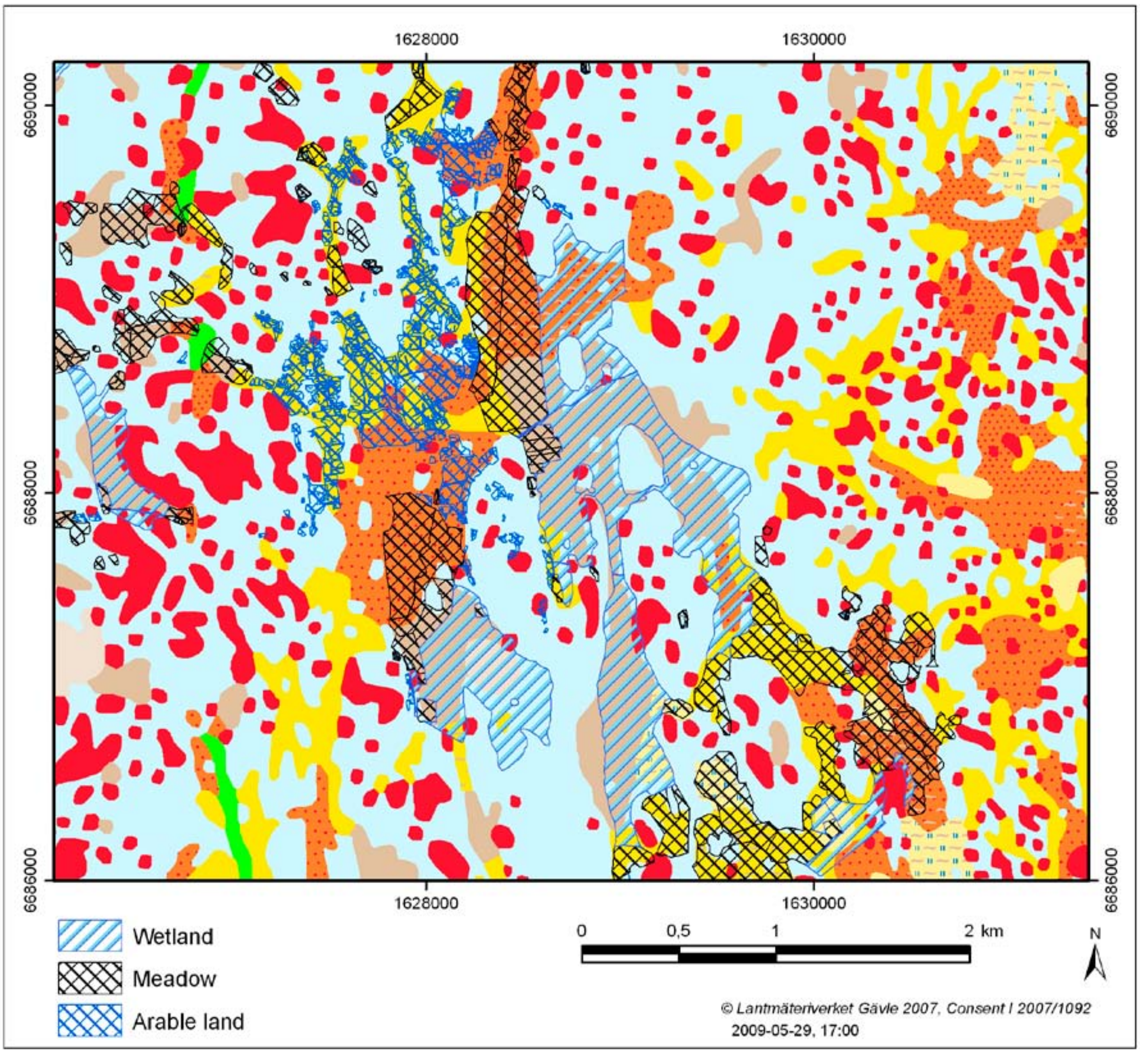


***Figure 5-16.** The map shows the distribution of arable land, meadows and wetland at the beginning of the 18th century (1709) around the village of Valö west of Forsmark. Most arable land was situated on till (blue) or glacial clay (dark yellow). The distribution of Quaternary deposits (QD) was mapped by SGU for presentation at the scale 1:50,000 (see Figure 4-10 for QD map).*

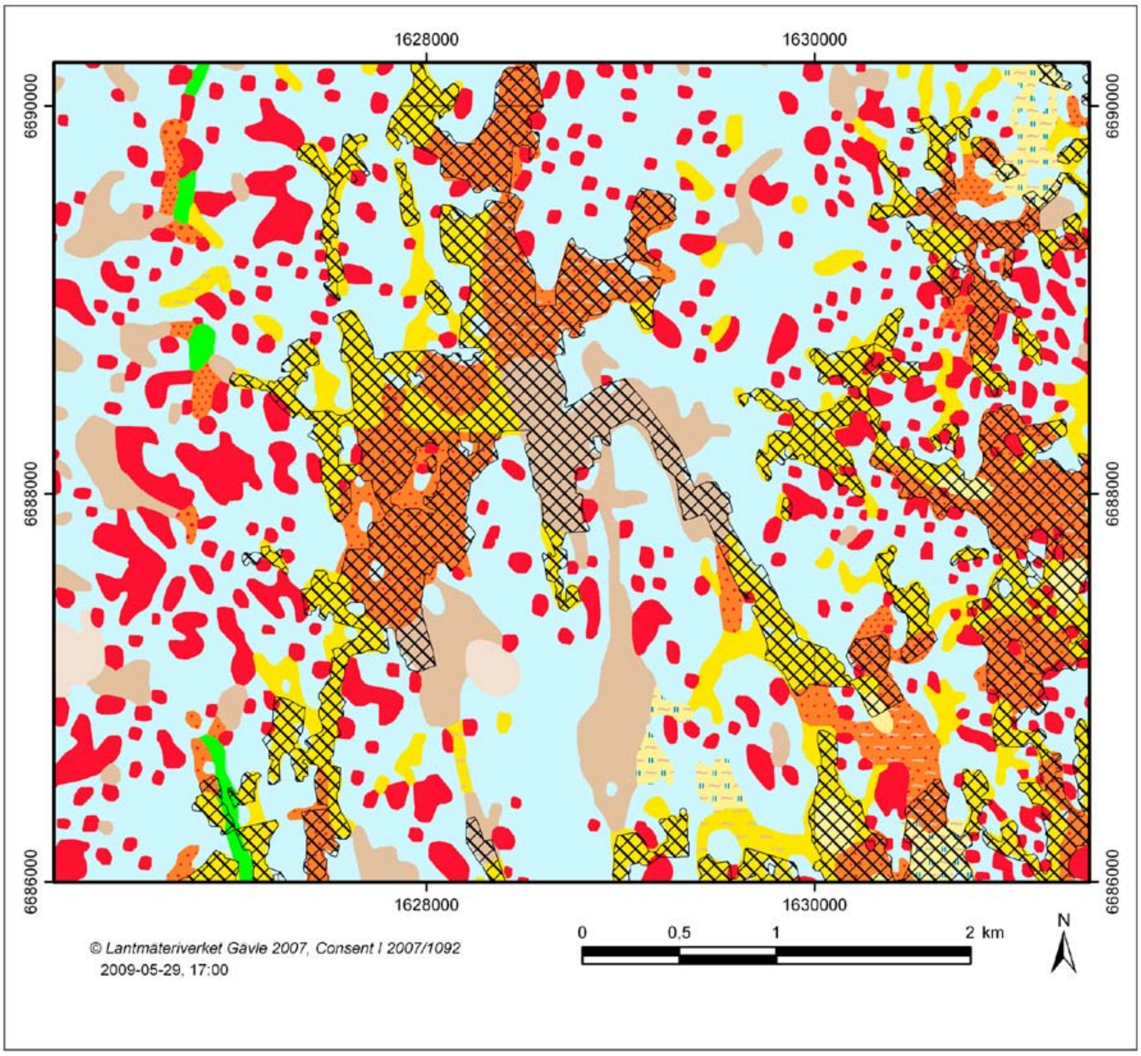


Figure 5-17. The present distribution of arable land (crosshatched) close to Valö west of Forsmark. Most of the arable land in this area is situated on peat (brown), clay (yellow) or sand (orange). The distribution of Quaternary deposits (QD) was mapped by SGU for presentation at the scale 1:50,000 (see Figure 4-10 for QD map).

5.5.2 Present land-use in Forsmark and Uppsala county

Today most arable land in the County of Uppsala is situated on glacial and postglacial clay (see Table 5-4). These deposits are, however, almost lacking in the terrestrial part of the present Forsmark area and the proportion of arable land is therefore low.

According to the land-use data, the agricultural land in the Forsmark area comprises 84 ha, of which 34 ha is arable area and 50 ha is classified as semi-natural grasslands or pastures /Löfgren 2010/. Only around 10% of the total agricultural area (arable area and pasture) is used for production of grain and vegetables. According to /Johansson 2005/ the total agricultural area (including the area needed to produce imported food) for food consumed in Sweden 1997–2000 was 4 million ha, or 0.44 ha per capita. The dominant crop type was fodder crops for animal production, which were grown on 74% of the agricultural area. This means that 26% of the agricultural area is used for production of grain and vegetables for human consumption in Sweden. Accordingly, the current land-use situation in the Forsmark area is more concentrated on production of fodder and grass for domestic animals than the agricultural land area in Sweden in general.

To be able to predict the land-use in the future Forsmark area, the land-use possibilities in areas that resemble the future Forsmark were studied. The municipality of Östhammar and the County of Uppsala were chosen for that purpose. Focus was put on studying which QD are presently cultivated. The proportional distributions of QD in the County of Uppsala and the municipality of Östhammar are shown in Table 5-5. Sandy till is the outstanding most commonly occurring QD in these two areas.

Table 5-4. The proportional distribution of Quaternary deposits on arable land in the County of Uppsala and municipality of Östhammar.

Quaternary deposit	Uppsala %	Östhammar %
Peat	2.9	5.5
Young fluvial sediments	0.4	0.1
Gyttja	0.0	0.2
Clay gyttja – gyttja clay	6.1	13.5
Postglacial sand	4.4	11.4
Postglacial clay	41.3	12.2
Glacial clay	34.9	40.1
Silt	2.5	0.9
Gravel	0.1	0.5
Glaciofluvial sediments	0.4	0.7
Gravelly till	0.1	–
Clayey till	0.4	3.4
Sandy till	4.5	7.5
Outcrops	2.0	3.9
Artificial fill	0.0	–

Table 5-5. The areal distribution of Quaternary deposits in the County of Uppsala and municipality of Östhammar.

Quaternary deposit	Uppsala %	Östhammar %
Peat	9.4	11.3
Young fluvial sediments	0.3	0.0
Gyttja	0.0	0.1
Clay gyttja – gyttja clay	2.3	3.0
Postglacial sand	3.3	3.3
Postglacial clay	11.7	1.7
Glacial clay	15.3	9.7
Silt	0.9	0.2
Gravel	0.5	0.7
Glaciofluvial sediments	1.1	0.6
Gravelly till	0.8	–
Clayey till	1.2	2.9
Sandy till	40.3	45.8
Outcrops	12.7	20.5
Artificial fill	0.2	0.2

Arable land shown on the GSD-Topographic Map (from: Lantmäteriet) was compared in GIS with the distribution of QD shown on SGU's maps (Scale 1:50,000). Table 5-4 shows that most of the arable land is situated in areas with water deposited clays (glacial and postglacial) and postglacial sand. Only a small fraction of the arable land is situated in areas with peat and till. The till in most areas has a high content of boulders and stones and is therefore not suitable for cultivation. However, areas with fine-grained till with a low content of stones and boulders can be cultivated relatively easily. Large areas with clayey till with a low boulder frequency are rare in the County of Uppsala. However, one such area is the cultivated clayey till around Storskäret in the Forsmark regional model area (Figure 5-18). That is one of the largest coherent areas with clayey till in the County of Uppsala. Since most arable land in the Forsmark area is situated on till, that area differs from the County of Uppsala in general.

The proportions of different QD used as arable land in Uppsala County and Östhammar municipality are shown in Table 5-6. It is clear that a high proportion of the glacial and postglacial clays are used for cultivation. Almost all postglacial clay is used as arable land whereas a smaller proportion of the glacial clay is cultivated. Only a small proportion of the peat-covered areas are cultivated.

Table 5-6. The proportion of Quaternary deposits, which are used as arable land in the County of Uppsala and municipality of Östhammar.

Quaternary deposit	Uppsala %	Östhammar %
Peat	7.2	5.9
Young fluvial sediments	24.9	88.4
Gyttja	13.2	28.2
Clay gyttja – gyttja clay	61.6	54.6
Postglacial sand	30.2	42.3
Postglacial clay	81.1	86.0
Glacial clay	52.4	49.7
Silt	62.2	50.0
Gravel	6.0	7.9
Glaciofluvial sediments	7.2	12.8
Gravelly till	1.6	
Clayey till	8.7	14.1
Sandy till	2.5	2.0
Outcrops	3.6	2.3
Artificial fill	3.4	0.5
Total	22.9	12.0

Figure 5-18. *In the Forsmark model area a relatively large proportion of the arable land is situated on clayey till. The till is unsorted with respect to grain size and has a high content of stones and gravel compared to most other soils used as arable land. In a regional perspective, clayey till is not frequently occurring and the arable land in Forsmark is one of the largest cultivated areas with clayey till in the County of Uppsala.*

5.5.3 Cultivation of peat

The successional stage of a wetland is of importance for the possibility to drain the wetland and use it for agricultural purposes. A mire may be considered to be a discharge area. At a certain point, the peat accumulation will make the surface of the mire hydrologically independent of the landscape, and a bog has developed. At that point, the wetland has reached an ombrotrophic stage where the production of vegetation is all rain-fed. The peat developed during ombrotrophic conditions has low nutritious value (i.e. the C:N-ratio is high /Osvald 1937/) and low pH, and this peat can therefore be regarded as less suitable for agricultural purposes /Berglund 1996b/. Moreover, the potential accumulation in vegetation of radionuclides entering from below will level off as the bog plane rises.

Although the proportion of peat used as arable land has decreased in the last few decades, peat is still used as arable land (Figure 5-19 and Figure 5-20). It is, however, likely that many areas that today consist of postglacial clay or clay gyttja formerly were covered by peat layers, which now have oxidised. Peat presently used as arable land is almost always situated in areas bordering areas with sand or clay, whereas organic deposits such as gyttja are uncommon in areas used for cultivation. That suggests that the cultivated peat is underlain by minerogenic fine-grained deposits, which can be used as arable land when the peat has oxidised. That also suggests that peat underlain by gyttja is not commonly cultivated. Peat underlain by gyttja is often found in wetlands which have been preceded by a lake stage. Former lakes are consequently not frequently used as arable land.

Fen peat is often suitable for cultivation due to large amounts of plant-accessible nitrogen. It is possible to cultivate peat areas where the peat layer is several metres thick. One large disadvantage with the use of peat areas for cultivation is that the peat layers subside fast after the onset of ditching. The ditches must therefore be deepened at short intervals, which may be expensive and take a lot of work. That problem is further discussed in the text below.

The areas used as arable land in eastern Uppland have decreased since 1950 (cf. /Berg et al. 2006/). Also the proportion of small areas used for cultivation has decreased since 1950. A qualitative comparison between the present and 1950 distributions of arable land shows that the types of QD that are used for cultivation have not changed significantly (Figure 5-20). However, the proportion

Figure 5-19. *A cultivated peat covered area where the groundwater table has been lowered by ditches. The peat material, which is exposed in the mole heaps, is characterised by its distinctive black colour (Photo: Esko Daniel SGU).*

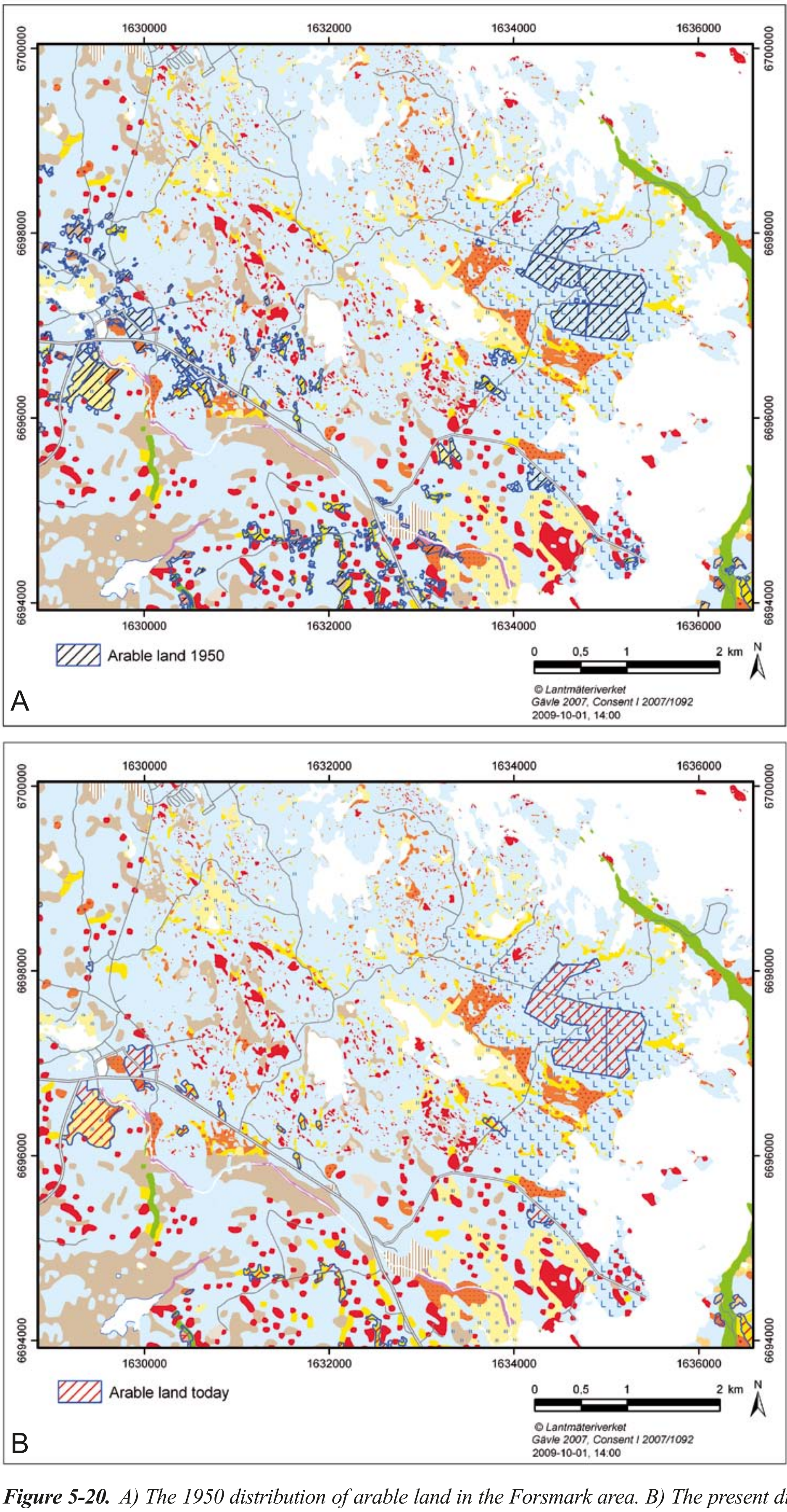


Figure 5-20. *A) The 1950 distribution of arable land in the Forsmark area. B) The present distribution of arable land in the Forsmark area. Many of the small areas used for cultivation have been abandoned since 1950. The maps of Quaternary deposits (QD) from /Hedenström and Sohlenius 2008/ is shown as a background (see also Figure 4-10).*

of organic deposits used for cultivation in the whole of Sweden has decreased significantly during the last 60 years. According to /Hjertstedt 1946/ 12.3% of all areas with organic deposits in Sweden were used as arable land during the mid 20th century.

This corresponded to 20% of all cultivated land, or 705,000 ha. Most of these organic deposits were classified as peat, but a minor proportion was classified as gyttja (11%). /Berglund Ö et al. 2009/ has compared SGU's maps of QD and the area used as arable land. According to that study around 6% of the cultivated land is presently situated on peat deposits, which corresponds to 160,000 ha. That value also includes areas shown as a thin coverage of peat (<0.5 metre) on SGU's maps of QD. Additionally, c. 2% of the cultivated areas are situated on gyttja deposits mainly clay gyttja and gyttja clay (cf. /Berglund Ö et al. 2009/). Since the quality of the QD maps is much higher now than 60 years ago, the estimation of cultivated organic deposits made by /Berglund Ö et al. 2009/ is most probably better than the estimations made by /Hjertstedt 1946/.

The present proportion of cultivated peat deposits in the County of Uppsala (5.0%) is close to the Swedish average /Berglund Ö et al. 2009/. The proportion of arable land with peat coverage exceeding 0.5 metre is 2.9% (Table 5-4). One reason for the decreased proportion of cultivated peat areas during the last 60 years may be that the peat layers have oxidised and many present areas with arable land are situated on deposits underlying the former peat layer. It is, however, clear that large peat areas formerly used for cultivation have been abandoned. Today it is generally not allowed to make new ditches in areas unaffected by ditches, and peat-covered wetlands are at present not converted to arable land in Sweden.

/Osvald 1937/ made one of the most thorough discussions regarding cultivation of Swedish peat covered wetlands. Bog peat is characterised by low pH and low contents of nutrients and is consequently not suitable for cultivation. It is, however, possible to cultivate bog peat after adding sand and clay. Fen peat is more often suitable for cultivation, since the pH and contents of nutrients are relatively high. It is not possible to cultivate wetlands with thin peat layers if the peat is underlain by deposits that are not suitable for cultivation (e.g. till). /Osvald 1937/ never discusses how thick the peat layer must be to make cultivation possible. The groundwater table has to be situated around one metre below the ground surface to make cultivation of peat possible. The peat subsides considerably when the groundwater is lowered and the original peat layer must therefore be considerably thicker than one metre to make cultivation possible. It can therefore be assumed that a peat layer must be at least 2 metres thick, when underlain by deposits not suitable for cultivation. The thickness of the peat must be even larger to make cultivation possible if the peat is underlain by till with large boulders.

/Runefelt 2008/ describes the cultivation of a large number of the peat covered wetlands in Sweden during the beginning of the 20th century. /Berglund 2008/ discusses cultivation of peat and in what manner ditching and subsidence affect the peat layers. One example of that is a result from studies of an area with peat north of the town of Uppsala (Bälinge mosse) /McAfee 1985/. The groundwater table in that area was lowered by ditches during the beginning of the 20th century and the peat layers have thereafter successively subsided. More than 1.5 metres of peat have disappeared on large parts of the cultivated former mire. The peat is underlain by clay which is well suitable for cultivation. It has, however not been possible to continue the use of the whole area as arable land since it is partly difficult to drain. That example shows that many former wetlands can only be used for cultivation for a short period of time. Whether an area can be used for cultivation after the oxidation of the peat depends on the properties of underlying deposits and the drainage possibilities. One reason for the decreasing proportion of cultivated peat areas is most probably that it is difficult to maintain the drainage due to subsidence of the peat.

As mentioned earlier, the peat slowly oxidises in areas where the groundwater table has been lowered by ditches. The rate of that oxidation has not been measured in the investigated area. Data presented in /Kasimir-Klemedtsson et al. 1997/ show that the total subsidence in cultivated peat areas can vary between 0.5 and 3 cm/year. Around 70% of that subsidence can be attributed to oxidation.

The rate of peat subsidence depends on several factors. The first years after draining are dominated by a relatively fast subsidence, which is caused by consolidation of the peat. The magnitude of that consolidation is to a large extent determined by the thickness of the initial peat layer. After some years the thickness of the peat layer decreases more slowly and oxidation is the main process involved in that decrease. The rate of oxidation is to a large extent determined by the type of crops that are cultivated /Kasimir-Klemedtsson et al. 1997/. Cultivation of potatoes and carrots demands intensive mixing of the soil and causes fast oxidation (2–3 cm/year). The oxidation during cultivation of cereals is 1–2 cm/year whereas an area used for grass subsides at 0.5 cm/year. Around 70% of the cultivated organic deposits are today fallow field or grazing ground. The rate of subsidence on large part of the cultivated organic deposits is consequently relatively low.

/Stenberg 1936/ studied a peat covered mire in Jämtland where the groundwater table was lowered by ditches. The uppermost 50 cm subsided 14 cm during the first ten years after draining (Table 5-7). /Agerberg 1956/ studied the lowering of the ground surface in a cultivated area with fen peat in Norrbotten. The study lasted for more than 40 years after the area was cultivated. During that time the ground surface was subsided c. 0.8 metre. The original thickness of the peat was 2.6 metres.

/Berglund 1989/ studied the lowering of the ground surface in a cultivated area with bog peat in Småland. The study lasted for almost 30 years. During that time the ground surface subsided almost 0.8 metre. The original thickness of the peat layers was 3.4 metres. Subsidence was fastest during the first five years. Later on the relative importance of oxidation increased.

According to /Berglund 1996a/ (Table 5-8) the dry density of fen peat in cultivated areas typically varies between 0.2 and 0.6 g/cm^3. In another study /Berglund 1996b/ determined the dry density of peat in a cultivated area. The density varied between 0.18 and 0.26 g/cm^3. The dry density of the undrained peat in the Forsmark area is around or below 0.1 g cm^3. That means that the thickness of the uppermost, cultivated peat layer will decrease by at least a factor of two or three after draining. That is a high value compared to the result presented by /Stenberg 1936/. However, Stenberg's study comprises a relatively short period of time (10 years) and it is likely that the total subsidence is higher in a peat-covered area that has been cultivated for several tens of years. It is not known for how long the peat studied by /Berglund 1996b/ has been cultivated.

Table 5-7. The average decrease of peat thickness during the first ten years (1922–1932) after a mire in northern Sweden was cultivated /Stenberg 1936/. The decrease of thickness is mainly due to compaction.

Original depth of peat (cm)	Subsidence (cm)	The subsidence in % of the original peat depth
0–50	14	43.0
60–100	20	24.0
110–150	24	18.3
160–200	27	15.4
210–250	33	14.2
260–300	38	14.2
>300	41	12.4

Table 5-8. Physical characteristics of cultivated organic soils in comparison with mineral soils (from /Berglund 1996a/).

Type of QD	Dry bulk (density g/cm^3)	Porosity (% by volume)
Moss peat	0.07–0.2	85–95
Fen peat	0.1– 0.6	70–91
Gyttja	0.2– 0.4	81–89
Clay gyttja	0.3– 0.8	69–84
Gyttja clay	0.5– 1.1	60–78
Mineral soils	1.0– 1.7	40–60

Also gyttja sediments subside as an effect of draining. /Berglund et al. 1989/ has determined the properties of cultivated gyttja sediments from different parts of Sweden. The organic content is not higher in the upper parts of the soil profiles situated above the groundwater table compared to the sediment at lower levels. It can therefore be assumed that the organic material in the gyttja soils has not been subjected to any significant oxidation. The dry bulk densities in these samples are between two and three times higher compared to samples with corresponding content of organic material from lakes in the Forsmark area. It can consequently be assumed that the thickness of the gyttja sediments investigated by /Berglund et al. 1989/ is two to three times thinner than their original thickness. It is not known for how long the sites investigated by /Berglund et al. 1989/ have been cultivated.

In summary, it can be assumed that the thickness of both the cultivated peat and gyttja layers may decrease by a factor of two or three due to cultivation. Even though a relatively small proportion of the former wetlands have been drained for agricultural purposes many of the former wetland areas in the County of Uppland have been drained for improving forest growth. That has caused subsidence and oxidation of peat in large areas. These processes are, however, much slower in forested areas compared to areas used as arable land. Some wetlands have been drained for exploration of fuel peat. Peat is a national energy resource although at present it is only used to a small extent. /Fredriksson 2004/ studied the composition of peat in two wetlands in the Forsmark area. The sulphur content is higher than normal in one of the wetlands, “Stenrösmossen”, which often is the case in this type of fen along the Baltic coastline. That peat is therefore not suitable as fuel for environmental reasons. Furthermore, both the thickness of the peat layers and the peatland areas are small. It is therefore possible that the peats in the area generally do not fulfil the demands of the present peat industry.

5.6 Future land-use at Forsmark

Historical land-use can be used to evaluate the future land-use as described above. Below follows a discussion on types of agricultural land and wetlands that may be used for agriculture and development of agricultural land. A land-use model is described where four variants of future land-use are modelled. The input data are fully described and resulting maps of possible future land-use are presented below.

5.6.1 Land-use development

Many of the features typical of the present interglacial are probably also typical for past and future interglacials. The development from a relatively cold climate with coniferous forest to a warmer climate with deciduous forest and finally back to a colder climate is typical for the development during an interglacial. The succession of different types of forests may however be altered by human land-use. The interglacial climate may partly be warmer than the present and it is possible that the temperature during the present interglacial will increase as an effect of burning of fossil fuels. This may result in a higher yield from the arable land (cf. /Eckersten et al. 2007/). It is also likely that cold conditions with permafrost or sparse forest will characterise the County of Uppsala during many thousands of years in the future. Such periods with a climate colder than during the interglacials are often referred to as interstadials. Such conditions will be unfavourable for agriculture. It can, however, not be ruled out that certain areas can be cultivated in some form also under permafrost conditions /Archegova 2007/.

The future development of the Forsmark area will be strongly affected by shoreline regression. The general distribution of QD in the County of Uppsala will probably be similar to the present after the next glaciation, with topographical high areas dominated by till and exposed bedrock, and low areas dominated by clay and peat (see Section 4.2). However, the geographical distribution of glaciofluvial eskers is dependent on glacial hydrological conditions and may therefore be different after the next glaciation. Furthermore, the proportion of QD and exposed bedrock can probably vary between the interglacials, due to e.g. different glaciological conditions during the formation of till.

If humans are around after the next glaciation it is likely that suitable deposits will be cultivated. That may take place faster than after the latest deglaciation since the technical and agricultural knowledge then probably will be higher. In the future it is therefore possible that arable land on peat and clay can be cultivated as soon as the hydrological conditions permit. The deposits most favourable for cultivation, glacial and postglacial clays, are situated in the valleys. The County of Uppsala will probably be covered by water after the next deglaciation, and the first areas uplifted will be dominated by till and exposed bedrock. The proportion of arable land will therefore be low during the initial phase of an interglacial, but will increase significantly as the valleys are lifted above sea level.

Future use of arable land

The present and past distribution of arable land can be used to predict which areas are likely to become cultivated in the future. In the present Forsmark area, most arable land is situated on clayey till (Figure 5-18). The cultivated till areas differ from most other areas where arable land is situated on water-laid deposits. The former deposits are often situated in the topographical high areas whereas the latter are situated in the lowest areas. There are no observations showing the occurrence of clayey till on the present sea floor. However, clayey till occurs both on the island of Gräsö and on the mainland and it is consequently likely that clayey till also occurs on the present sea floor. All areas with clayey till are not suitable for cultivation. As an example, the relatively large areas with clayey till on Gräsö are not cultivated, probably due to a high boulder frequency. Moreover, all areas with till that potentially can be used as arable land on the present mainland are probably not cultivated. For example, there are areas with clayey till with a low boulder frequency around Storskäret, which today are covered by forest or used for pasture (Figure 5-21).

The most frequent QD used as arable land in the County of Uppsala and the municipality of Östhammar are water-deposited clays (Table 5-4). Especially the postglacial clay is to a large (over 80%) extent used for cultivation (Table 5-6). Relatively large areas with postglacial sand are also used for cultivation, especially in the municipality of Östhammar (Table 5-4). In the Forsmark model area, a relatively low proportion of the mainland is covered by sand and clay. However, the floor of Öregrundsgrepen between the island of Gräsö and the mainland comprises in a large proportion water-deposited clay and sand (Figure 5-22). When uplifted, the landscape will be similar to the landscape which is typical of the present inland, and it is likely to become cultivated in the future. Parts of the clay and sand dominated areas will, however, become covered by shallow lakes and wetlands, which successively will be covered with a layer of fen peat. Parts of the shallow wetland can probably be relatively easily drained and cultivated. Such land-use is in analogue with the present land-use on the mainland in the County of Uppsala. There are also areas with sand and clay on the present mainland which probably could be cultivated (Figure 5-21).

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

In many western nations, marginal agricultural land has been abandoned /MacDonald et al. 2000, Cramer et al. 2008/. That trend can also be seen in the Forsmark area (Figure 5-20). One reason for that trend is that artificial fertiliser has improved the yields, which has decreased the demand for arable land. The need for arable land may, however, increase in the future, due to e.g. increasing global demand for food. That would probably cause an increase in small areas used as arable land and many of the areas cultivated 60 years ago may be cultivated again. Furthermore, an increasing demand for food would probably also increase the areal use of peat as arable land.

In contrast to peat, areas with minerogenic deposits can probably be cultivated for many thousands of years. Most of the QD used as arable land, such as sand and clay, are dominated by minerogenic material. Erosion and weathering are slowly affecting these deposits. Erosion may be a fast process but not on the generally flat areas that are used as arable land in the County of Uppland. Chemical weathering is a slow process that only slowly dissolves the minerals in the minerogenic soils. The cultivated minerogenic soils will, however, be depleted in nutrients if not balanced by fertilisers.

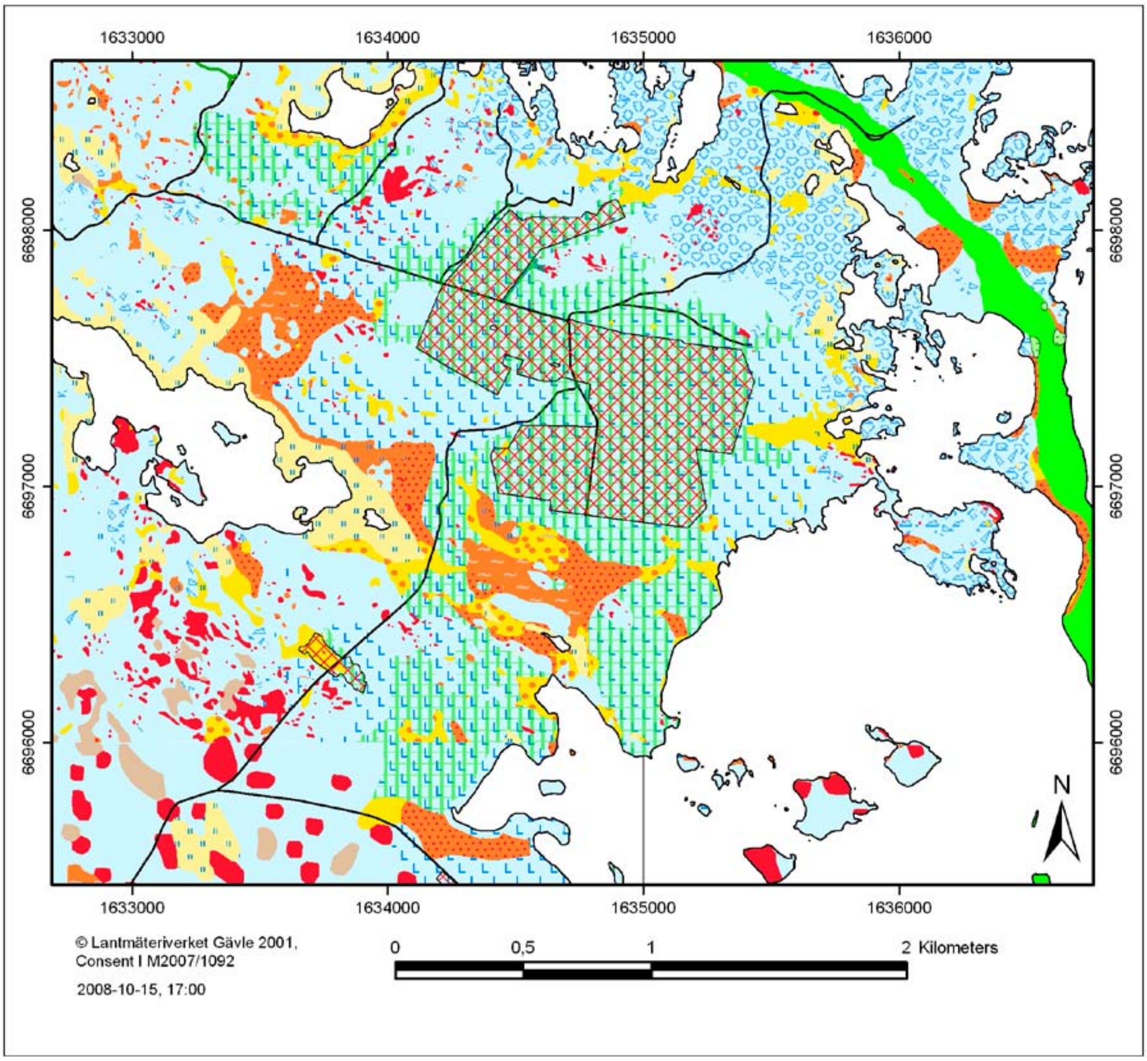


Figure 5-21. The present distribution of arable land in the south-eastern part of the Forsmark area (cross-hatched in red) is shown on the map. Almost all cultivated areas are situated on clayey till with a low frequency of boulders. There are large areas with clayey till with a low boulder frequency that are not used as arable land (green lines). These areas can probably to a large extent become cultivated in the future. Also the sand and clay can be cultivated (orange and yellow). The map of Quaternary deposits (QD) is from /Sohlenius et al. 2004/ (see also Figure 4-10).

Even though the present interglacial may last for many thousands of years, the climate will become colder in the future and permafrost will develop /Söderbäck 2008/ (see Chapter 3). Cultivation may occur also in areas with tundra soils /Archegova 2007/, but it is likely that the areal proportion of arable land would decrease significantly when tundra soils develop. A colder climate is probably the single most important factor that in the future will decrease the areas potentially used as arable land. Moreover, the cultivated species would be restricted to species for fodder production, such as grasses, in a tundra environment (e.g. /Archegova 2007/).

In the near future the climate may become warmer due to an increased greenhouse effect. That may cause increasing yields in the Forsmark area. A comparison between the present-day barley yield in the far south of Sweden (Skåne) and the Stockholm region suggests an increase of 16% (for approximately a difference of +1.5°C) /Eckersten et al. 2007/. A similar comparison between southernmost Sweden and the County of Västerbotten in northern Sweden shows a difference in yield of 122% (for an approximate difference of +5°C) /Eckersten et al. 2007/. The differences in soil properties in the compared areas were not taken into account.

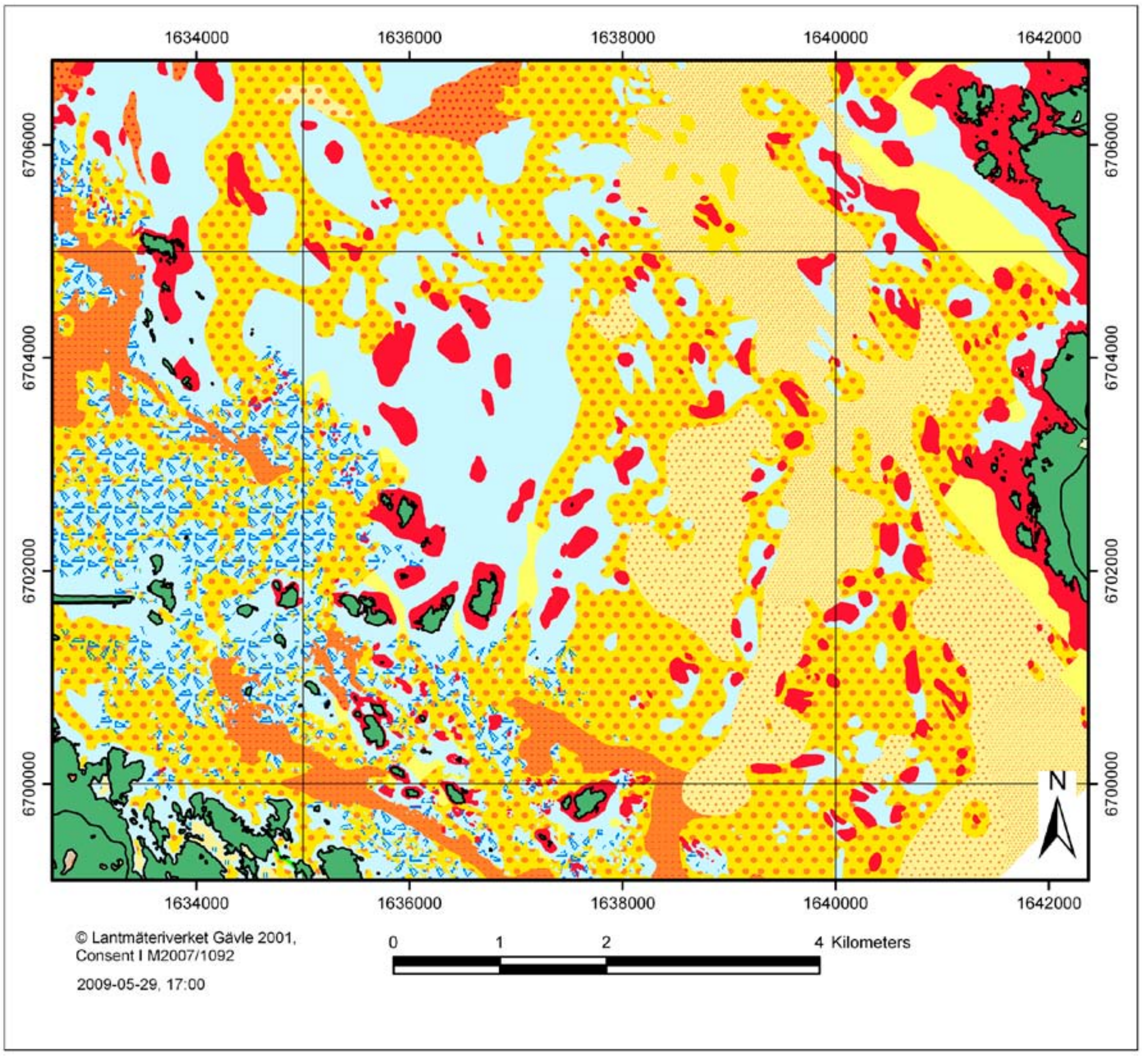


Figure 5-22. *A large part of the present sea floor of Öregrundsgrepen is covered by clay (different shades of yellow) and sand. A large proportion of those deposits are likely to become arable land in the future. The map of Quaternary deposits (QD) is from /Hedenström and Sohlenius 2008/ (see also Figure 4-10). Present day land is shown in green.*

Future land-use of wetlands

Today, almost all agricultural land in Forsmark is situated on clayey till and discharge of groundwater only occurs in parts of these areas /Werner et al. 2007/. Future areas suitable for cultivation will mainly consist of clay and sand, which today are situated at the floor of Öregrundsgrepen. The floor of such valleys may be discharge areas for groundwater (see Chapter 4), and will, when uplifted above sea level, turn into a lake or wetland. Many of the wetlands that will form directly upon the clay or sand can probably relatively easily be drained and used as arable land. The wetlands which will form after a lake stage can also be used as arable land. However, even though the lake and wetland deposits are underlain by minerogenic deposits suitable for cultivation it will be difficult to maintain the drainage of these areas due to subsidence of the organic deposits, which is illustrated by the example from "Bälinge mosse" discussed above /Berglund 2008/.

Many areas in Forsmark that at present are or will be covered with peat are not suitable for cultivation. The reason is that the peat in many areas rests directly upon deposits that are difficult to cultivate (cf. /Osvald 1937, Fredriksson 2004/), e.g. till with large boulders or thin layers of clay. Such peat areas can only be used for cultivation during a short period due to the relatively fast subsidence and oxidation of the peat after ditching. As mentioned in Section 5.5.3, areas that are used for cultivation must have an original peat layer with a thickness of at least 2–3 metres, when the peat is underlain by deposits that are not suitable for cultivation. In the present land-use model, all present and future wetlands that have a peat layer thicker than 1 metre are used for cultivation. That assumption probably overestimates the future areas used as arable land, but should be seen as an attempt to estimate the maximum distribution of future arable land.

The most suitable of the present lakes for future cultivation is probably Lake Fiskarfjärden. That lake is the only lake in the area which is surrounded and underlain by significant sand and clay deposits. Several other lakes, such as Lake Bolundsfjärden, are shallow and the floor is covered with boulder-rich till. In the future these lakes will be covered by only thin layers of peat and consequently probably never be cultivated. Future areas with peat that will form in the clay and sand dominated areas on the present floor of Öregrundsgrepen can, however, be suitable for cultivation. That is since these areas of peat will become underlain by sand and clay, useful to cultivate when the peat has disappeared. Certain future wetlands will never be cultivated, even though the QD are suitable for cultivation. That is because many areas with thick layers of peat are difficult to drain.

Although it is likely that the peat in the area generally does not fulfil the demands of the present peat industry, this may change in the future. The demands of the industry might change, and it is also possible that the properties of the peat might change in the future. It is therefore possible that some of the peat in the Forsmark area will be used as fuel peat.

5.7 Land-use development in Forsmark from 1500 BC to 35,000 AD

This section covers a description of the method for modelling of land-use development in the Forsmark model area. It also provides description of four variants of land-use modelled for the period from 1500 BC to 35,000 AD. At 1500 BC land first rises above sea level and at 35,000 AD no sea exists in the model area and all lakes are infilled with sediment and peat. In one of the animations showing the land-use development, the landscape is also shown from 9000 BC when the Weichselian ice sheet has retreated and the area is completely covered by the Baltic. This time span is assumed to be representative for the development during a typical interglacial.

5.7.1 Variants of future land-use and criteria for the land-use model

Four different variants of land-use development have been produced. The knowledge of the conditions during the present interglacial is used as a basis for these land-use variants. These conditions include properties such as rate of land upheaval and QD distributions. The variants are based on both data from the present Forsmark area and models estimating the past and future properties of the landscape. The variants are:

1) A land-use similar as the present, when the most suitable land areas are cultivated.
2) All areas that can be cultivated are used as arable land.
3) A land-use development unaffected by humans.
4) A permafrost variant unaffected by humans.

The first three variants assume an interglacial climate similar to the present, whereas Variant 4 demonstrates the possible development of land-uses in a considerably colder climate. Most priority has been put on estimating the distribution of wetlands and areas used as arable land. Most other areas are shown as unspecified forest. However, forest on outcrops is show as a separate type of forest in three variants. In the forth variant, forest is completely lacking due to cold conditions with permafrost.

Variant 2 (when all areas that can be cultivated are used as arable land) is the land-use applied to the radionuclide model for the biosphere in SR-Site. Variant 2 was therefore modelled in more time steps than the other three variants and shows the potential land-use during altogether 33 time steps between 1500 BC and 35,000 AD. The other three variants only show the potential land-use at three time steps (2000, 5000 and 10,000 AD).

The criteria for the land-use of different QD are summarised in Table 5-9 and are described in the text below. The methods used for modelling land-use through time are described in Section 5.7.3. In Variants 1 and 2 certain QD can be used for cultivation if situated more than 2 metres above the present sea level. Areas at lower levels are assumed to be too difficult to drain for cultivation. The thickness of organic and inorganic deposits must exceed 1 metre and 0.5 metre, respectively.

Variant 1 – Land-use similar to present conditions

The distribution of QD was compared with the present and historical distributions of arable land. The QD most frequently used for cultivation today are also used as arable land in this variant (Table 5-9). The thickness of QD suitable for cultivation must exceed 0.5 metre to allow cultivation in the model. However, clay gyttja sediment subsides considerably when the ground water table is lowered (see above). These deposits (postglacial clay and clay gyttja/gyttja clay in Table 5-9 must therefore be thicker than 1 metre to allow cultivation.

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

There are several types of QD that to a minor extent are used for cultivation at present (e.g. sandy till and peat). These deposits are not cultivated in Variant 1, which may cause a small underestimation of the cultivated areas. However, all areas with QD used as arable land in Variant 1 are not completely cultivated at present (Table 5-9), e.g. only around half of the areas with glacial clay are cultivated at present. In Variant 1 all areas with glacial clays larger than 1 ha are cultivated. It can consequently be concluded that Variant 1, overestimates the total areas used for cultivation, when compared to the present, even though some areas with glacial clay that today are cultivated are smaller than 1 ha.

Postglacial sand is, to a large extent used for agriculture today, but is not shown in the coupled regolith-lake model (RLDM), which was used to model the land-use development. However, the postglacial sand is always underlain by glacial clay in the regolith depth model. Since glacial clay is used for cultivation in Variant 1, all areas with postglacial sand will accordingly be used for cultivation.

Future wetlands situated at the present sea floor in areas with deposits suitable for cultivation (see above) will be arable land in this variant. However, wetlands that follow a lake stage will be covered by peat and will remain wetlands in Variant 1.

At present the groundwater table in many peat-covered former wetlands has been artificially lowered. These areas are unaffected by human activities in Variant 1, which consequently overestimates the present areas with wetlands. The wetlands may be open or covered by forest. Most of the present wetlands close to the coast are open and to a large extent covered with reed. Some of the bogs in the inland of Uppland are also free of forest due to nutrient-poor conditions. The type of vegetation in the wetlands has, however, not been specified in the model.

Table 5-9. The dominating land-use of QD in the four modelled variants. Note that all types of QD will be wetlands in areas with a high wetness index (except in Variant 2 where all uplifted wetlands are drained). A = Arable land, F = forest, W = wetland, PF = Pine forest on bedrock. For Variant 4 B = Barren outcrops, TH = Tundra heath.

QD	Variant 1	Variant 2	Variant 3	Variant 4
Peat and gyttja	W	F, A if thicker than 1 metre	W	W
Postglacial clay and clay gyttja/gyttja clay	W[1], A if >1 ha and thicker than 1 metre	F, A if thicker than 1 metre	W[1]	W[1]
Glacial clay	A if >1 ha	A	F	F
Postglacial sand	A if >1 ha	A	F	TH
Glaciofluvial deposits	F	F	F	TH
Clayey till with a low frequency of superficial boulders	A if >1 ha	A	F	TH
Till with normal or high frequency of superficial boulders	F	F	F	TH
Postglacial gravel	F	F	F	TH
Outcrops[2]	PF	PF	PF	B

[1] Postglacial clay and clay gyttja/gyttja clay will in most areas be wetlands. However in certain areas these deposits will be covered with forest. [2] "Precambrian bedrock" on the QD map (Section 4.2).

Variant 2 – All areas that possibly can be cultivated are used as arable land

In this variant all areas with deposits suitable for cultivation are used as arable land. Areas smaller than 1 ha and all wetlands with suitable deposits are consequently also cultivated in this variant. All former lakes are cultivated as soon as covered by peat. The thickness of clay gyttja, peat and gyttja must exceed one metre in areas where these deposits are resting directly upon the till. In reality it is difficult to cultivate a peat layer that is only one metre thick and rests upon till. That is because the peat surface will subside considerably when the groundwater table is lowered which will complicate the cultivation. It is therefore likely that this variant overestimates the peat areas that can be cultivated.

It must also be pointed out that areas with peat underlain by till only can be cultivated for a relatively short period of time, due to the fast oxidation of peat after draining. It will also be difficult to maintain arable land after the peat has oxidised in many areas where the peat is underlain by deposits suitable for cultivation. That is because it will be difficult to keep the groundwater table low enough when the peat has disappeared. The ground surface will then have more or less the same elevation as before the peat formed in the wetland/lake. Furthermore, in reality it will be difficult to lower the groundwater table in all present and future wetlands in the Forsmark area. Many of the wetlands can only be cultivated by the use of extremely long and deep ditches, due to the flatness of the landscape.

It is possible that some of the areas with sandy/silty till that are covered by forest in Variant 2, could be cultivated. Historical maps also show that small areas with such till have been cultivated in the past. However, a large proportion of the till in the Forsmark area has a relatively high proportion of superficial stones and boulders. It is therefore unlikely that significant areas with sandy/silty till can be cultivated.

In this variant all wetlands situated at least 2 metres above the sea level will be drained and either used for forestry or used as arable land. Mires with peat or gyttja layers too thin for cultivation are used for forestry. The groundwater table in these mires will be lowered to improve forest growth. There will consequently be no natural succession to open bogs in the present variant. The only wetlands in this variant are situated close to the coast (below 2 m.a.s.l.) and around lakes that partly have been covered by peat.

Variant 3 – Forsmark is unaffected by human activities.

In this variant the terrestrial part of the Forsmark area is almost completely covered with forest. The pine-dominated forest on outcrops is separated from other types of forest. The areas with open land are difficult to estimate and may vary through time due to different natural processes, e.g. fires. The largest areas with open land are situated in the wetlands. A large proportion of open wetlands is situated at low altitudes along the coast were the wetlands are covered by reed. Open wetlands also occur at high altitudes where many of the wetlands have developed to raised bogs. There are too many parameters involved to model these two types of wetlands in a reliable manner. The open and forested wetlands have, therefore, not been distinguished.

Variant 4 – Permafrost and no influence of human activities.

The distribution of outcrops, lakes and wetlands is the same in this variant as in Variant 3. However, forest is completely lacking due to the cold conditions. All areas covered by forest or pine forest on bedrock in Variant 3 are consequently covered by tundra heath and barren outcrops respectively. The permafrost will cause lower permeability of QD which probably in turn will cause changes of the groundwater flow patterns (Section 4.3). The distribution of wetlands may consequently be different from that shown by the resulting model.

5.7.2 The properties of wetlands used for agriculture

The crops growing on peat in former wetlands may take up radionuclides. Special effort has therefore been put on estimating in what manner peat deposits can be cultivated. As mentioned above, the bog peat is low in nutrients and it is therefore not likely that bogs will be drained for agricultural purposes. At a point when the bog peat has reached a certain depth, mixing of the surface layer, e.g. by ploughing, will not reach the more nutrient-rich fen peat below the bog peat. Here, a wetland is considered to be less suitable for agriculture when the bog peat has reached a depth of 1 m. A bog peat depth of 2 m in the central parts of the bog is assumed to also represent a stage where most of the mire is covered with bog peat to a depth that makes it unsuitable for cultivation. This can be used to define an upper limit in age where the mire as a whole is considered to be less suitable for cultivation. An upper age limit for wetlands to be suitable for agricultural purposes can be estimated by calculating the time for 2 m of bog peat to develop and to this add the estimated time elapsed between the fen formation and the start of the bog development.

/Mäkilä and Goslar 2008/ presented data of bog peat accumulation where the mean accumulation on raised bogs during the last 500 years was 20 $gCm^{-2}y^{-1}$. The calculated accumulation rate of bog peat (0.64 mm y^{-1}) implies that it takes approximately 3,000 years (3,126 years) to develop 2 m depth. Here, it was consequently estimated that it takes 3,000 years for a wetland to develop into a bog, which is not suitable for cultivation. However, results obtained by /Lundqvist 1963/, from a bog 70 km west of Forsmark, show that it took only 1,000 years for 2 metres of bog peat to form. Similarly, data from Rönningarna in Forsmark suggest that 1.5 m of peat was developed during 850 years /Sternbeck et al. 2006/. Consequently, from a dose assessment point of view the calculated estimate of 3,000 years has to be considered as pessimistic.

Data from the bog studied by /Lundqvist 1963/ suggest that the fen period persisted for 3,000 years before it started to accumulate peat under more ombrotrophic conditions. That wetland is a large bog (2.5 km across) and larger than most of the biosphere objects in Forsmark. It is reasonable to assume that the development from a fen to a bog will be prolonged in large wetlands. Here it is assumed that bogs in the Forsmark area will be rejected as potential agricultural land, in favour of more productive land, for cultivation of crops 6,000 years after the development of the object into a fen. Since the development has gone faster so far (see above), partly due to the small size of biosphere objects in Forsmark, this is a cautious estimate.

Here it is assumed that peat covered wetlands can be used as arable land for a period of 50 years at each time step and over this period give rise to a radiation dose to humans. The radionuclide inventory of the peat and 0.25 m of the sediments below the peat is assigned to the agri_z_regoUp parameter (defined as 0.25 m deep), which is equal to the rooting depth parameter (see Section 7.7 and /Avila et al. 2010/ for definitions ot the parameters discussed here). This is done in order to include peat consolidation and oxidation in a cautious way.

A factor/function for each regolith type is used to describe the subsidence (Table 5-10). The total subsidence during a 50 year period was calculated for each layer. If the subsidence for the peat layer (Ter_regUp) is larger than the Ter_regoUp + 0.25 m (agri_z_regoUp) for the biosphere object then the regoMid is included. If it is possible to separate between gyttja sediments and glacial clay the individual subsidence for each layer is calculated. Otherwise a depth is calculated that is used for the regoMid, based on the subsidence of gyttja sediments. That generates figures describing how much of the regolith may be used as arable land during a 50-year period (and thereby the depth from which the inventory of radionuclides should be used).

Peat: Data presented in /Kasimir-Klemedtsson et al. 1997/ show that the total subsidence in cultivated peat areas can vary between 5 and 30 mm/year depending on the intensity of the management. Accordingly, high management intensity may cause a subsidence as large as 1.5 m during a 50 year period.

It is assumed that the future peat lands in the Forsmark area can be cultivated for at least 50 years. By using data from /Berglund 1996a, b/, describing bulk densities of cultivated peat soils and site data for peat it was possible to calculate a subsidence factor as the ratio between the uncultivated peat and cultivated peat. This gave an estimated ratio of 2.5 (Table 5-10), which does not include oxidation. The subsidence of peat soils may therefore be larger than shown in Table 5-10, since these soils also subside due to oxidation. The values shown in Table 5-10 have, however, to be regarded as conservative since the calculation of subsidence is based on 50 years of cultivation, whereas the soils investigated by /Berglund et al. 1989, Berglund 1996a, b/ may have been cultivated for much longer.

Gyttja sediments: Subsidence of gyttja sediments was calculated in a similar way as for peat, where reference dry bulk densities from cultivated gyttja and clay gyttja soils were taken from /Berglund et al. 1989/. Based on sediment cores from seven lakes in the Forsmark area it was assumed that the future arable land will be a mixture between gyttja (90%) and clay gyttja (10%), and the dry bulk density was weighted accordingly. The large subsidence of the gyttja sediments is an effect of the organic material, which causes a high porosity and thereby low stability of soils developed on these sediments.

Glacial clay: The glacial clays will also subside when the groundwater table is lowered. Since the glacial clay lacks significant amounts of organic matter, that subsidence will be less than for the organic deposits described above. No attempt was therefore made to quantify the subsidence of glacial clay.

Table 5-10. Estimated subsidence of Quaternary deposits during a period of 50 years. The calculations are based on the density difference between drained and undrained soils.

Quaternary deposit	Density (kg m^{-3})		Factor of subsidence	Subsidence (m)	Subsidence m y^{-1}
	Undrained soils	Soils on arable land			
Gyttja sediments (90% gyttja+10% gyttja clay)	92.3*	342.6***	3.7	0.73	0.014614
Fen peat	84.5*	213.3**	2.5	0.60	0.012078

*Data from Forsmark, **/Berglund 1996/, *** /Berglund et al. 1989/.

5.7.3 Input data to the land-use model

The four variants showing potential land-use development are produced by the use of several data sets. The most important factor that determines the distribution of land-use types in these variants is the proportion of land/water and the geographical distribution of QD in the terrestrial areas. Both these factors change throughout the interglacial. The terrestrial areas increases as an effect of the land uplift and as the lakes are infilled. The distribution of QD changes both due to erosion and deposition of regolith. In Table 5-11, the input data used to calculate distributions of past and future terrestrial areas, QD distribution, QD depths and potential future land-use are listed.

In the coupled regolith-lake development model (RLDM) the geographical distribution of glacial QD as shown by the regolith depth model (RDM) was used. The distribution of postglacial deposits during the different time steps was thereafter modelled (see Section 4.1). The land-use model used data from the regolith depth model together with the modelled distribution of postglacial deposits to model the land-use through time. The map showing the present distribution of QD /Hedenström and Sohlenius 2008/ was consequently not used as input to the land-use model, except for defining areas with clayey till with a low frequency of superficial boulders. An additional model showing the observed distribution of present land-uses has also been produced. That map was used to evaluate the modelled distribution of land-uses.

Table 5-11. Data input used to model distributions of future terrestrial areas, QD, and wetlands, QD depths and potential future land-use.

Type of modelling	Input data
The distribution of future and past terrestrial areas	The shoreline displacement model showing the distribution between terrestrial and marine areas through time /Brydsten 2009/.
	The results from the sedimentation model showing the future and past distribution between land and lakes /Brydsten and Strömgren 2010/.
The future and past distribution of QD	The regolith depth model /Hedenström et al. 2008/.
	The coupled regolith-lake model (RLDM) /Brydsten and Strömgren 2010/.
	Maps showing the present distribution of QD /Hedenström and Sohlenius 2008/.
The distribution of wetlands	The digital elevation model (DEM) was used to model both the distribution of future wetlands on the present seafloor and wetlands in the presently terrestrial areas /Brydsten and Strömgren 2010/.
	The coupled regolith-lake development model (RLDM) was used to determine when a lake is developed into a wetland /Brydsten and Strömgren 2010/.
The thicknesses of the QD	The regolith depth model (RDM) shows the present thickness of different glacial deposits /Hedenström et al. 2008/.
	The results from the coupled regolith-lake model (RLDM), which shows the thickness of postglacial deposits through time /Brydsten and Strömgren 2010/.
Areas that may be used as arable land	Areas with a low superficial boulder frequency situated on clayey till are regarded as suitable for cultivation. The boulder frequency of the clayey till were taken from the mapping of QD in the terrestrial area /Sohlenius et al. 2004/.
	Only areas situated more than 2 m above sea level can be used as arable land in the land-use model. The elevation above the future and past sea level is modelled by using the digital elevation model (DEM) /Strömgren and Brydsten 2008/ and the shoreline displacement model.
	For cultivation, the organic deposits in the land-use model must have a thickness larger than one metre when directly underlain by till. Information about the thickness of these deposits through time was taken from the coupled regolith-lake development model (RLDM).

5.7.4 Land-use modelling

ArcGis 9.3 was used for all GIS-calculations. Most of the data were produced in ESRI raster format using a 20-metre cell size. The extension of these raster layers is 1625290 west, 1644970 east, 6712090 north, and 6693190 south in the RT 90 coordinate system. The geographical properties necessary for the modelling of the land-use development variants are described earlier in this chapter. The classification of land-use types is shown in Table 5-12.

Variant 2 (when all areas that can be cultivated are used as arable land, see Section 5.7.1 for details) is the land-use applied to the radionuclide model for the biosphere in SR-Site. Variant 2 was therefore modelled in more time steps than the other three variants and shows the potential land-use during altogether 33 time steps between 1500 BC and 35,000 AD. The land-use development for Variant 2 was produced in 500-year time steps from 1500 BC to 12,000 AD and in 5,000 year time steps from 15,000 AD to 35,000 AD. The land-use development for Variants 1, 3, and 4 was only produced for three time steps: 2000, 5000 and 10,000 AD.

Eleven different types of data were necessary for the modelling. The calculations were performed using Map Algebra in the Spatial Analyst extension and the Spatial Analyst Tools in Arc Toolbox. For these calculations, the cells representing different data in the raster layers were assigned unique numeric codes. The data types, references to the data, and the numeric codes used for the Map Algebra calculations are summarised in Table 5-13.

Raster layers referring to land areas from 1500 BC to 35,000 AD used in land-use development modelling were produced by /Brydsten and Strömgren 2010/. These land areas were divided in cells situated two metres above sea level and cells situated below this level.

Table 5-12. Classification of land-use types in Variants 1–4. "X" refers to the land-use classification used for each variant.

Land-use classification	Variant 1	Variant 2	Variant 3	Variant 4
Forest	X	X	X	
Pine forest on bedrock	X	X	X	
Arable land	X	X		
Wetland	X	X	X	X
Lake	X	X	X	X
Tundra heath				X
Barren outcrop				X

Table 5-13. Different types of data and numeric codes used in the Map Algebra calculations of the land-use development.

Description of data used in the Map Algebra calculations. The numeric codes used in the Map Algebra calculations are put within parentheses	Reference
Land 2 m above sea level (20,000) and other land areas (0)	/Brydsten and Strömgren 2010/
Glacial clay (3) and other areas (0)	/Hedenström and Sohlenius 2008/
Postglacial sand (3) and other areas (0)	SGUs database
Clayey till (3) and other areas (0)	/Hedenström et al. 2008/
Till (1) and other areas (0)	/Hedenström and Sohlenius 2008/
Other deposits (1) and other areas (0)	/Hedenström and Sohlenius 2008/
Bedrock outcrops (2) and other areas (0)	/Hedenström and Sohlenius 2008/
Postglacial deposits >1 m (30), other postglacial deposits (10), and other areas (0)	/Brydsten and Strömgren 2010/
Wetlands (400) and other areas (0)	/Brydsten and Strömgren 2010/
Lake development (wetland within original extension of lake (4,000), lake (5,000), and other areas (0))	/Brydsten and Strömgren 2010/
Infilled lakes (100,000) and other lakes (0)	/Brydsten and Strömgren 2010/

The raster layers referring to glacial clay, till, and bedrock outcrops were produced from the QD map from the RLDM (the coupled regolith-lake development model /Brydsten and Strömgren 2010/) for the time step 9500 BC. The RLDM at 9500 BC shows the distribution of glacial Quaternary deposits shortly after the latest deglaciation. The distribution of these deposits was taken from the QD map which was used for modelling regolith depth and stratigraphy (RDM) /Hedenström et al. 2008/. The QD map is based on the original map presented in /Hedenström and Sohlenius 2008/.

The raster layer referring to postglacial sand was produced from the marine QD map (SGU's database) outside the RLDM area. Areas referring to clayey till or boulder clay, clayey till with a thin surface layer of postglacial sand, and clayey till with a thin surface layer of peat (hereafter are all these deposits called clayey till) are raster layers produced from the QD map /Hedenström et al. 2008/. All cells not referring to glacial clay, postglacial sand, till, clayey till, and bedrock outcrops were classified as other deposits (glaciofluvial sediments and artificial fill). These cells are assigned the same numeric codes as till in the Map Algebra calculations, since these areas are assumed to have similar properties to till.

The total thickness of postglacial deposits at every time step was calculated by addition of the raster layers for marine accumulation and erosion, raster layers for thickness of lacustrine deposits, and raster layers referring to thickness of peat for all time steps. All these raster layers are produced in the RLDM. From 11,500 AD and onwards, the same raster layer for thickness of marine deposits was used for all following time steps since no more accumulation or erosion occurs in the sea after 11,500 AD. Areas with postglacial deposits thicker than one metre were calculated from the raster layers showing the total thickness of postglacial deposits. These areas were later used to demonstrate which areas may be used as arable land.

Wetlands and data showing succession of lakes used in the land-use development modelling were produced in the RLDM /Brydsten and Strömgren 2010/. The exception was data for the small and shallow present lakes not modelled in the RLDM. For these lakes, field data from /Brunberg et al. 2004/ were used as input referring to the extents of wetland and water surfaces in the lakes for the time step 2000 AD (the present). All present lakes not modelled in the RLDM are small and shallow and consequently assumed to be infilled at 2500 AD. The calculation of the peat growth in these lakes is described in /Brydsten and Strömgren 2010/.

In some small areas, cells with glacial clay, postglacial sand, till, and clayey till were overlapping. Some wetland and lake cells were also overlapping. The use of data from different maps and from the RLDM is the cause of these overlapping cells. Since these overlaps are not necessary for the MapAlgebra calculations overlapping cells were removed. Cells from raster layers in the column "Raster layer 2" in Table 5-14 were removed. Till was removed when overlapping clayey till or glacial clay in order to maximise the area of arable land. Cells from clayey till were removed when overlapping glacial clay even though both result in arable land, and wetland was removed when overlapping cells referred to as lake.

Additions of the eleven raster layers described in Table 5-15 were done using Single Output Map Algebra in ModelBuilder for all time steps from 1500 BC to 35,000 AD. For some of these data, the same raster layers were used for all time steps, for other data new raster layers were used in almost every time step. New raster layer has to be used since the terrestrial area and distribution of lakes and wetlands are changing through time. Raster layers referring to lakes and infilled lakes were not used in the first time steps, since no lakes had developed at that time. This procedure is exemplified in Figure 5-23 for the time step 2000 AD. Input data to the land-use modelling for all time steps are summarised in Table 5-15.

Raster layers with, in total, 123 unique numeric codes were produced in the Map Algebra calculations. These unique numeric codes were used for land-use classification in Variant 2. The numeric codes were reclassified to five land-use types using a reclassification table and the Spatial Analyst Tools. In Figure 5-24, the procedure for the reclassification and the resulting legend are illustrated.

Table 5-14. Overlapping 20-metre cells in input data used for the land-use development modelling.

Raster layer 1	Raster layer 2	Number of overlapping 20-metre cells removed from raster layer 2
Clayey till	Till	4,829
Glacial clay	Clayey till	68
Postglacial sand	Till	6,599
Lake	Wetland	12

Table 5-15. Data used in the Map Algebra calculations of the land-use development (Variant 2) from –1500 AD (1500 BC) to 35,000 AD. For some of these data the same raster layer was used for all time steps or from a certain time step and onward (O), for other data new raster layers were used for every time step (X).

Time step (Year AD)	Land >2 m	Glacial clay	Postglacial sand	Clayey till	Till	Other deposits	Bedrock out-crops	Postglacial deposit >1 m	Wetland	Lake develop-ment	Infilled lakes
–1500	X	O	O	O	O	O	O	X	O		
–1000	X	O	O	O	O	O	O	X	O		
–500	X	O	O	O	O	O	O	X	O		
0	X	O	O	O	O	O	O	X	O		
500	X	O	O	O	O	O	O	X	O		
1000	X	O	O	O	O	O	O	X	O	X	
1500	X	O	O	O	O	O	O	X	O	X	
2000	X	O	O	O	O	O	O	X	O	X	X
2500	X	O	O	O	O	O	O	X	O	X	X
3000	X	O	O	O	O	O	O	X	O	X	X
3500	X	O	O	O	O	O	O	X	O	X	X
4000	X	O	O	O	O	O	O	X	O	X	X
4500	X	O	O	O	O	O	O	X	O	X	X
5000	X	O	O	O	O	O	O	X	O	X	X
5500	X	O	O	O	O	O	O	X	O	X	X
6000	X	O	O	O	O	O	O	X	O	X	X
6500	X	O	O	O	O	O	O	X	O	X	X
7000	X	O	O	O	O	O	O	X	O	X	X
7500	X	O	O	O	O	O	O	X	O	X	X
8000	X	O	O	O	O	O	O	X	O	X	X
8500	X	O	O	O	O	O	O	X	O	X	X
9000	X	O	O	O	O	O	O	X	O	X	X
9500	X	O	O	O	O	O	O	X	O	X	X
10,000	X	O	O	O	O	O	O	X	O	X	X
10,500	X	O	O	O	O	O	O	X	O	X	X
11,000	X	O	O	O	O	O	O	X	O	X	X
11,500	O	O	O	O	O	O	O	X	O	X	X
12,000	O	O	O	O	O	O	O	O	O	X	X
15,000	O	O	O	O	O	O	O	O	O	X	X
20,000	O	O	O	O	O	O	O	O	O	X	X
25,000	O	O	O	O	O	O	O	O	O	X	X
30,000	O	O	O	O	O	O	O	O	O	X	X
35,000	O	O	O	O	O	O	O	O	O	X	X

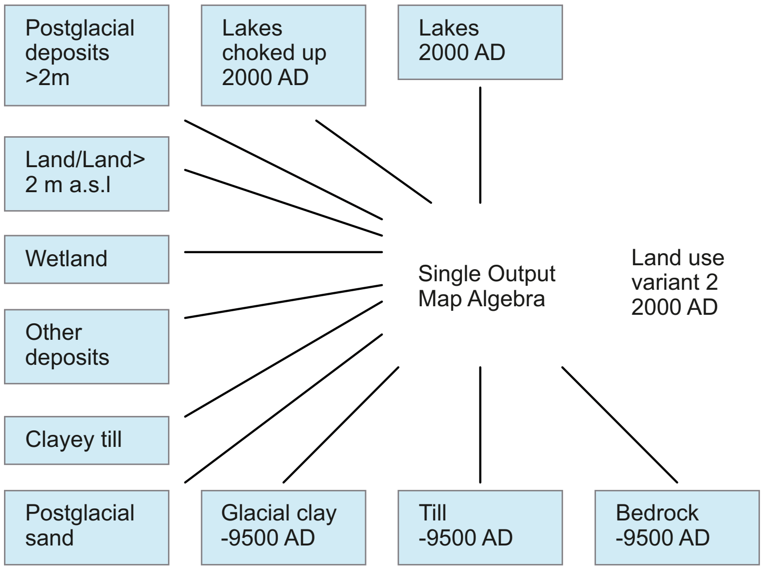
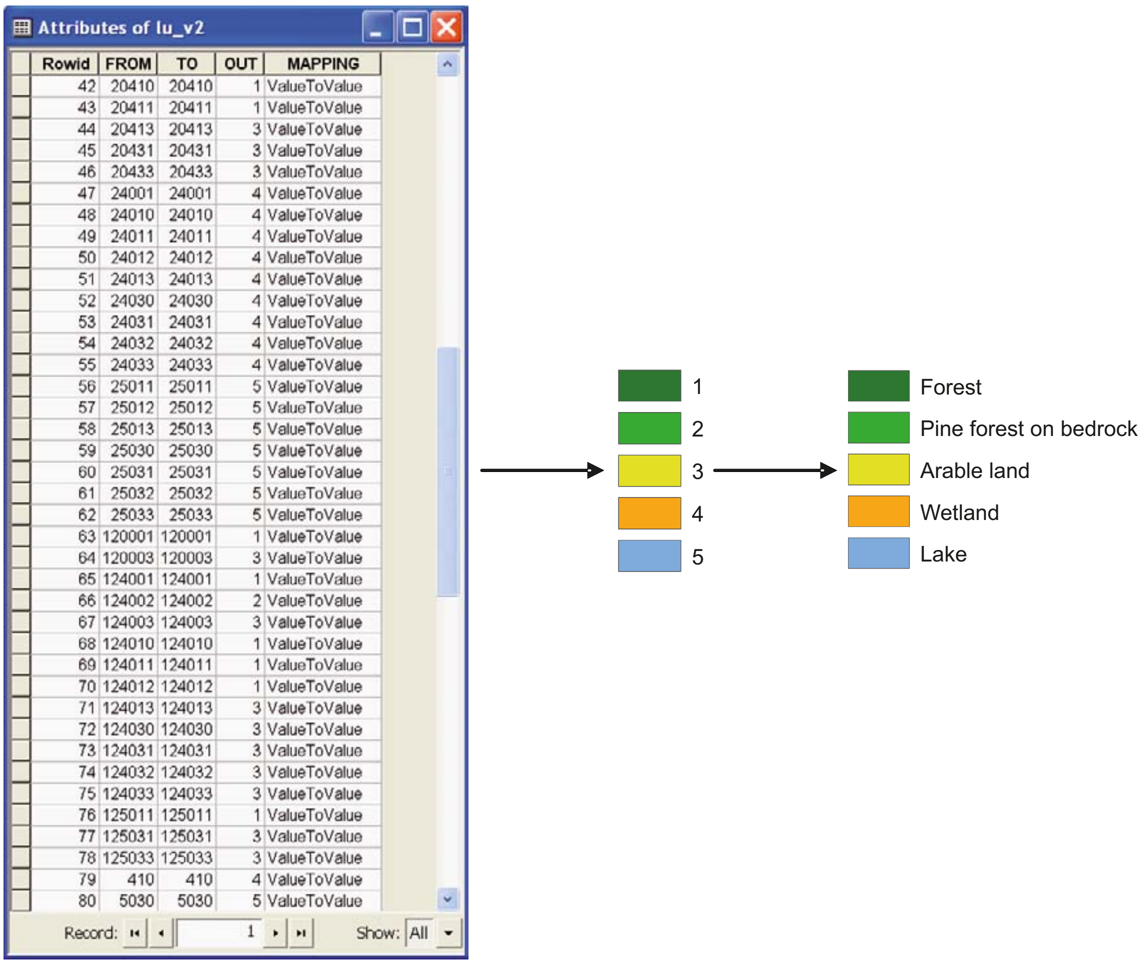


***Figure 5-23.** Schematic illustration of the addition of eleven raster layers used in the land-use development (Variant 2) for the time step 2000 AD using Single Output Map Algebra in ModelBuilder.*



Attributes of lu_v2

Rowid	FROM	TO	OUT	MAPPING
42	20410	20410	1	ValueToValue
43	20411	20411	1	ValueToValue
44	20413	20413	3	ValueToValue
45	20431	20431	3	ValueToValue
46	20433	20433	3	ValueToValue
47	24001	24001	4	ValueToValue
48	24010	24010	4	ValueToValue
49	24011	24011	4	ValueToValue
50	24012	24012	4	ValueToValue
51	24013	24013	4	ValueToValue
52	24030	24030	4	ValueToValue
53	24031	24031	4	ValueToValue
54	24032	24032	4	ValueToValue
55	24033	24033	4	ValueToValue
56	25011	25011	5	ValueToValue
57	25012	25012	5	ValueToValue
58	25013	25013	5	ValueToValue
59	25030	25030	5	ValueToValue
60	25031	25031	5	ValueToValue
61	25032	25032	5	ValueToValue
62	25033	25033	5	ValueToValue
63	120001	120001	1	ValueToValue
64	120003	120003	3	ValueToValue
65	124001	124001	1	ValueToValue
66	124002	124002	2	ValueToValue
67	124003	124003	3	ValueToValue
68	124010	124010	1	ValueToValue
69	124011	124011	1	ValueToValue
70	124012	124012	1	ValueToValue
71	124013	124013	3	ValueToValue
72	124030	124030	3	ValueToValue
73	124031	124031	3	ValueToValue
74	124032	124032	3	ValueToValue
75	124033	124033	3	ValueToValue
76	125011	125011	1	ValueToValue
77	125031	125031	3	ValueToValue
78	125033	125033	3	ValueToValue
79	410	410	4	ValueToValue
80	5030	5030	5	ValueToValue

Record: 1 Show: All

***Figure 5-24.** Schematic illustration of the reclassification procedure of a raster layer with unique numeric codes (field "FROM" and "TO") to the five land-use types used in Variant 2 (field "OUT").*

However, some small adjustments were necessary after the reclassification of the raster layers produced for Variant 2. In some areas, cells first classified as arable land or till were classified as pine forest on bedrock in the next time step. This is not in accordance with the presumed development of the area and the cells with arable land followed by pine forest on bedrock were therefore reclassified to pine forest on bedrock. This can be explained by the use of different digital elevation models in the land-use development modelling and the RLDM /Brydsten and Strömgren 2010/, causing small deviations between areas referred to as land in these two models. The deviations between these two models also caused some land cells to become sea cells in the next time step. In that case, land cells that in the next time step became sea cells were reclassified to sea cells. The adjustments described above only affect less than one percent of the total number of 20 m cells in the model area. Specifically, it only affects cells close to the sea, and most of these cells are situated close to the island Gräsö.

For the modelling of the land-use development in Variant 1 (a land-use similar to the present), the final raster layers produced for Variant 2 for the time steps 2000, 5000, and 10,000 AD were used. Variant 1 differs from Variant 2 in that only QD suitable for cultivation having an area of more than 10,000 m^2 (1 ha) are used as arable land. Furthermore, peat is not used as arable land and the infilled lakes are consequently not cultivated in Variant 1. All areas with arable land less than 1 ha were identified. From these cells separate raster layers referring to arable land less than 1 ha were produced.

The final raster layers for Variant 2, i.e. the raster layers referring to arable land less than 1 ha, wetlands and data from lakes used for the calculation of Variant 2 (to show differences in the development of wetlands and lakes between Variant 1 and 2) were added to one raster layer. This procedure was repeated for all time steps. The raster layers used for these calculations are summarised in Table 5-16. Using a reclassification table, the land-use classification according to the rules set up for Variant 1 of the land-use development was done.

In the modelling of Variant 3 (development unaffected by humans), the raster layers produced for Variant 2 for the time steps 2000, 5000, and 10,000 AD were used again. Variant 3 differs from Variant 2 in that no arable land exists and no wetlands are affected by ditches. The succession of wetlands and lakes is therefore only an effect of natural processes. The wetlands and data from lakes used for Variant 2 were added to these raster layers once more. The raster layers used in these calculations are summarised in Table 5-17.

In the animation showing the permafrost landscape (Variant 4) the raster layers for Variant 3 were used and a legend produced for Variant 4, i.e. no new raster layers were produced for Variant 4. This reclassification is illustrated in Figure 5-25.

The raster layers referring to the four different land-use developments (Variants 1–4) were used to produce pictures for animations. In these animations, other GIS-data were also used. The GIS-data used and the adjustments made for these animations are saved in ArcGis-projects. The ArcGis projects and a short description of the data used are stored in the SKB document handling system (SKBdoc 1263189).

Table 5-16. Data used in the Map Algebra calculations for Variant 1. For some of these data the same raster layer was used for all time steps (O), for other data new raster layers were used for every time step (X).

Time step (Year AD)	Land-use development Variant 2	Arable land <1 ha in land-use development Variant 2	Wetland	Lake development	Infilled lakes
2000	X	X	O	X	X
5000	X	X	O	X	X
10,000	X	X	O	X	X

Table 5-17. Data used in the Map Algebra calculations for Variant 3. For some of these data the same raster layer was used for all time steps (O), for other data new raster layers were used for every time step (X).

Time step (Year AD)	Land-use development Variant 2	Wetland	Lake development	Infilled lakes
2000	X	O	X	X
5000	X	O	X	X
10,000	X	O	X	X

Figure 5-25. *Schematic illustration showing how the legend from Variant 3 was transformed to the Variant 4 legend.*

5.7.5 Resulting land-use development

Areal distribution of land-use

Below is a description of Variants 1–3. The focus of the description is on Variant 2, which is the variant used in the radionuclide model for the biosphere in SR-Site. Land-use development in Forsmark for Variant 2 (all areas that can be cultivated are used as arable land) for the time steps 2000, 5000, and 10,000 AD are shown in Figure 5-26. This variant was modelled from 9000 BC when the area was deglaciated and thereafter covered by the Baltic. The last modelled time step occurs at 35,000 AD when the last lakes have been infilled with peat and sediments.

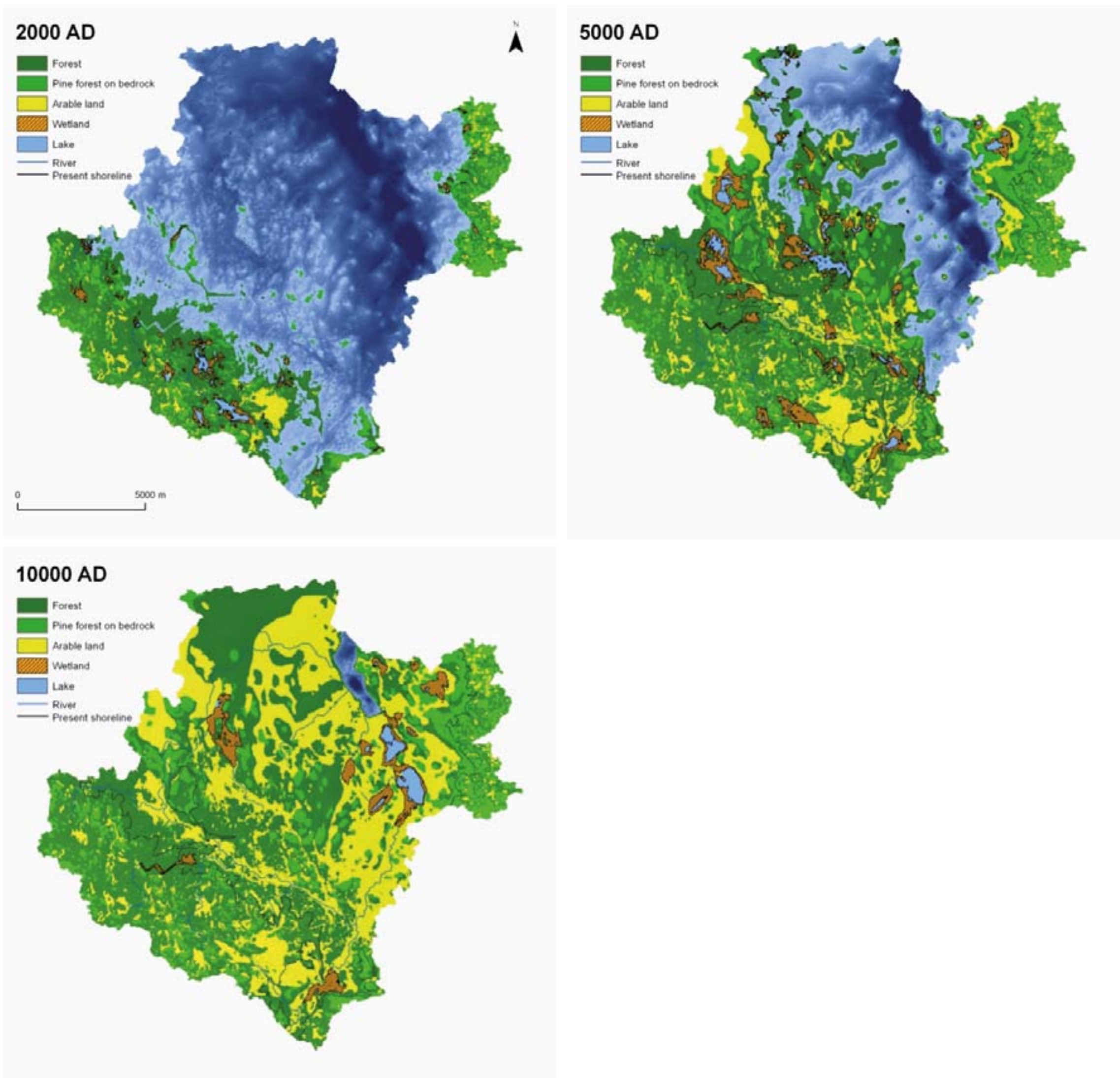


Figure 5-26. *The time steps 2000, 5000 and 10,000 AD for Variant 2 (land-use dominated by arable land) of the land-use development in the Forsmark model area.*

In Figure 5-27, the areas of different land-use types are shown for all time steps modelled from –1500 AD (1500 BC) to 35,000 AD. It should be noted that the modelling has not been done in 500 years intervals after 12,000 AD. The next time step modelled is 15,000 AD and thereafter the modelling has been done in 5,000 years intervals to 35,000 AD. The share of arable land in the model area increases over time and is around 40% at 35,000 AD, which is slightly more than 73 km^2 (the total model area is 189 km^2).

The proportions of forest and forest on bedrock increase to 6500 AD and are thereafter more or less the same for all following time steps to 35,000 AD. The share of wetland increases in almost every time step from 1500 BC to 5500 AD, and constitutes between 5 and 7 percent of the model area in all following time steps to 8000 AD. It is obvious that the shoreline displacement will cause a fast future increase of the terrestrial share of the modelled area. That in turn will cause an increase in areas that can be used as arable land.

The area that can be used as arable land will further increase when the lakes have been filled up with sediment and peat. In the future, the proportion of terrestrial areas that can be used for agriculture will be larger than at present since the proportion of QD, mainly clay, will increase when the present sea floor is uplifted. In Variant 2, all former wetlands that can be cultivated are used as arable land simultaneously. However, many of the wetlands can probably only be cultivated for a short period due to the relatively fast subsidence of the peat layers. It is therefore not likely that all former wetlands will be cultivated simultaneously.

After 8000 AD the area of wetland decreases and at 35,000 AD there are no wetlands. At that time the groundwater table in all former wetland has been lowereds by ditches to improve forest growth or to make cultivation possible. The total lake area is largest at 5500 AD (less than 2 percent of the modelled area). Most of the lakes are infilled at 8500 AD and the lake area is comparably small at this time step (less than 0.5 percent). Only the deepest lakes are left at 15,000 AD and after 20,000 AD only parts of these lakes are still not infilled. At 35,000 AD all former lakes are infilled and either used as arable land or covered by forest.

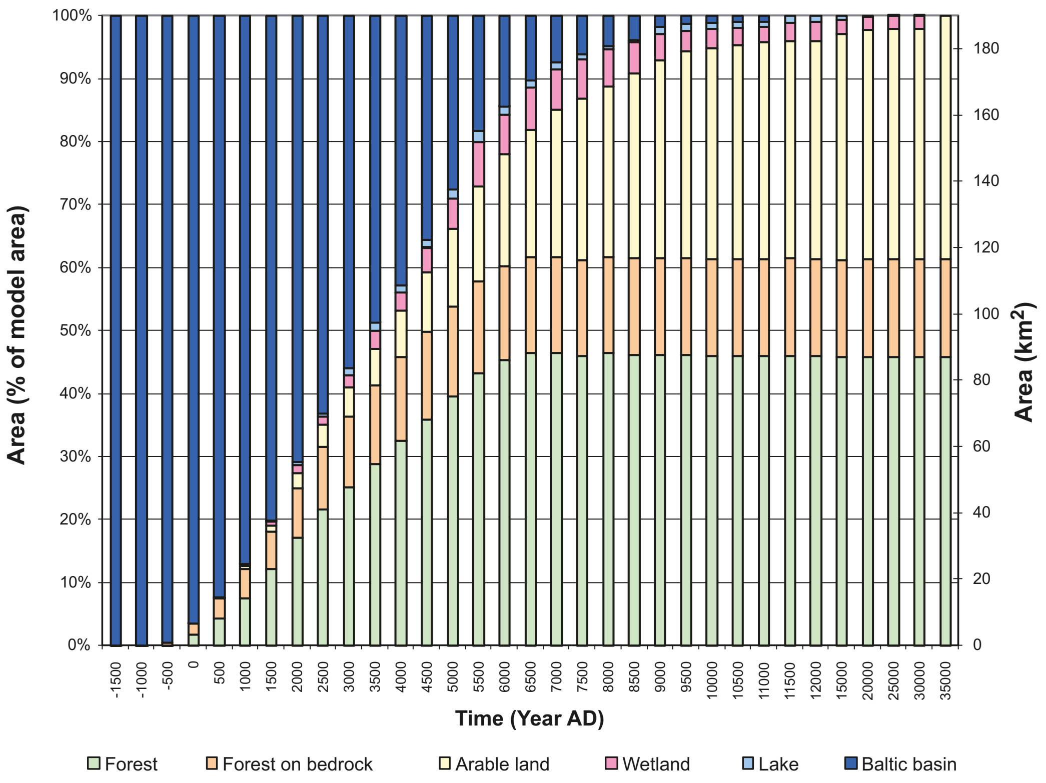


Figure 5-27. *Share of different land-use types used in Variant 2 of the land-use development in the Forsmark model area from –9000 AD (9000 BC) to 35,000 AD. The time scale is in 500-year intervals from –1500 AD to 12,000 AD, a 3,000-year interval between 12,000 AD and 15,000 AD, and 5,000-year intervals from 15,000 AD to 35,000 AD.*

Figures 5-28 and 5-29 show Variants 1 and 3, i.e. a land-use similar to the present and a land-use development unaffected by humans, respectively, for the land-use development in the Forsmark area for the time steps 2000, 5000, and 10,000 AD. In Figure 5-30, the shares and area of the different land-use types modelled in Variants 1, 2, and 3 are shown for the time steps 2000, 5000, and 10,000 AD. In Variant 1 the shares of the land-use types forest, forest on bedrock, arable land, and wetland increase over time. In that variant, arable land constitutes almost 27 percent (almost 50 km^2) of the total model area at 10,000 AD. Arable land amounts to a little less than 34 percent (a little more than 64 km^2) of the total area at the same time step for Variant 2. In Variant 1 all lakes become wetlands when infilled, since peat is not used as arable land in that variant.

Most of the former lake areas are used as arable land in Variant 2. That explains the higher proportion of arable land in Variant 2. Furthermore, in Variant 2 areas smaller than 1 ha are cultivated, which is not the case in Variant 1. In Variant 3, the shares of the land-use types forest, forest on bedrock, and wetland increase from 2000 AD to 10,000 AD. Wetland constitutes almost 19 percent (a little less than 36 km^2) of the total area at 10,000 AD in this variant.

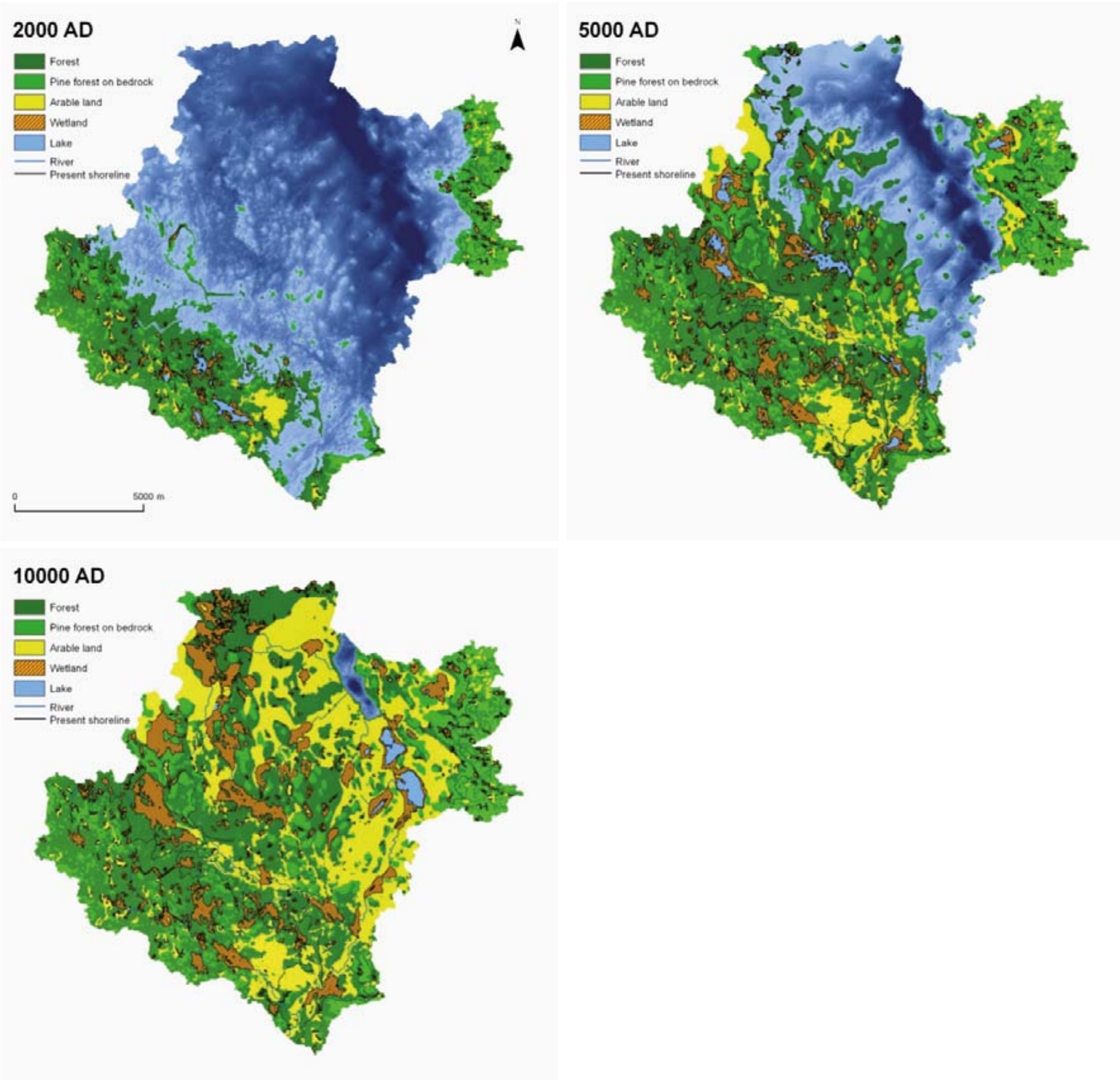


Figure 5-28. *The time steps 2000, 5000 and 10,000 AD for Variant 1 (land-use similar to present) of the land-use development in the Forsmark model area.*

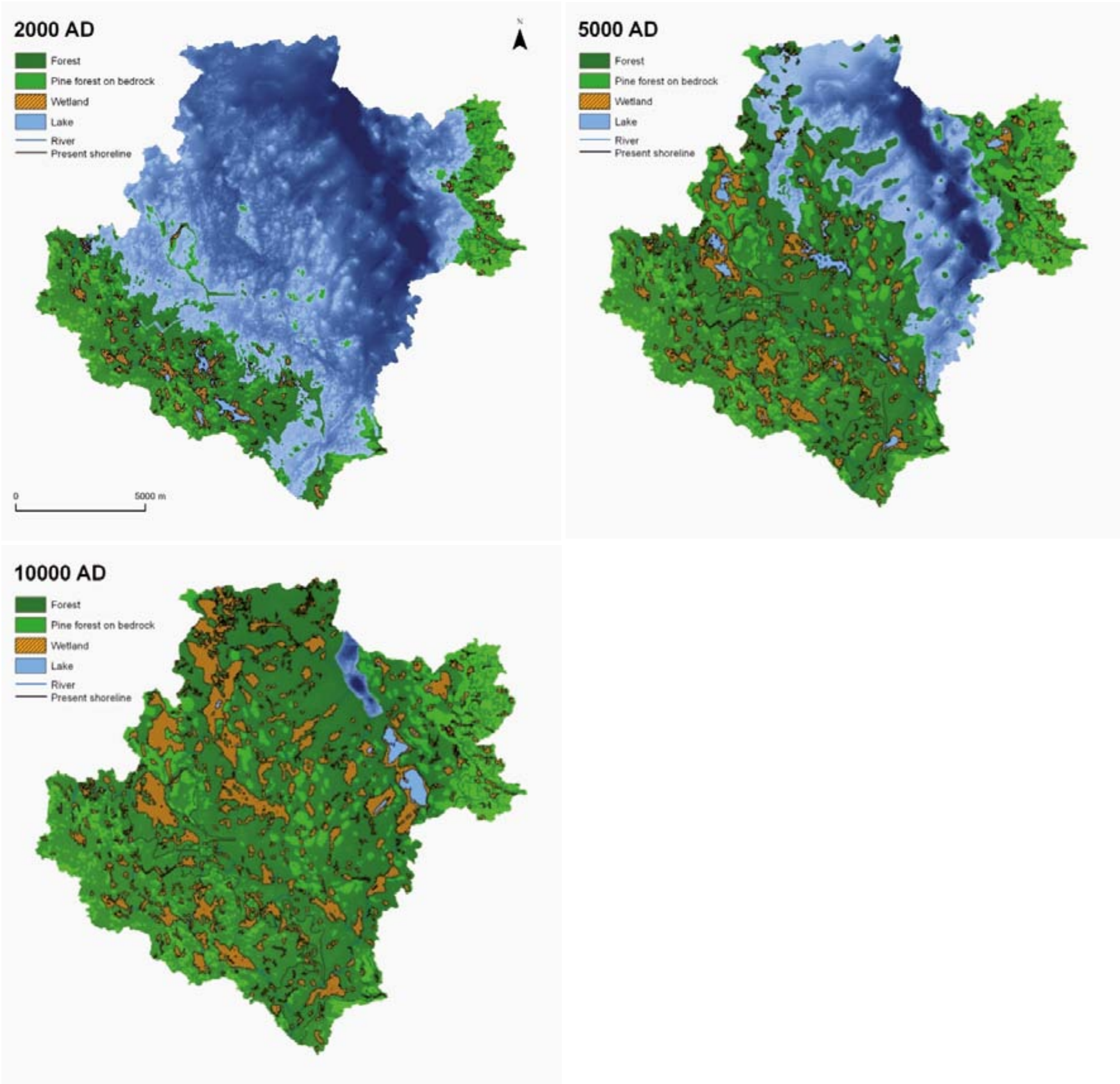


Figure 5-29. *The time steps 2000, 5000 and 10,000 AD for Variant 3 (land-use without agriculture) of the land-use development in the Forsmark model area.*

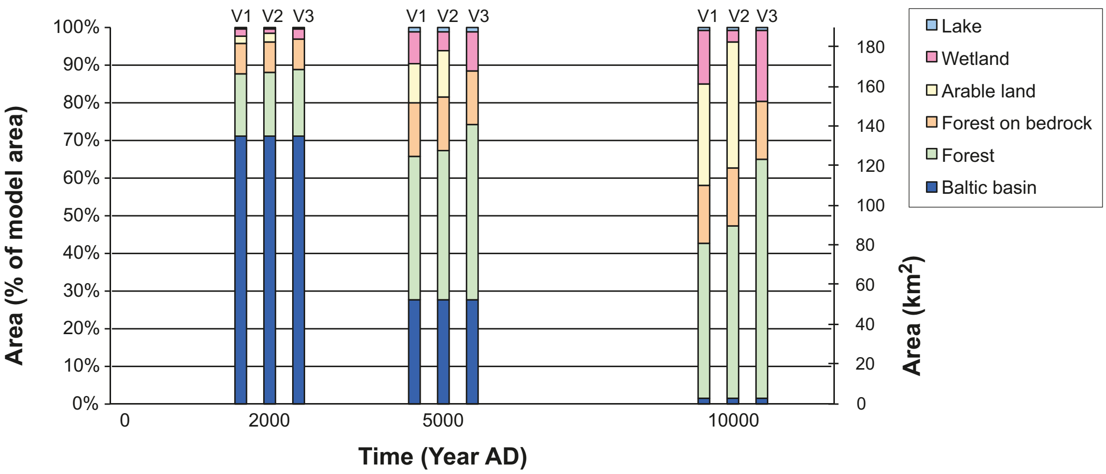


Figure 5-30. *Shares of different land-use types used in the modelling of Variants 1 (V1), 2 (V2), and 3 (V3) of the land-use development in the Forsmark model area for the time steps 2000, 5000, and 10,000 AD.*

Future human population

The four variants of land-use development give different conditions for humans and the number of people that possibly can live in the area is strongly dependent on the distribution of different land-use types. The numbers presented below are extremes and are not used as direct input in further calculations, but as indicators on how landscape variants respond to different assumptions.

Figure 5-31 shows the maximal number of persons that can live on food produced in the area during the different modelled time steps in Variant 2. The data used for this calculation is values for carbon (kgC/m^2/year) produced in forest, wetland, and arable land (see Chapter 13 in /Löfgren 2010/), and carbon produced in the sea /Aquilonius 2010/ and lakes /Andersson 2010/, assuming a yearly carbon intake by humans of 110 kg C/year /Nordén et al. 2010/. In Table 5-18, the areas of different land-use types that are needed for supporting one person are shown. Note that the land-use types forest and forest on bedrock are both shown as forest in the table.

The arable land needed to support one person is several hundred times smaller than the corresponding areas of the other land-use types. The size of future arable land will consequently be crucial for the number of people that can live on food from the area. The total size of arable land is correlated with the successive increase of land area caused by the land uplift. The size of arable land, and population, is further increased when the lakes are successively infilled and converted in to arable land. However, many of these former lakes can probably not be used for agriculture for long periods of time. Therefore, all former lakes will probably not be cultivated at the same time and the number of people that can live simultaneously in the area is consequently slightly overestimated.

Table 5-19 shows the number of people that can live in the different land-use types of Version 2. That table further demonstrates that the area of arable land is crucial for the number of people that can live in the area. The number of people that the Forsmark landscape can sustain in Variant 1 is lower than in Variant 2, since the infilled lakes are not used as arable land in Variant 1. The size of arable land needed for one person would be considerably larger than shown in Table 5-18 without the use of fertiliser. /Jansson et al. 2006/ showed that at the end of the 19th century a person in Laxemar-Simpevarp needed a three times larger area of arable land to produce the food needed. Furthermore, the value for arable land, shown in Table 5-18, was calculated on the assumption that humans would live entirely on vegetables.

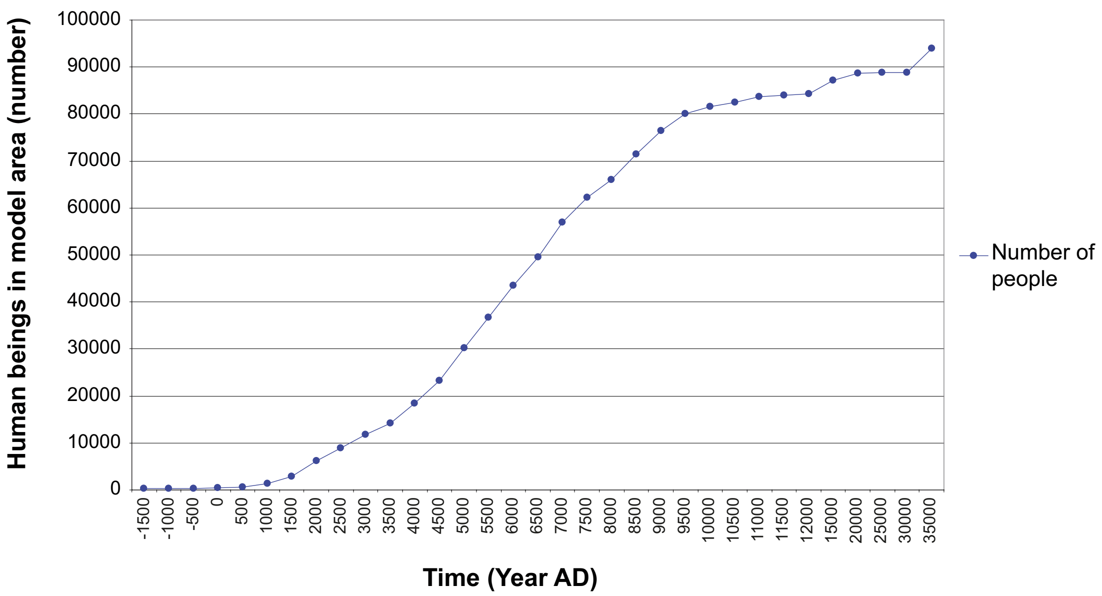


Figure 5-31. *The curve shows the modelled number of humans that may live one food produced within the Forsmark area between –1500 AD (1500 BC) and 35,000 AD in land-use Variant 2. The number of people increases as more land is uplifted above sea level. Note that the time scale is not linear.*

Table 5-18. The areas of different land-use types that are needed to support one person with food. The area of arable land needed to support one person is several hundred times smaller than the corresponding size of the other land-use types.

Land-use type	The area (m^2) needed to support one person
Forest	423,000
Arable land	780
Wetland	478,000
Lake	370,000
Baltic basin	502,000

Table 5-19. The number of people that can live on food produced in Version 2 within different types of land-uses, between –1500 AD (1500 BC) and 35,000 AD 2. It is obvious that the size of the future population of the Forsmark area is strongly dependent on the size of future areas used as arable land. Note that the land-use types forest and forest on bedrock are both shown as forest in the table.

Time AD	–1500	–1000	–500	0	500	1000	1500	2000	2500
Forest	0	0	2	15	33	54	81	112	141
Arable land	0	0	0	10	185	1,050	2,440	5,858	8,567
Wetland	0	0	0	0	1	1	3	5	5
Lake	0	0	0	0	0	0	0	3	3
Baltic basin	376	376	374	363	347	327	302	267	238
Totalt	376	376	377	389	566	1,433	2,826	6,244	8,953

Time AD	3000	3500	4000	4500	5000	5500	6000	6500	7000
Forest	163	185	205	222	241	259	269	275	276
Arable land	11,333	13,824	18,085	22,945	29,874	36,308	43,188	49,190	56,543
Wetland	8	12	11	16	19	28	25	26	26
Lake	5	7	6	6	7	9	7	6	6
Baltic basin	211	183	161	134	104	69	54	38	28
Totalt	11,719	14,210	18,467	23,323	30,244	36,672	43,542	49,536	56,877

Time AD	7500	8000	8500	9000	9500	10,000	10,500	11,000	11,500
Forest	274	276	275	275	275	274	274	274	275
Arable land	61,951	65,697	71,107	76,168	79,744	81,240	82,231	83,422	83,688
Wetland	25	23	20	17	12	12	11	10	11
Lake	4	2	2	6	5	5	5	4	6
Baltic basin	23	18	14	6	5	4	4	3	0
Totalt	62,276	66,017	71,417	76,472	80,042	81,535	82,525	83,713	83,980

Time AD	12,000	15,000	20,000	25,000	30,000	35,000
Forest	274	274	274	274	274	274
Arable land	84,051	86,908	88,437	88,549	88,549	93,699
Wetland	11	9	8	8	8	0
Lake	5	3	1	0	0	0
Baltic basin	0	0	0	0	0	0
Totalt	84,342	87,193	88,719	88,831	88,831	93,973

However, to produce meat much larger areas are needed. /Johansson 2005/ have calculated that the average person in Sweden today needs over 4,000 m^2 to produce food, i.e. a five times larger area than shown in Table 5-18. It can be noted that in both Variants 1 and 2, at 2000 AD, several thousand people might live on food produced within the area. That can be compared with the present situation when the area almost lacks a stationary population. At present, most people in Sweden are not living only on locally produced food. However, in historical times people lived more on locally produced food in a way which is more similar to the scenarios modelled here.

In Variants 1 and 2 many thousands of people may live on food produced in the future Forsmark area. These people must live in or close to the area since they are assumed to live entirely on food produced there. Such a large population would need infrastructure and buildings. It is therefore not likely that all areas with QD suitable for cultivation can be used as arable land. There are consequently several arguments suggesting that the number of people that can be sustained in Variants 1 and 2 are overestimated in the model.

In Variant 3 the number of people is considerably lower than in Variants 1 and 2, since no areas are used as arable land. The number of people that can live in the area in Variant 4 has not been calculated but can be assumed to be lower than in Variant 3, due to the cold conditions.

5.7.6 Uncertainties in land-use modelling

The four land-use variants give information about how the landscape in the Forsmark region may develop in the future. There are obviously several uncertainties in predicting the future. The cases illustrated by the four variants show how the land-use may develop under different assumptions. Variants 1–3 show different influences of human land-use during a climate similar to the present and Variant 4 the development in a tundra climate. Even though the timing of the development is uncertain the variants give plausible cases of future land-use. Variant 2 shows a scenario where all areas that can be used as arable land are cultivated and is the landscape model used within the SR-Site modelling work.

The largest uncertainties in the four variants concern factors such as future climate and rate of land uplift. Other smaller uncertainties concern geological data and the digital elevation model (DEM). The development of lakes and wetland distribution is strongly dependent on the reliability of the DEM, which is discussed in Chapter 4 and by /Strömgren and Brydsten 2009/. The land-use model is to a large extent based on the present geographical distribution of Quaternary deposits (QD) as shown by the regolith depth model, which mainly is based on the different maps of QD that was produced during the site investigation.

The uncertainties of these maps are related to the different mapping techniques. The uncertainties are especially large in parts of the areas which presently are covered by the Baltic Sea, i.e. Öregrundsgrepen. The modelled regolith depths /Hedenström et al. 2008/ have uncertainties in the same areas as the geographical distribution of Quaternary deposits. The DEM in the marine area is also to a large extent based on data collected during mapping of QD and has consequently uncertainties in the same areas as the map of QD. The geographical distributions of QD and regolith depths are thoroughly discussed in /Hedenström and Sohlenius 2008/ and /Hedenström et al. 2008/ respectively.

Glacial clay is used as arable land in both Variants 1 and 2. However, some areas presently covered with glacial clay may erode during the future land uplift. That process is not modelled in the RLDM (see Chapter 4.1) and it is therefore possible that the areas of the sea floor that presently are covered with glacial clay may decrease in the future. The areas that in the future can be used as arable land may consequently be overestimated in the land-use model. However, the glacial clay on the floor of Öregrundsgrepen is situated in an area with relatively sheltered conditions on the inside of the Island of Gräsö. The clay areas will become even more sheltered in the future as more land is uplifted. It is therefore likely that most of the areas with glacial clay will be preserved from erosion. The future distribution of arable land is therefore probably not significantly affected by future erosion of glacial clay.

The distribution of future lakes depends on the topographical level of the lake thresholds. In areas where the DEM has a low resolution the modelled extent of future lakes has consequently a relatively high degree of uncertainty /Strömgren and Brydsten 2009/. Furthermore, the level of the threshold may be lowered by erosion affecting the size of the lake. That is likely to occur in areas with sand or postglacial clay, since these deposits are easily eroded. Erosion was not accounted for when modelling the distribution of future lakes.

The future lakes in Öregrundsgrepen, close to Gräsö, are situated in an area where the DEM has a low resolution. These lakes as well as most other of the modelled future lakes are situated in environments dominated by clay, i.e. environments with deposits suitable for agriculture. In Variant 2, all infilled lakes with suitable deposits (e.g. clay and peat) thick enough will end up as arable land. Since most modelled lakes are situated in clay dominated areas, the lakes will therefore end up as arable land when the lakes have been infilled. Even though the extent of the future lakes may differ from the modelled extent, the distribution of areas suitable for arable land are consequently likely to be similar to those shown in Variant 2.

A comparison between modelled and observed land-use at 2000 AD shows that there are some features which are not shown in the land-use model. Special effort was put on comparing the result from Variant 1 with the observed present land-use. That is because Variant 1 models land-use that should be similar to that at the present. Some of discrepancies between modelled and observed land-use have only a small impact on the appearance of the land-use model.

The following discrepancies between modelled and observed land-use have been recorded.

1) All of the wetlands shown on the topographic map and situated close to the coast are not show in the land-use model. These wetlands are situated in flat areas close to the present sea level, which explains the wet conditions. Many of the wetlands situated close to the coast will not be maintained as wetlands when further uplifted. This discrepancy between observed and modelled wetlands does not affect the distribution of areas that in the future can be used as arable land.

2) At present the groundwater table in many former wetlands has been lowered by ditches to improve forest growth. In Variant 1, the only wetlands that have been ditched are used as arable land. All wetlands situated in areas not suitable for agriculture have been unaffected by human activities in that variant. Several of the wetlands shown in the Variant 1 (2000 AD) have consequently disappeared in reality due to ditching. These former wetlands are today covered with forest.

3) All of the bogs are not classified as wetlands on the topographic map but are wetlands in Variants 1 and 3. The bogs are mature peat-covered areas which may be rather dry in their central areas, at least during parts of the year. The transition from fen to bog has not been modelled. Even though bogs may be occasionally dry they are situated in discharge areas and characterised by a groundwater table situated close to ground surface. The classification of bogs as wetlands in the resulting land-use model can therefore be justified.

4) A comparison with the QD map shows that the areas covered by forest on bedrock are overestimated in the land-use model. That is because the bedrock layer from the regolith depth model was used. In that model, all pixels containing a bedrock outcrop were completely classified as bedrock. The area covered by bedrock is consequently larger in the regolith depth model than the area covered with observed outcrops. This discrepancy only affects the proportion between forest and forest on bedrock.

5) Variant 1 is meant to model a land-use similar to the present. The areas used as arable land are, however, larger in the modelled 2000 AD variant compared to the areas presently cultivated. In Variant 1, all QD that at present are frequently used for agriculture were more or less completely cultivated. However, none of the deposits suitable for agriculture are completely cultivated today. The modelled overestimated proportion of arable land was therefore not unexpected. All areas that presently are used as arable land are arable land in the Variant 1 model.

6) In all variants many of the modelled lakes at 2000 AD are smaller than the present lakes. These lakes are on the other hand surrounded by wetlands that are larger than the present ones (see e.g. Lake Bolundsfjärden). The reason for that discrepancy is that the wetland areas covered with *Phragmites* (reed) peat are overestimated around these too small lakes. *Phragmites* peat is, in the land-use model, formed in areas with a water depth of less than 2 metres. These areas are characterised as wetlands. However, most of the present lakes have a water depth of less than two metres even though *Phragmites* is absent (cf. /Hedenström 2004/). The shallow parts of the lakes are consequently infilled too fast in the model. Since the lakes in the Forsmark area are shallow this discrepancy has a relatively large impact on the land-use appearance of the area.

7) There are some wetlands shown in the land-use model that are absent on the topographic map. Based on field observations made during the detailed mapping of QD /Sohlenius et al. 2004/ it can be concluded that some non-existing wetlands have been modelled (e.g. on "Trollgrundet" and "Stora Tixlan"). These wrongly modelled wetlands are caused by small discrepancies in the

DEM. Since these wetlands are small and few they do not have any effect of the general appearance of the land-use model.

8) In all variants there is a general overestimation of the areas covered by water along the present coast. That is because the *Phragmites* belt was not modelled in sea areas that will not be followed by a lake stage. There are consequently areas with *Phragmites* that are classified as sea in the land-use model and as land (wetland) on the topographic map.

9) The occurrence of clayey till with a low frequency of boulders has not been mapped on the sea floor. It is therefore possible that some till areas on the present sea floor will be suitable as arable land in the future.

6 Discharge areas and near-surface transport conditions

6.1 Background and scope

6.1.1 Objectives and main inputs

This chapter describes the identification and characteristics of potential discharge areas for deep groundwater in Forsmark. Specifically, it presents results of flow and transport modelling performed to locate and describe discharge areas for groundwater from the planned repository volume. The main objective of the description below is to provide background and supporting information for the landscape modelling presented in the next chapter. However, another important objective is to summarise modelling results considered to be of relevance for supporting the radionuclide transport and dose model presented in /Avila et al. 2010/.

The presentation in this chapter is based on modelling results obtained from the SR-Site modelling of bedrock hydrogeology, which considers the whole bedrock-regolith system including the repository, and the SR-Site Biosphere modelling of flow and transport, which is focused on the regolith and the upper part of the bedrock. In particular, the following topics and main inputs are considered.

- ***Locations of discharge areas for deep groundwater.*** Discharge areas are obtained from the modelling of groundwater flow under temperate conditions presented in /Joyce et al. 2010/. These discharge areas are identified based on modelled flow paths from individual deposition holes within the planned repository. The results include discharge areas for a suite of snapshots-in-time, ranging from past submerged stages into the future when shoreline displacement has created new land areas outside Forsmark.
- ***Solute transport in discharge areas for deep groundwater.*** This part of the presentation is based on modelling of discharge locations and solute transport by advection and dispersion presented in /Bosson et al. 2010/. The modelling is focused on the regolith and the upper part of the bedrock. The results are used to describe detailed discharge locations and solute spreading within local model domains containing discharge areas for deep groundwater from the repository.
- ***Radionuclide retention and reactive transport in discharge areas.*** This modelling consists of conceptual and numerical modelling of retention processes and coupled (with advection and dispersion) reactive transport presented in /Piqué et al. 2010/. Retention processes that could affect radionuclide transport in the regolith layers in Forsmark are identified based on an analysis of chemical data from the site. Numerical modelling of reactive transport is used to test whether the identified processes are likely to affect radionuclide transport in the regolith at the site.

In the list above, only the main reference for each part of the modelling is provided. Additional contributions to the knowledge about flow and transport conditions in discharge areas are described below. The identification of discharge areas is presented in Section 6.2, and the detailed analysis of non-reactive solute transport in some of the identified areas is described in Section 6.3. Section 6.4 summarises the results of the conceptual and numerical modelling of radionuclide retention and reactive transport, whereas Section 6.5 presents the conclusions of this part of the landscape modelling.

Although some information about the repository (e.g. the overall layout and the individual canister positions) and the safety assessment (biosphere objects and how radionuclide transport is modelled) is used as an input to the present description, these aspects are not described in detail here. The present analysis is focused on typical (site-specific) conditions and processes of relevance for model development and the description of a relevant future development of the Forsmark area. In some cases, specific canister positions and biosphere objects are considered in the description below. This is done to ensure that the analysis considers relevant site conditions, but the modelling in which the biosphere objects are identified is described in Chapter 7.

6.1.2 Conceptual models

Figure 6-1 shows a generic conceptual model of solute transport from the repository at a depth of c. 500 metres in the bedrock up to the surface and further within and between different types of surface ecosystems. A hypothetical flow path, along which dissolved radionuclides could be transported, is shown as a red dotted line in the figure. Note that the figure emphasises the mainly horizontal transport near and on the surface, whereas the mainly vertical transport through fractures and deformation zones in the bedrock is greatly simplified.

This conceptual model provides a common basis for the ecosystem and landscape models. It also illustrates the main roles of the modelling of bedrock hydrogeology and surface hydrology. The transport of radionuclides from the repository to the surface system may follow a variety of different pathways leading to human exposure. With reference to the pathway indicated in Figure 6-1, a possible case describing the transport of a radionuclide through the deep rock and the surface ecosystems can be outlined as follows /Berglund S et al. 2009/.

- The radionuclide is released from its origin in the repository. This implies that the radionuclide is transported through the "engineered barrier", i.e. out from the canister, through the bentonite surrounding it, and into the rock.
- After being transported through fractures and deformation zones in the deep rock, the radionuclide reaches the uppermost part of the rock, which marks the entry point to "the surface system". Thus, the surface system (as defined in the hydrological modelling) includes the upper part of the bedrock.
- The transport continues through the upper, usually more fractured, part of the bedrock, and further by the groundwater in the regolith to a surface stream or possibly directly to terrestrial (e.g. forest) or aquatic (e.g. lake) objects. In the present example, the radionuclide enters a mire, from which it is further transported by a stream to a lake.
- The flow and transport within objects is represented by separate models, e.g. the mire and the lake in the figure, are modelled by means of object-specific process models and data. The modelled radionuclide pathway shows which objects to consider in the model, and hence for which objects hydrological and other data are needed.
- The surface water system transports the radionuclide from the most downstream onshore object to the sea; also the offshore part of the system can be divided into several linked objects, within and between which transport takes place.

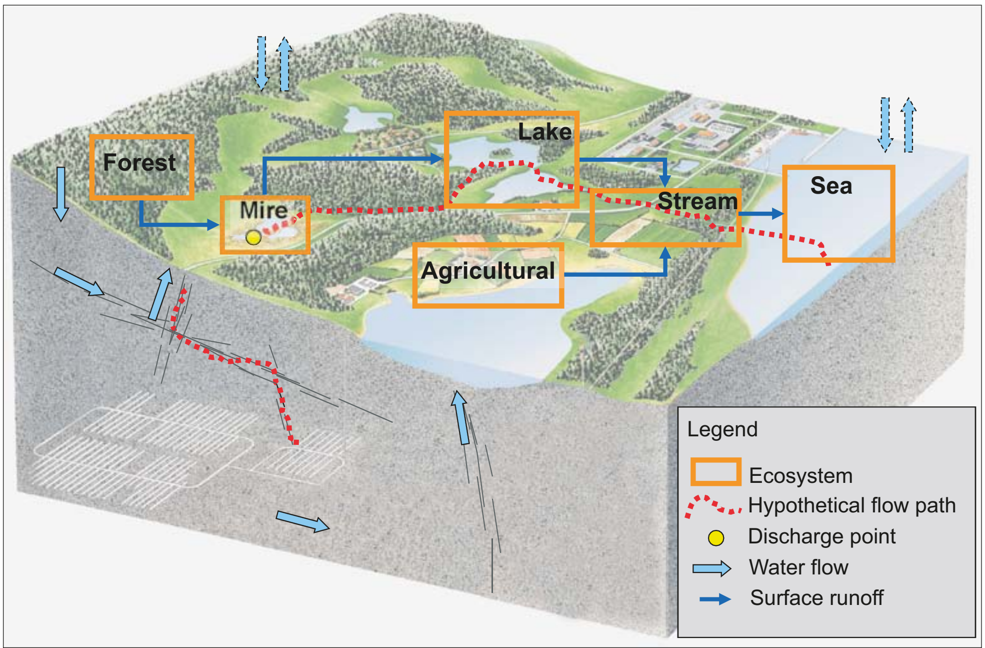


***Figure 6-1.** Conceptual model of solute transport along a hypothetical flow path from the spent fuel repository, which is indicated by the white lines in the grey bedrock part of the model, up to a discharge point (the yellow dot), and further through different types of ecosystems to the sea. Figure taken from /Lindborg 2008/.*

Site-specific geological and hydrogeological data and models are instrumental when developing conceptual transport models for a particular site. As discussed in detail in the reporting of the site descriptive modelling, see /Follin et al. 2008, Follin 2008/, the upper part of the bedrock within the so-called target area in Forsmark contains structures that may affect solute transport from the deep rock towards the surface. The target area is the north-western part of the Forsmark candidate area (see Figure 6-2). During the site investigations, it was selected as the most suitable area for hosting the repository; consequently the planned repository considered in SR-Site is located there. Figure 6-2 also shows the drill sites (DS) where the deep core-drilled boreholes are located and the locations of percussion-drilled boreholes in the upper rock (HFM).

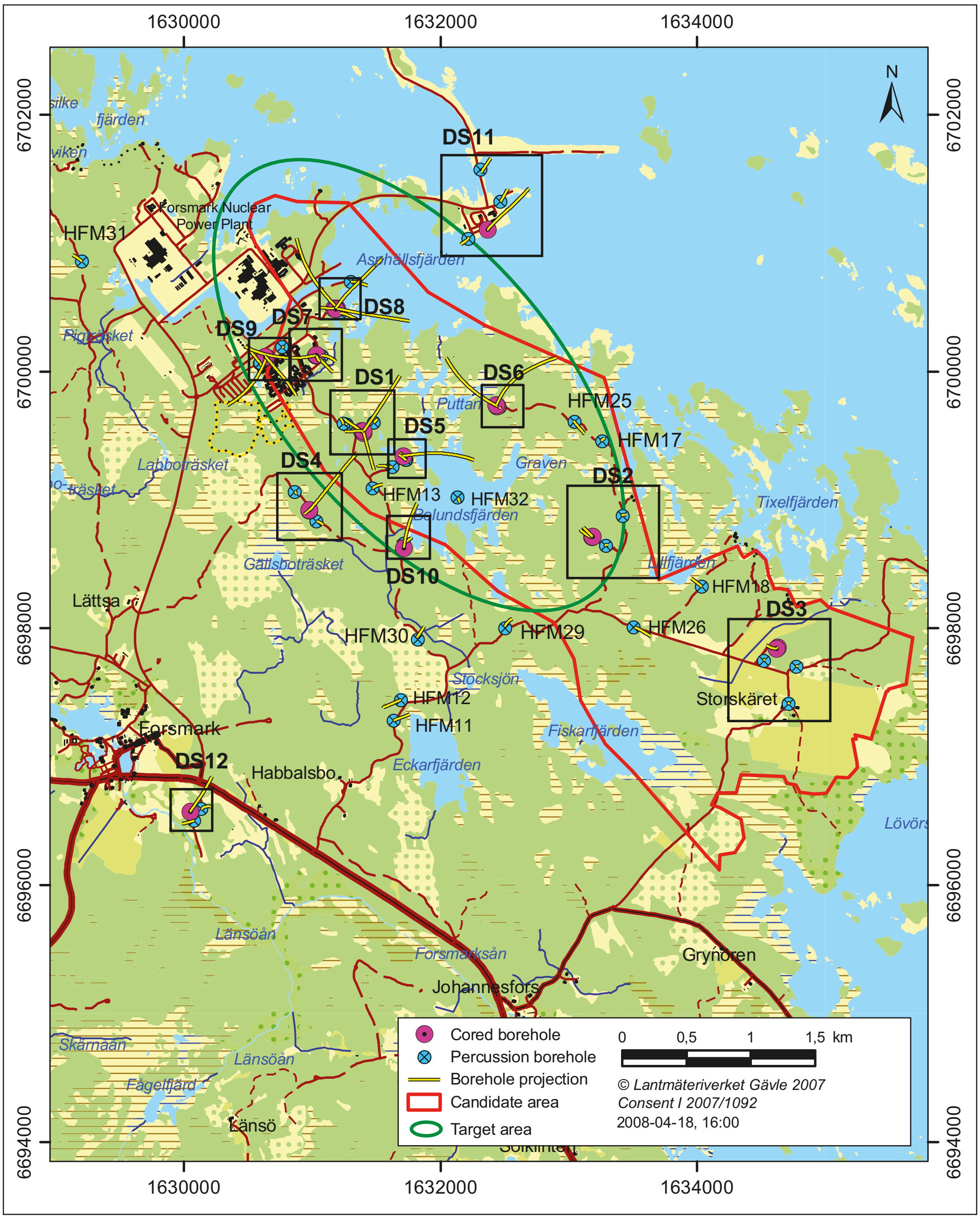


Figure 6-2. *The Forsmark candidate area (bounded by red line) with the target area in the north-western part (ringed in green) and the locations of drill sites with core-drilled boreholes (DS) and percussion-drilled boreholes (HFM). The drill sites are labelled DS1 to DS12, where the numbering corresponds to that of the core-drilled borehole(s) at each site (for example, KFM01 is at DS1). The projection of each borehole on the ground surface (due to inclination) is also shown. Figure taken from /SKB 2008/.*

Specifically, the highly transmissive horizontal fractures/sheet joints encountered in the target area suggest that there may be a well-connected network of structures with highly anisotropic hydraulic properties in the uppermost c. 150 m of the bedrock. The bedrock at larger depths is much less fractured, and the strong contrast in the structural-hydraulic properties with depth creates a hydraulic phenomenon that short-circuits the near-surface flow system. The groundwater levels monitored in the QD and in the bedrock suggest that the near-surface fracture network short-circuits the recharge from above as well as the anticipated discharge from below.

This means that the highly transmissive shallow bedrock, which in the site descriptive modelling is referred to as a shallow bedrock aquifer, acts as a drain for water coming from below. Thus, the available data indicate that flow systems involving the bedrock do not have discharge areas on land in the northern part of the candidate area, including the target area, and hence discharge into the sea. The only occasions when data from this area show a continuous upward flow gradient are during dry summers when the groundwater level in QD may fall below the level in the bedrock /Johansson 2008, Lindborg 2008/.

Figure 6-3 is an attempt to illustrate the key role of the horizontal fractures/sheet joints for present and future flow and transport within the target area in Forsmark. The figure shows the present conditions with recharge to the upper bedrock on land, and groundwater discharge to the sea. Red arrows indicate hypothetical pathways for groundwater carrying solutes from the deep rock. To the right in the figure, a future lake forming as a consequence of the ongoing shoreline displacement is also shown. This outlook into the future is included to clarify that deep groundwater may discharge to surface waters and other objects on the surface, even though there are no indications of such discharge taking place within the target area. Discharge areas in present and future Forsmark landscapes are discussed in Section 6.2.

As described in more detail elsewhere in this report, areas with lakes or streams surrounded by wetlands are of particular interest when defining and describing transport conditions in the biosphere objects that constitute the main components of the landscape model (see Chapter 7). The landscape model consists of a set of interconnected biosphere objects. Due to shoreline displacement and other processes contributing to formation, infilling and terrestrialisation of lakes and wetlands, these objects are subject to a succession, which in many cases includes submerged (by the sea), lake, wetland and terrestrial stages. In particular, lakes will gradually decrease in size and become wetlands, and then possibly further develop into land areas that in some cases may be suitable for agriculture.

Since low-lying lake-wetland areas are important potential discharge areas for deep groundwater from the repository and also central for the landscape development in Forsmark, models describing solute transport in such areas are needed. Figure 6-4 illustrates alternative or complementary conceptualisations of transport from a deformation zone in the bedrock, through the QD, and up to the lake water or to the surrounding wetland. Since till is present everywhere where there is regolith, solutes travelling with the deep groundwater first enter the till layer. Depending on the hydrogeological properties and boundary conditions governing flow in the regolith, solutes may be spread over a large part of the till layer or remain concentrated, before entering the overlying glacial and post-glacial sediments.

As indicated in Figure 6-4, solute transport in the regolith may result in direct transport to the lake water, transport to the surrounding wetland, followed by transport by streams or other overland or groundwater discharging to the lake, or a combination of these pathways. When developing site-specific conceptual and numerical models, it is of particular interest to find out whether solutes travelling with deep groundwater consistently end up in specific parts of the system, and in which parts, and to quantify "typical" distributions of deep groundwater between potential discharge locations. Detailed transport simulations investigating these issues are presented in Section 6.3.

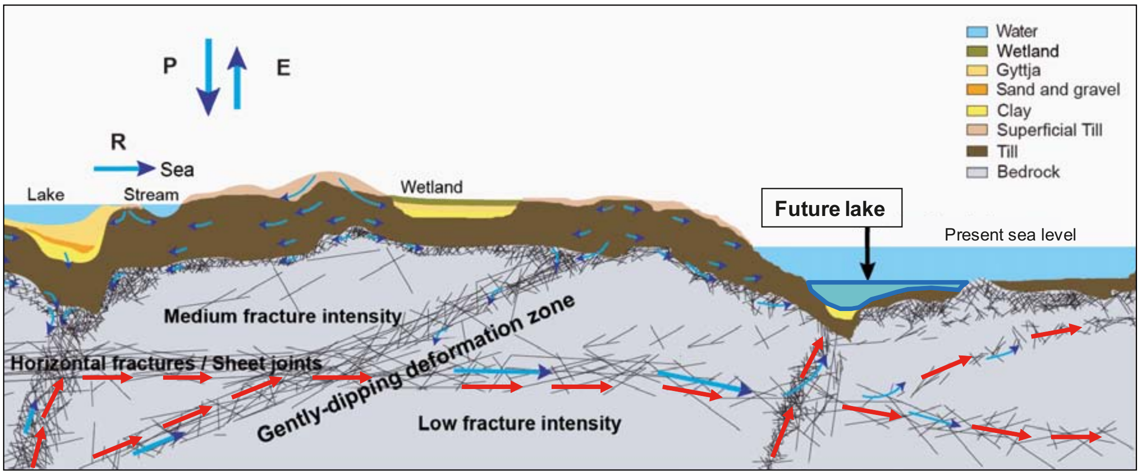


Figure 6-3. *Possible influence of horizontal fractures/sheet joints on groundwater flow and solute transport from the deep bedrock. Blue arrows indicate water flow directions and red arrows solute transport directions from deep rock towards the surface (only directions, not magnitudes); P, E and R denote precipitation, evapotranspiration and runoff, respectively. Figure modified from /Lindborg 2008/.*

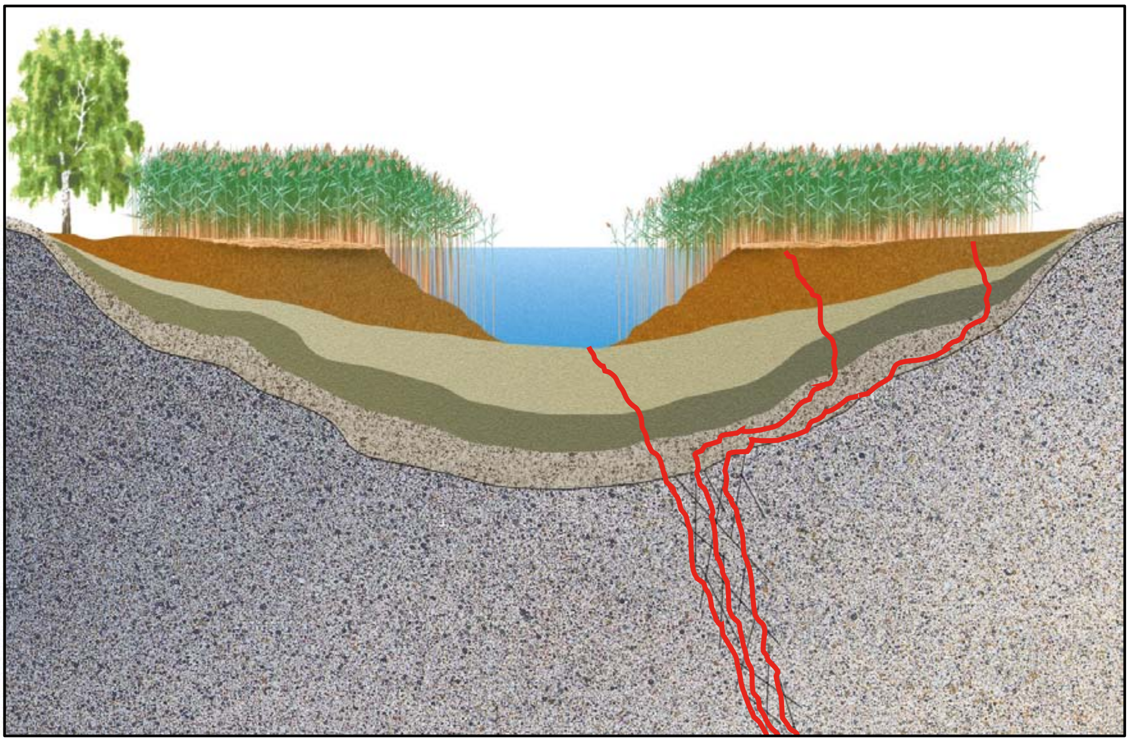


Figure 6-4. *Cross section through a lake-wetland object with examples of possible transport pathways from the deformation zone in the bedrock to the lake or to the surrounding wetland. Figure modified from /Löfgren 2010/.*

6.1.3 Bedrock and surface system models

For several of the disciplines involved in the site descriptive modelling (SDM) work, e.g. geology, hydrogeology and hydrogeochemistry, a distinction was made between the surface system and the bedrock system. The reasons for this distinction were both practical (large amounts of data, different objectives and different users of results) and historical, as the SKB work traditionally has been focused on the bedrock system. Clearly, the delimitation between the surface and bedrock systems in the SDM was somewhat artificial and arbitrary /SKB 2008, Follin 2008/. However, a similar distinction between the two systems has been made also in SR-Site, where the surface system modelling was performed within the framework of SR-Site Biosphere (see Chapter 1).

In the site descriptive modelling, the interface between the surface and bedrock systems was considered in the evaluation of shallow and deep groundwater movement, as well as in the groundwater chemistry description. The conceptualisation of the hydraulic properties of the Quaternary deposits was implemented into the near-surface part of the bedrock hydrogeology model and also into modelling and evaluation of the impact of infiltration on the present groundwater composition. The shallow groundwater system was modelled so as to include the upper part of the bedrock, with properties and flow conditions consistent with the bedrock hydrogeological model (see Figure 6-5).

The handling of the interfaces in the SDM hydrogeological models was described in the bedrock hydrogeology modelling reports /Follin et al. 2008, Follin 2008/ and in the reports describing the modelling of the near-surface hydrogeology /Johansson 2008, Bosson et al. 2008/. The corresponding descriptions of the SR-Site models are given in /Joyce et al. 2010/ (bedrock hydrology during the temperate period) and in /Bosson et al. 2010/ (near-surface hydrogeology, summarised in Section 4.3 of the present report). Figure 6-5 was produced as a description of the SDM modelling, but is, in principle, valid also for SR-Site. The figure indicates that the numerical modelling of groundwater flow in the bedrock is performed with ConnectFlow, whereas the surface hydrology modelling is undertaken with the MIKE SHE tool. In SR-Site, this holds for the modelling of the initial temperate period after closure of the repository only; bedrock hydrogeology during other periods is modelled using DarcyTools (see Section 6.2).

The regional ConnectFlow model used in SR-Site has its bottom boundary at a depth of c. 1,200 m, whereas the bottom boundary of the MIKE SHE models is at a depth of c. 600 m below ground. Thus, a relatively large depth interval in the bedrock is included in both models. This means that the differences between the two modelling activities concern the purposes of the modelling and which properties and

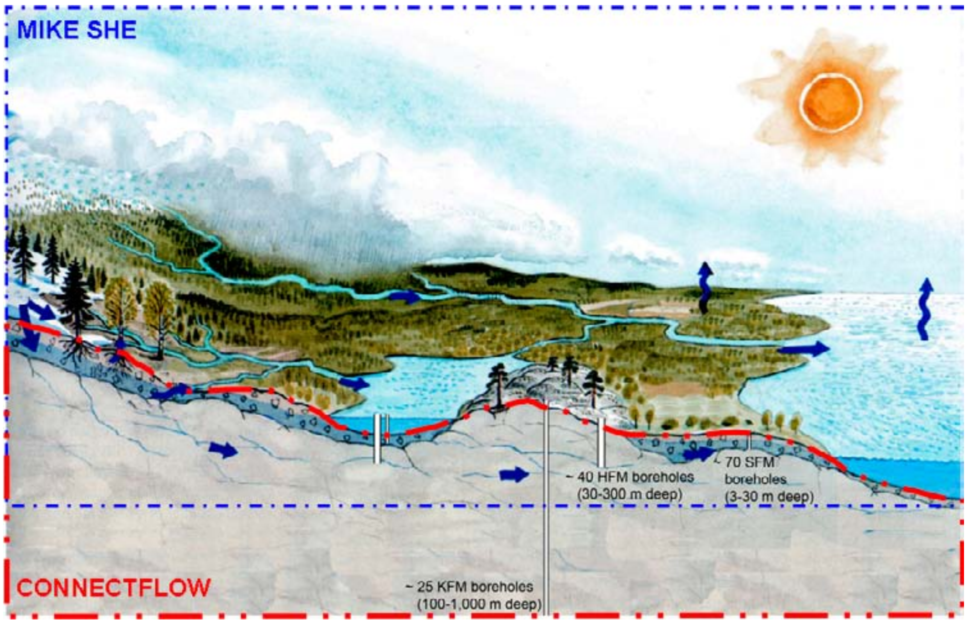


Figure 6-5. *Illustration showing how the modelling of the hydrologic cycle in SDM and SR-Site is divided into a surface-based system and a bedrock-based system. The former is modelled with the MIKE SHE numerical modelling tool and the latter with the ConnectFlow modelling tool (applies to the modelling of the temperate period). Reproduced from /Follin 2008/.*

processes are handled in detail, more than the actual model domains considered in each activity. For example, the repository and a detailed representation of the surrounding bedrock is included in the ConnectFlow model, whereas the MIKE SHE model includes a detailed representation of the regolith and also quantifies the hydrological processes at the surface (including exchanges with the atmosphere).

In SR-Site, the ConnectFlow modelling of bedrock hydrogeology delivered the discharge points used as a basis for the identification of biosphere objects in the landscape modelling (see Section 6.2). The MIKE SHE modelling of surface hydrology and near-surface hydrogeology was used to support the development of the radionuclide transport model used for dose calculations, including calculations of water fluxes between different compartments in the model. However, the dose modelling is not described in the present report, see instead /SKB 2010b/ for an overview and /Avila et al. 2010/ for a detailed description. In this chapter, the focus is on the MIKE SHE simulations performed in order to improve the understanding of site-specific transport conditions (Section 6.3).

6.2 Identification and characterisation of discharge areas

6.2.1 Bedrock hydrology modelling in SR-Site

The modelling of bedrock hydrogeology in SR-Site consists of three modelling studies focusing on different time periods in the life span of the repository. These are referred to as the excavation and operational phases, the initial period of temperate climate after closure, and the remaining part of the reference glacial cycle. The modelling methodology, data utilisation and numerical model setup, and summary of results of these studies are presented in /Selroos and Follin 2010/.

Figure 6-6 indicates the time period handled by each bedrock flow modelling study and where the results are presented. The three studies employed different computer codes and modelling teams. The studies conducted by /Svensson and Follin 2010/ and /Vidstrand et al. 2010/ were made with DarcyTools, whereas the study by /Joyce et al. 2010/, which deals with the temperate period, was made with ConnectFlow. During the excavation and operation phases, the tunnels will be at atmospheric pressure and there will be inflow of groundwater to the open repository. This may potentially result in drawdown of the groundwater table, infiltration of near-surface waters into the deeper parts of the bedrock, and in up-coning of saline water from depth. Open repository conditions are not further discussed in the present report (see /Svensson and Follin 2010/ and /Mårtensson and Gustafsson 2010/ for open repository modelling focusing on the bedrock and surface systems, respectively).

The hydrogeological development during the temperate period after repository closure involves two distinct time intervals. The first is that for saturation of the repository once pumping of the open tunnels has ceased. The subsequent time interval deals with the evolution of the saturated repository during the remaining part of the period with temperate climate conditions. The SR-Site biosphere assessment is primarily concerned with the latter part of the temperate period, which is therefore the main focus here.

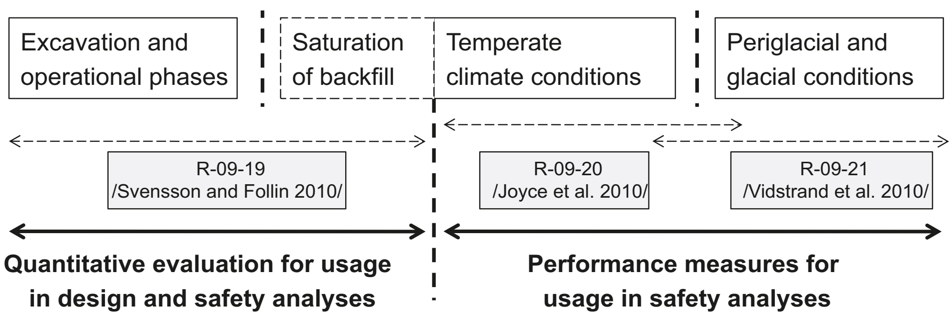


Figure 6-6. Overview of SR-Site bedrock hydrogeology modelling studies. Discharge points for the biosphere assessment were obtained from the /Joyce et al. 2010/ modelling of the temperate period. Figure modified from /Selroos and Follin 2010/.

The remaining part of the reference glacial cycle includes periods with both periglacial (permafrost) and glacial climate conditions. The hydrogeological conditions during such periods are addressed in the bedrock modelling. However, the analyses performed are more of a bounding nature than trying to accurately predict the future evolution /Selroos and Follin 2010/. Hydrogeological modelling of a periglacial system with permafrost using MIKE SHE is described in Section 4.3 of the present report, but modelling results for periglacial or glacial conditions are not discussed in this chapter.

The two codes used for simulation of groundwater flow in the SR-Site modelling of bedrock hydrogeology, DarcyTools and ConnectFlow, supplement each other and essentially solve the same problems (i.e. the same equations). Both codes are capable of simulating density-driven groundwater flow and include matrix diffusion of salt and/or other solutes (density-driven flow and matrix diffusion are not considered in the MIKE SHE modelling). However, ConnectFlow has the capability for an explicit representation of fractures, i.e. an option to include Discrete Fracture Network (DFN) models. The DFN parts can also be up-scaled to Equivalent Continuous Porous Medium (ECPM) models. DarcyTools is an ECPM model code, which also utilises up-scaling of DFN models. In addition, both codes can have Continuous Porous Medium (CPM) descriptions included.

Three different scales of model are used in the SR-Site temperate period modelling; these scales are referred to as the regional-scale, the site-scale and the repository-scale, see /Joyce et al. 2010/. Information on parameter values and particle transport is passed between the different model scales. Figure 6-7 shows the relationship between the scales, the embedding of the rock representations that they use and how data are passed between them. The different model scales and their uses can be summarised as follows, see /Joyce et al. 2010/ for details.

- The regional-scale model corresponds to the SDM-Site model (the final version of the SDM) and covers the same domain. The model is transient and takes the time-dependent boundary condition caused by shoreline displacement into account. It uses an ECPM representation in the part of the model volume where fracture domains are defined and a CPM representation elsewhere, including the regolith. The model is used to calculate the transient evolution of coupled groundwater flow and reference water transport with rock matrix diffusion (RMD) from 8000 BC to 12,000 AD. The calculated pressure and fluid density values are exported from this model for particular times for use at the two other scales.
- The site-scale model replaces the part of the regional-scale ECPM model local to the repository area with an explicit embedded DFN representation of the rock mass between the deformation zones. The DFN region was chosen to encompass all the repository features and to extend from the bottom of the regolith to a depth of a few hundred metres below the repository. The sheet joints in the upper part of the rock are represented as three fracture surfaces, each at a different depth. Fractures with appropriate hydraulic and transport properties are also used to represent the repository structures. The site-scale model is primarily used to continue particles originating from the repository-scale model, but it is also used to track particles from the repository to provide discharge locations for the biosphere assessment (cf. below).
- The repository-scale model uses a CPM representation of the main tunnels, deposition tunnels and deposition holes in the repository. This provides a suitable representation of the tunnel backfill, which is a porous medium, and allows detailed particle tracking within the tunnels. These structures are embedded within a DFN representation of the rock mass, including the smaller fractures around the repository structures. It is not practical to model these fractures everywhere, but they provide transport pathways for particles released from deposition holes.

A major objective of the SR-Site hydrogeological modelling is to compute groundwater flow paths from each deposition hole (there are 6,916 in total) to the surface. The approach taken was to track particles moving with the advective flow velocity from release points around the deposition holes until they reach the top surface. Flow paths and associated discharge points were computed with both the site-scale and the repository-scale models. However, it should be noted that the particle tracking simulations in SR-Site also served other purposes than to determine discharge locations; most notably, they were utilised to calculate performance measures (e.g. travel times and flow-related transport resistances, see /Joyce et al. 2010/ for definitions) used in the radionuclide transport modelling.

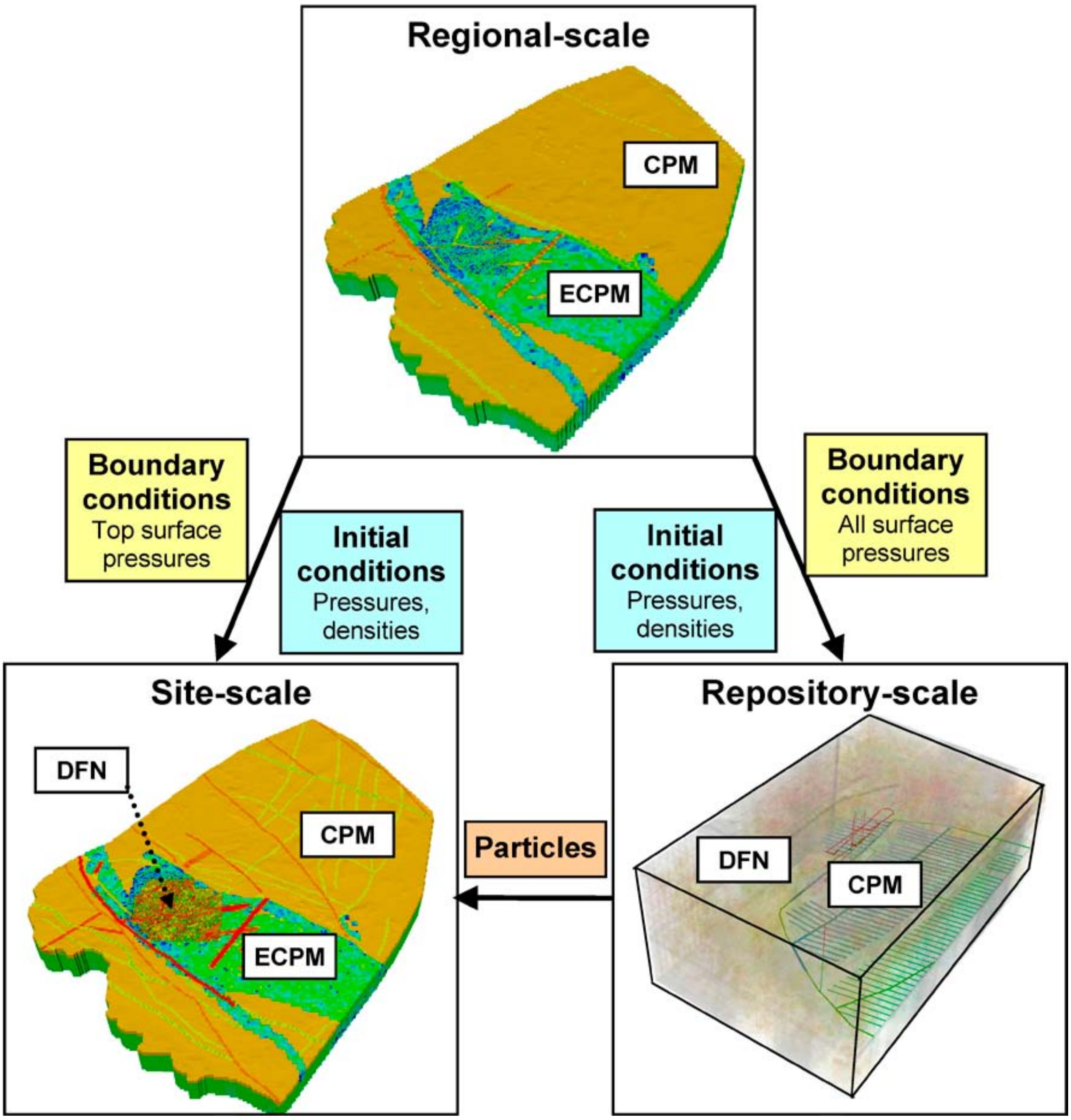


Figure 6-7. *Illustration of the three model scales considered in the hydrogeological modelling of the temperate period, and of the transfer of data between scales. Figure reproduced from /Joyce et al. 2010/.*

In the particle tracking calculations, three release paths for radionuclides are considered (Figure 6-8):

1. The Q1 path – a fracture intersecting the deposition hole.
2. The Q2 path – the excavation damaged zone (EDZ), if such a zone exists, located below the floor of the deposition tunnel that runs above the deposition holes.
3. The Q3 path – a path through the backfilled tunnel and into a fracture intersecting the deposition tunnel.

Individual particles are released at each deposition hole position, i.e. three particles per deposition hole, and the flow pathways are tracked, see /Joyce et al. 2010/ for details. Note that the repository-scale model has a much more detailed and explicit representation of the various parts of the repository and the adjacent rock than the site-scale model. In the site-scale model, some features modelled as CPM in the repository-scale model (e.g. tunnels) are represented as equivalent fractures. However, for all three release paths Q1, Q2 and Q3 flow paths are generated within both models. Since there are no deposition holes represented in the site-scale model, particles were started from the closest fracture intersection (weighted by flux) to each of the Q1, Q2 and Q3 release points.

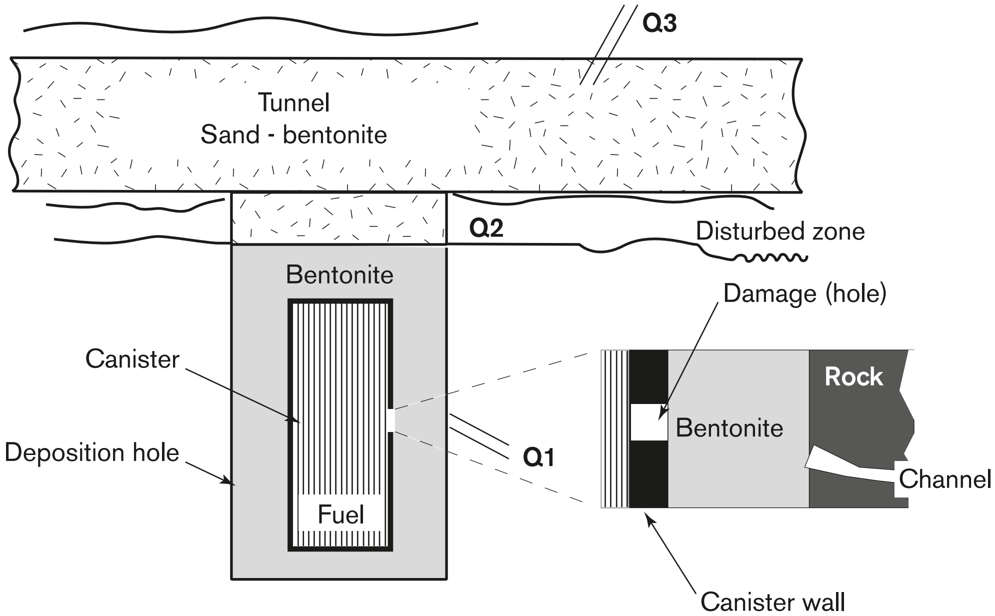


Figure 6-8. Schematic view of the repository design, showing location of the considered transport paths into near-field rock. Figure reproduced from /Joyce et al. 2010/.

The particle tracking simulations providing discharge points for the biosphere landscape modelling and transport parameters for the geosphere radionuclide transport modelling were performed in steady flow fields representing specified times during the period considered in the transient modelling with the regional-scale model. This means that particles were released and traced in fixed flow fields extracted at different times during the continuous development of the transient groundwater flow field.

Specifically, the particle tracking in the site-scale model was performed for every 1,000 years from 0 AD to 12,000 AD, whereas the corresponding modelling in the repository-scale model considered the times 2000 AD, 3000 AD, 5000 AD and 9000 AD. Thus, when referring to a particular set of discharge points using a specific time, this means that the particles were released simultaneously at all deposition hole positions at that time and then traced in the flow field existing at the release time. Particle tracking simulations were also carried out for 10 realisations of the stochastic features of the model at 2000 AD.

6.2.2 Discharge points for biosphere assessment

In this section, calculated discharge points are displayed on different types of maps representing present or future topographical or land-use conditions in Forsmark. As explained above, the biosphere assessment is based on tracing of particles released in steady-state velocity fields at times from 0 AD to 12,000 AD in the site-scale model. In this model, the repository is included in a simplified manner expressed as equivalent fractures. A more detailed representation of the repository was included in the repository-scale simulations. The effect of model scale on discharge locations, i.e. a comparison between discharge points generated in the site-scale and repository-scale simulations, is discussed in Section 6.4.

The discharge points presented below were obtained from site-scale simulations using the Q2 release path. Starting with the whole dataset of flow paths from all canister positions for all release times, locations and performance measures for paths reaching the ground surface within 57,000 years (to include only paths discharging before the next glaciation) were extracted. A description of the analysis of the discharge point dataset leading to the identification of biosphere objects is provided in Chapter 7. The resulting dataset used for generating the figures presented below is stored at SKBdoc 1263189.

Changes in discharge locations with release time

The spatial distribution of discharge points from the site-scale hydrogeological model is shown in Figure 6-9 (taken from /Joyce et al. 2010/) for release times every 1,000 years from 0 AD to 12,000 AD; different colours correspond to different release times. The discharge points obtained from releases at earlier times, 0 AD (blue), 1000 AD (red) and 2000 AD (green) are located near the repository and show a very slight migration toward the 2000 AD shoreline with release time. The near-future discharge points, i.e. those for releases at 3000 AD (magenta), 4000 AD (cyan) and 5000 AD (yellow), appear to follow the retreating shoreline.

The far-future discharge points, i.e. the ones from the 6000 AD through 12,000 AD releases, congregate on the north-eastern model boundary. This suggests that the model domain should be extended further to the northeast. However, the boundary is consistent with the boundary of the SDM model, which corresponds to a bathymetric depression in the terrain in this area. This means that extending the model area would not necessarily have an effect on the discharge points. In addition, the CPM representation could make the discharge locations more dominated by the location of the shoreline than they would be if other model representations had been used. For a DFN or ECPM representation, the discharge points may be more influenced by the locations of outcropping deformation zones or fractures. This point is examined in the sensitivity analysis reported in /Joyce et al. 2010/.

Discharge points in present and future landscapes

Figure 6-10 shows all discharge points, i.e. discharge points for all release points and release times, on a map of the present topography and bathymetry. Thus, discharge points are shown on a map that does not represent the site conditions when most of the particles are released, or when they reach the surface. However, this presentation is made to show the coupling (or lack thereof) between discharge points and various features or objects of the present Forsmark landscape. Similar presentations linking discharge points to future landscapes are given below.

It is seen in Figure 6-10 that the discharge points to large extent are concentrated to areas near the present coastline, especially the bays just outside the nuclear power plant and in the vicinity of the SFR facility. However, clusters of particles can be observed also at larger distances from the coast. Darker blue areas in the sea indicate larger water depths; it is clear from the figure that discharge points are concentrated to areas with deeper water, i.e. to depressions in the bathymetry. Where the particle density is sufficiently low for patterns to be identified, there seems to be a general tendency for the discharge points to form patches or clusters or to appear along lines associated with structures in the bathymetry.

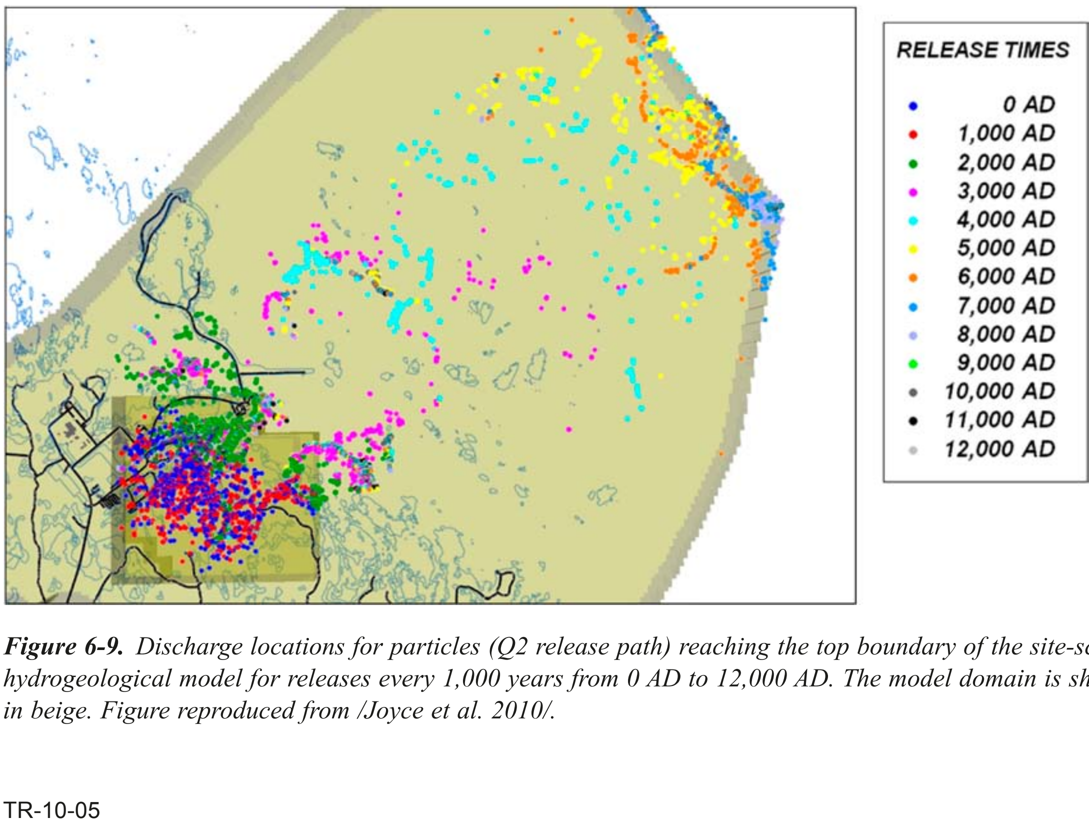


Figure 6-9. *Discharge locations for particles (Q2 release path) reaching the top boundary of the site-scale hydrogeological model for releases every 1,000 years from 0 AD to 12,000 AD. The model domain is shown in beige. Figure reproduced from /Joyce et al. 2010/.*

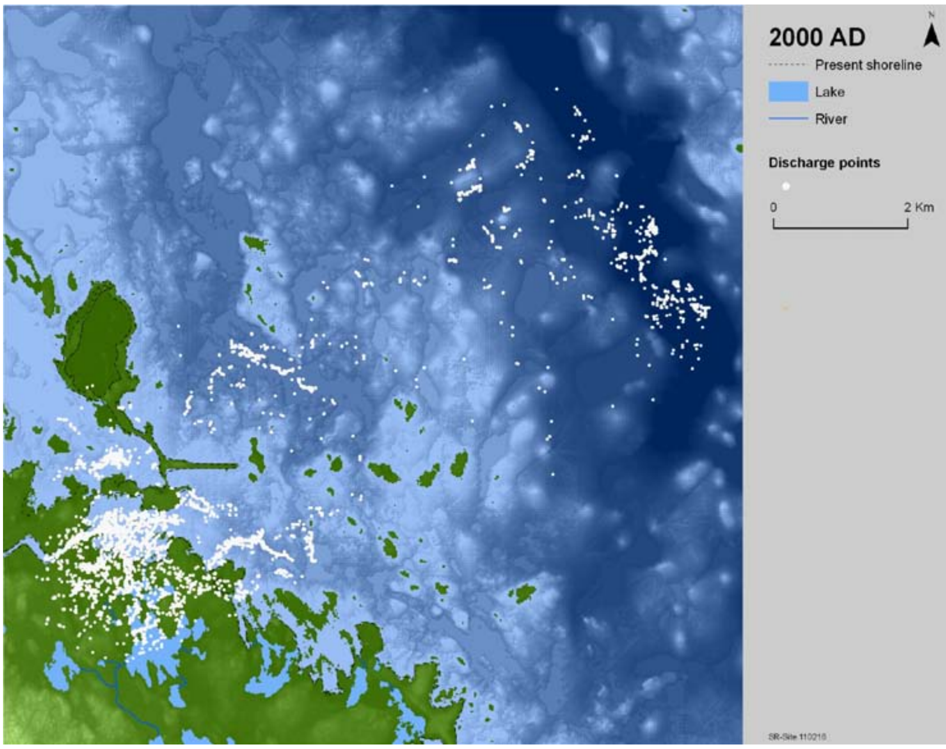


Figure 6-10. *Discharge points for all release times on a map showing the present topography and bathymetry. The topography is indicated by different green shades and the sea bathymetry by blue shades; darker shades correspond to lower elevations.*

Figure 6-11 and Figure 6-12 show the same set of discharge points on maps describing the topography and bathymetry at the site at 5000 AD and 10,000 AD, respectively. On these maps, the shoreline is located further towards north-east and new land areas and lakes have emerged in the presently submerged parts of the model area. Concerning the new lakes, it should be noted that their successive infilling due to sedimentation and other terrestrialisation processes has not been considered when producing these maps. Therefore, the lakes have the same sizes, which correspond to their maximum extents, on all maps discussed here. Discharge points displayed on land-use maps where the succession of lakes areas has been taken into account are presented below.

Consistent with the observation that discharge points are found in deep-water (dark blue) areas in the present sea (Figure 6-10), Figures 6-11 and 6-12 show that discharge locations outside the present coastline to large extent are found in lakes. With some exceptions, the discharge points appear as clusters within the boundaries of the future lakes. However, there are also some scattered points outside the lake areas. Although this may not be the case for all of these discharge points, a majority of them appear in relatively low-altitude (dark green) parts of the new land areas.

Examples of calculated travel times

As mentioned in Section 6.2.1, a set of performance measures characterising the flow paths is calculated in the particle-tracking simulations. Figure 6-13 shows discharge locations coloured according to the total advective travel time from each deposition hole in the repository to the corresponding discharge location on the surface. The figure shows the particles in the 2000 AD release on the 2000 AD map. This means that the discharge points are shown on a map describing the conditions at the release time, which, depending on the travel time, may or may not be a good representation of the site when discharge actually would occur. However, since the transport of most radionuclides is affected also by other processes (which increase travel times), the aim here is not to provide a complete picture of the transient processes. The intention is merely to show some results that exemplify the relation between travel times, travel distances and discharge areas.

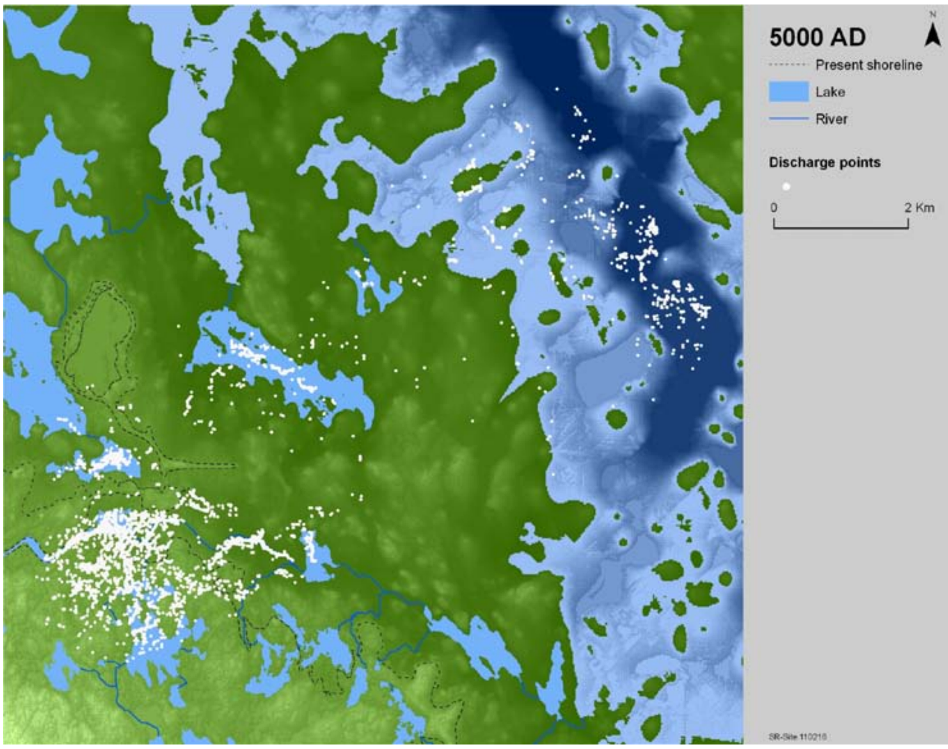


Figure 6-11. Discharge points for all release times on a map showing the 5000 AD topography and bathymetry. The topography is indicated by different green shades and the sea bathymetry by blue shades; darker shades correspond to lower elevations. Note that infilling of lakes is not considered; the largest extent of each lake is shown.

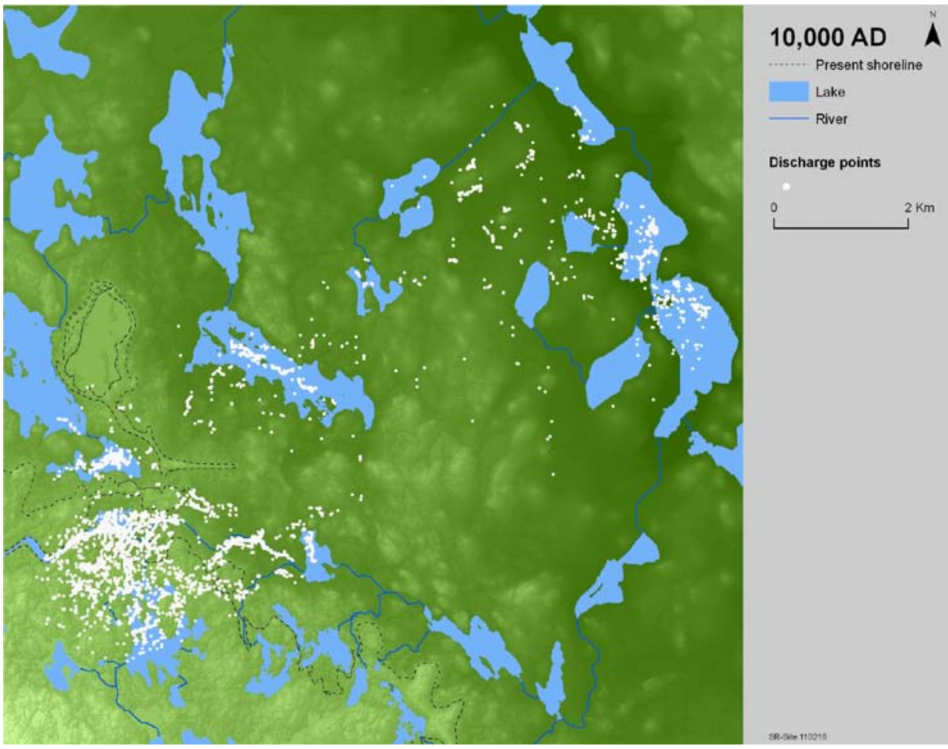


Figure 6-12. Discharge points for all release times on a map showing the 10,000 AD topography and bathymetry. The topography is indicated by different green shades and the sea bathymetry by blue shades; darker shades correspond to lower elevations. Note that infilling of lakes is not considered; the largest extent of each lake is shown.

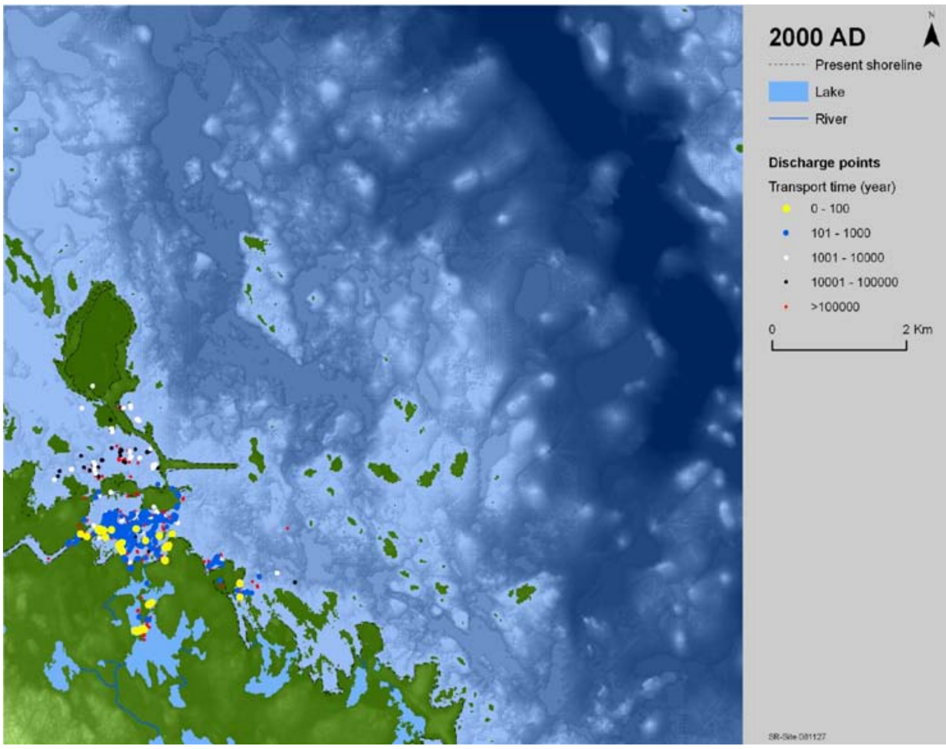


Figure 6-13. *Discharge points coloured according to calculated advective travel times for the 2000 AD release displayed on a map showing the 2000 AD topography and bathymetry. The topography is indicated by different green shades and the sea bathymetry by blue shades; darker shades correspond to lower elevations.*

Figure 6-13 indicates that most of the discharge points from the 2000 AD release are found very close to the planned repository, which is located in an area below and to the north-west of Lake Bolundsfjärden and also partly below the sea. The figure also shows that particles with short travel times (yellow and blue dots) almost exclusively are found in Lake Bolundsfjärden and near the present coastline, whereas particles associated with longer travel times (white, black and red dots) are found both close to the release area and at some distance from it.

Figure 6-14 shows the discharge points resulting from the 5000 AD release on the 5000 AD topography map. Interestingly, there seems to be a more obvious separation of these discharge points, so that points corresponding to short travel times are found close to the release area and those with longer travel times at more distant discharge locations. For example, almost all travel times of particles in the large future lake in the middle of the map are in the 1,000–10,000 years travel time interval. This is an effect of shoreline displacement. To some extent, this separation of the travel times may also be an effect of the model representation, i.e. the use of a CPM in the model volume outside the immediate vicinity of the repository. This is discussed in more detail in /Joyce et al. 2010/.

Discharge points on land-use maps

The figures in this section show discharge points for three selected release times, 2000 AD (Figure 6-15), 5000 AD (Figure 6-16) and 10,000 AD (Figure 6-17) on maps showing the land-use at each of these times. When producing land-use maps, the modeller must make additional assumptions regarding the human utilisation of the land. In this case, the maps are based on the assumption that all potentially arable land is used for agricultural purpose (Variant 2 in Chapter 5). Thus, whenever the succession of a lake to a terrestrial area results in land that can be used for agriculture, according to the criteria used in the modelling, it is assumed to be used for agricultural production.

Figure 6-15 shows the 2000 AD discharge points, without dividing them into travel time classes, on the 2000 AD land-use map. As noted above, most discharge points are in the sea or very close to the shoreline. However, some discharge points are located in Lake Bolundsfjärden and the wetland surrounding the lake.

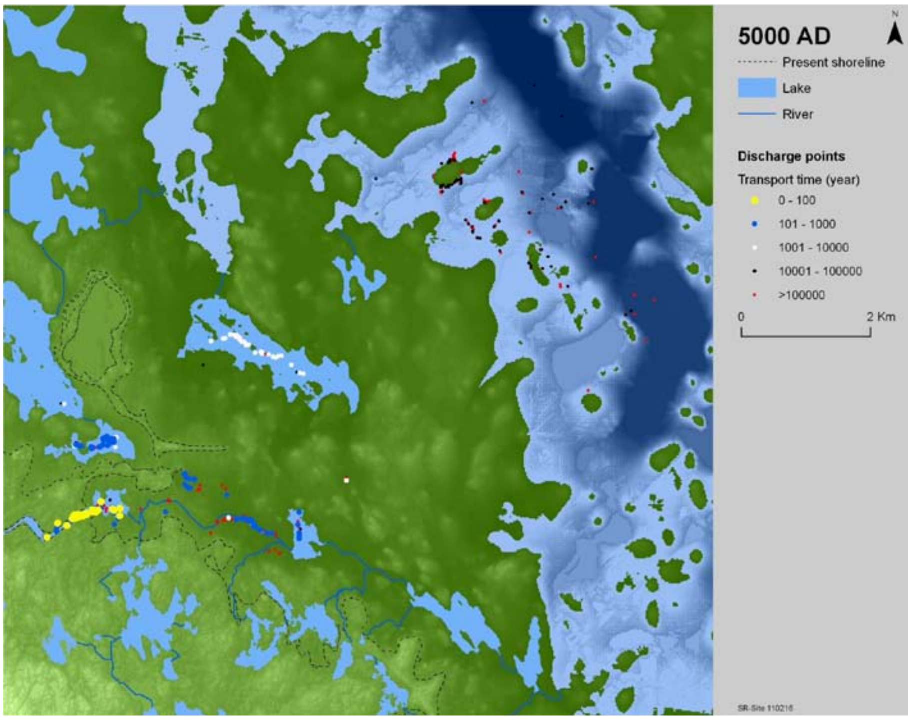


Figure 6-14. Discharge points coloured according to calculated advective travel times for the 5000 AD release displayed on a map showing the 5000 AD topography and bathymetry. The topography is indicated by different green shades and the sea bathymetry by blue shades; darker shades correspond to lower elevations. Note that infilling of lakes is not considered; the largest extent of each lake is shown.

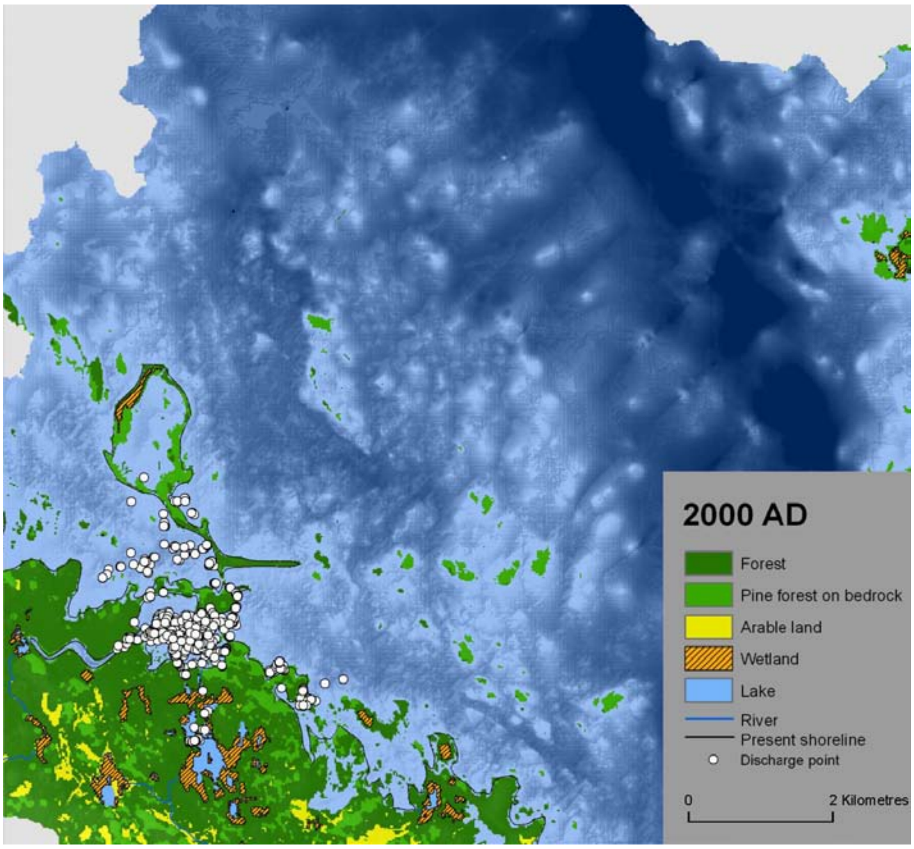


***Figure 6-15.** Discharge points for the 2000 AD release on a map showing land-use at 2000 AD; the land-use map is produced assuming that all potentially arable land is used for agriculture. Processes leading to infilling of lakes are taken into account.*

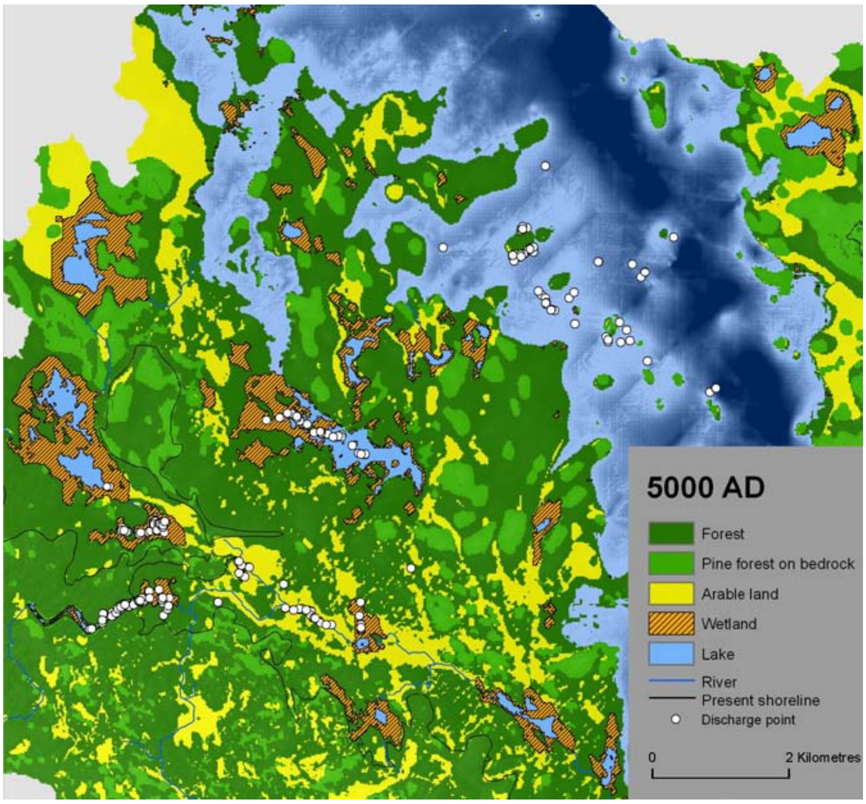


Figure 6-16. *Discharge points for the 5000 AD release on a map showing land-use at 5000 AD; the land-use map is produced assuming that all potentially arable land is used for agriculture. Processes leading to infilling of lakes are taken into account.*

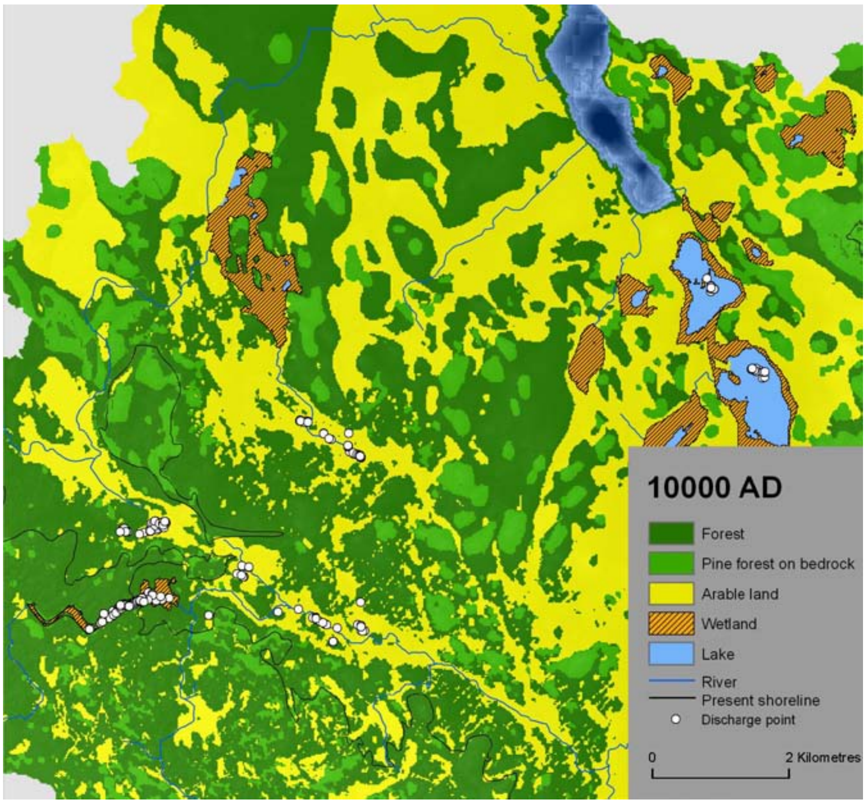


Figure 6-17. *Discharge points for the 10,000 AD release on a map showing land-use at 10,000 AD; the land-use map is produced assuming that all potentially arable land is used for agriculture. Processes leading to infilling of lakes are taken into account.*

Due to the shoreline displacement and the ongoing succession of lakes to wetlands and then – under certain conditions – to arable land, the 5000 AD land-use map contains new land areas with wetlands and arable land. Figure 6-16 shows that the 5000 AD discharge points to large extent are found on arable land or in areas consisting of lakes surrounded by wetlands. Many discharge points are still found in the intake canal to the nuclear power plant and the former bay outside it (south-western part of the area), which is a wetland on this map. Lake Bolundsfjärden has developed to arable land, but contains no discharge points at 5000 AD.

The pattern of the 10,000 AD discharge points on the 10,000 AD map in Figure 6-17 is not very different from that in Figure 6-16. The main differences are related to the continued shoreline displacement, with new land areas and lakes forming in the north-east, and succession creating more arable land. Thus, some discharge locations that were found in lakes or wetlands in Figure 6-16 are on arable land in Figure 6-17. This means that the main impression is that the discharge locations are relatively stable, whereas the nature of the areas where discharge takes place changes. It also appears that the clustering of the discharge points is stable, which means that there are still clusters of points in the former lake-wetland areas even though they have developed into arable land.

Sensitivity studies

Since the discharge points calculated with the hydrogeological models constitute the basis for the identification of biosphere objects, and thereby for the whole landscape model, it is important to assess the uncertainties associated with these models and the calculated locations. Sensitivity studies of different parameters and features of the hydrological models are reported in /Joyce et al. 2010/. Discharge points were not produced for all cases and variants considered, but the results can be used to assess the following aspects of the modelling.

- The effects of model scale are studied by comparing results from site-scale and repository-scale models.
- The effects of stochastically modelled spatial variability are assessed by comparing results from different realisations.
- The effects of model representation are assessed using results from sensitivity cases focusing on the spatial variability in the CPM part of the model volume.

The results and their implications for uncertainties in discharge points are discussed in Section 6.5. /Joyce et al. 2010/ also present other supporting analyses such as simulations investigating effects of dispersion along flow paths.

6.2.3 Evidence of deep groundwater discharge

The identification of the biosphere objects is based on modelled discharge points. It is therefore of some interest to investigate other types of evidence of discharge of deep groundwater in areas that coincide with, or are similar to, areas identified as biosphere objects. This section provides a brief summary of the data and modelling results obtained within the hydro(geo)logical and hydro(geo)chemical site descriptive modelling (see /Lindborg 2008, Johansson 2008, Tröjbom et al. 2007/ for details).

As described in Section 6.1.2, the highly transmissive shallow bedrock acts as a drain for water coming from above as well as from below. The available hydrogeological site data indicate that flow systems involving the bedrock do not have discharge areas on land in the northern part of the candidate area, including the target area, and hence discharge into the sea. Although the possibility of deep groundwater discharge within the target area cannot be ruled out based on this information, it means that it is unlikely that evidence of discharge of groundwater from the planned repository volume could be found within the present land area.

This, together with the fact that most of the areas considered in the landscape model are presently covered by the sea (Chapter 7), implies that the issue of deep groundwater discharge can be studied in a more general sense only, i.e. whether such discharge occurs in “typical objects” similar to those considered in the landscape model. Outside the tectonic lens and the target area, for example at drill site 4 (Figure 6-2) and in the area around Lake Eckarfjärden, measured data show that the groundwater levels in the bedrock may be well above the groundwater levels in the regolith in nearby low-lying areas, implying that flow systems involving the bedrock may have local discharge areas /Johansson 2008/.

In the case of Lake Gällsboträsket, which is also outside the target area, there are also indications that ongoing deep discharge from the Eckarfjärden deformation zone adds deep signatures to the discharging surface water. Similar deep signatures are also measured in one soil tube located in the vicinity of this lake, whereas groundwater samples from the till layer below the lake mainly correspond to relict marine signatures. Furthermore, a chloride balance calculation reported in /Johansson 2008/ indicated that there may be an additional source of chloride, i.e. upward flow of deep saline groundwater, in the Gällsboträsket area.

In shallow groundwater in the regolith below the lakes, more or less stagnant conditions have preserved relict marine signatures even at relatively shallow depths /Tröjbom et al. 2007/. These signatures, which are generally found in the groundwater of the bedrock down to several hundred metres depth, reflect a trapped relict marine groundwater that may have entered the deposits from below when the area was covered by the Baltic Sea, according to the conceptual model. The possible presence of deep saline influences (shield brine) at these locations is difficult to explain without a vertical discharge gradient at some time during the palaeohydrological history, especially as there are no hydrological indications of any deep discharge at the present date /Follin et al. 2008/.

6.3 Near-surface flow paths and solute spreading

This section summarises the MIKE SHE transport modelling performed in support of the biosphere assessment, and presents example results of particular relevance for the understanding of near-surface transport conditions in typical discharge areas in Forsmark. A detailed description of this modelling is provided in /Bosson et al. 2010/. As explained in Section 4.3 of the present report, flow and transport modelling with MIKE SHE of present and future conditions at Forsmark has been performed using two model scales, referred to as regional and local models (see Figure 4-21). The regional modelling is discussed in Section 4.3, whereas the present section is focused on the modelling of solute transport in the local models.

Two local domains were considered in the modelling, model A and model B (Figure 4-21). The transport analyses included particle tracking, in which flow paths are traced by imaginary particles that follow the flowing groundwater, and advection-dispersion simulations, in which a solute is transported both by the modelled groundwater flow field and by dispersion, which essentially is a lumped representation of small-scale velocity variations and diffusion. No processes other than advection and dispersion are taken into account in the present MIKE SHE modelling. However, reactive-transport simulations combining advection-dispersion with retention processes have been performed and are discussed below in Section 6.4.

The solute transport simulations have been performed using different types and locations of sources. In particular, the focus is here on simulations where the particle starting positions and the sources in the advection-dispersion models have been placed at c. –40 m along flow paths obtained from the ConnectFlow bedrock hydrogeology modelling (Section 6.2). This means that the emphasis here is on the transport in the uppermost part of the rock and the regolith. Other source configurations are also considered in the modelling, i.e. continuous and instantaneous injections distributed over the whole model area. The results of these simulations are given in /Bosson et al. 2010/, where also a set of sensitivity studies (e.g. relating to dispersion and plant uptake) are reported.

All local model calculations described below are based on the modelled 10,000 AD shoreline position and distribution of Quaternary deposits. This means that processes leading to terrestrialisation of present and future lakes are taken into account. At 10,000 AD all lakes within the local model areas are terrestrialised and the surface water system consists of a stream network only. Thus, the lake contours shown in the figures below indicate the sizes of the lakes when they are formed (their maximum sizes), and not the lake boundaries at the modelled time.

6.3.1 Particle tracking results from local model A

This section describes particle tracking results from local model A only. In the simulation with a particle release at –40 m along the ConnectFlow paths, a total number of 3,152 particles were introduced. After 1,000 years, 80% of the particles had left the model, and hence 20% were still in the model domain. Among the particles that had left, 41% went to the stream network and 59% to the unsaturated zone or to overland water (which cannot be separated in the model results). No particles left the model through the vertical (side) boundaries.

Figure 6-18 illustrates the discharge points in the particle-tracking simulation and the starting positions given by flow paths calculated with the ConnectFlow model; the red dots are discharge points and the green ones are starting positions at –40 m. Contours of terrestrialised lakes (cf. above) and surface streams are also shown. The figure illustrates that most particles are transported more or less vertically upwards to the surface, and that the discharge points are concentrated to the streams and along former shorelines of the terrestrialised lakes.

Figure 6-19 compares discharge points calculated with the MIKE SHE and ConnectFlow models. Since the starting positions of the particles in the MIKE SHE simulation were given by the ConnectFlow particle positions at –40 m, the particle positions are the same at this level. For the particles going to surface streams, the differences between the results from the two models are very small. However, some differences can be observed in the lake areas. The particles leaving the MIKE SHE model tend to be more concentrated along the shorelines of the terrestrialised lakes, whereas the particles from the ConnectFlow model appear in the central parts of the lakes.

This indicates that the boundaries between the lake areas and their surroundings have some relevance for groundwater discharge even when the lakes have been terrestrialised. Figures 6-20 and 6-21 illustrate the discharge point comparison in more detail. Figure 6-20 shows a more detailed view of the lake in the northern part of local model A. ConnectFlow particles appear in the central part of the lake, whereas the MIKE SHE particles appear close to the former shoreline and in connection to the stream going through the infilled lake.

Figure 6-21 provides a more detailed view of the lake in the eastern part of the model area. A similar pattern is seen also here, with the particles from the ConnectFlow model being more concentrated to the lake centre and those from MIKE SHE somewhat closer to the former shoreline. However, the most striking observation is the overall agreement between the two sets of model results. The

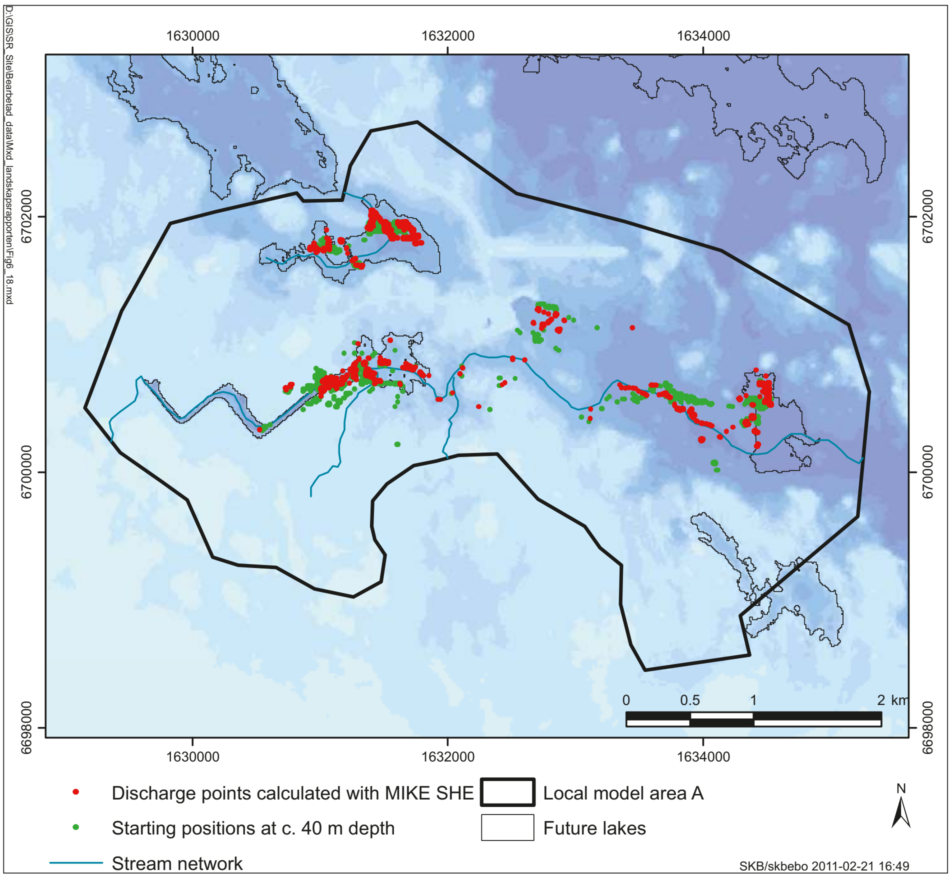


Figure 6-18. Discharge points calculated with MIKE SHE local model A (red dots) and particle starting positions at approximately –40 m (green dots).

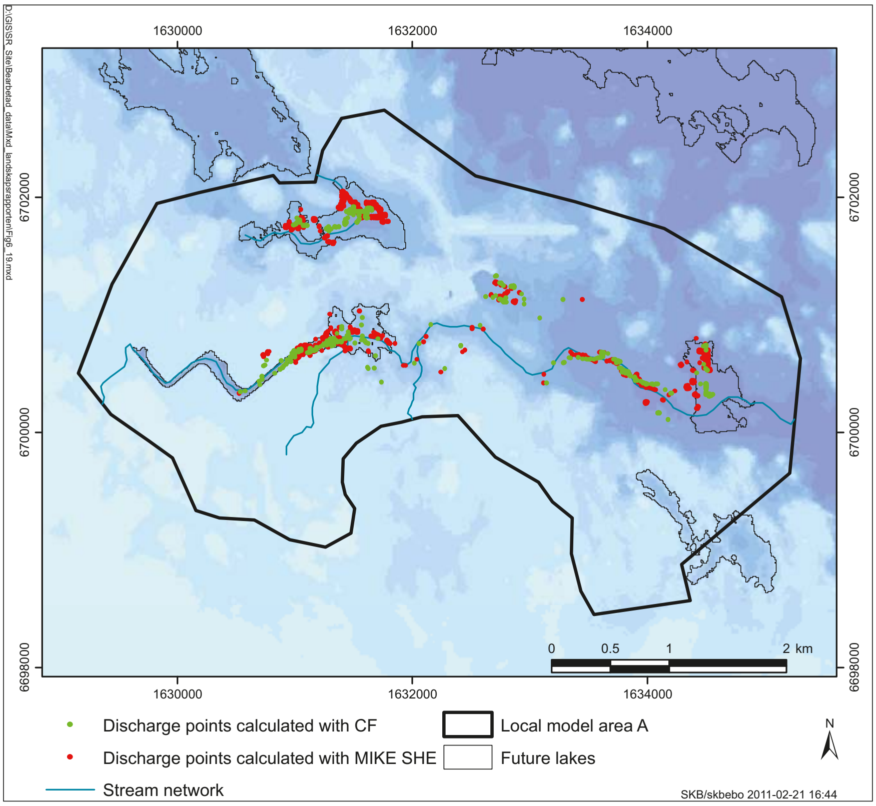


Figure 6-19. *Comparison of discharge points in local model A, calculated with MIKE SHE (red dots) and ConnectFlow (CF, green dots).*

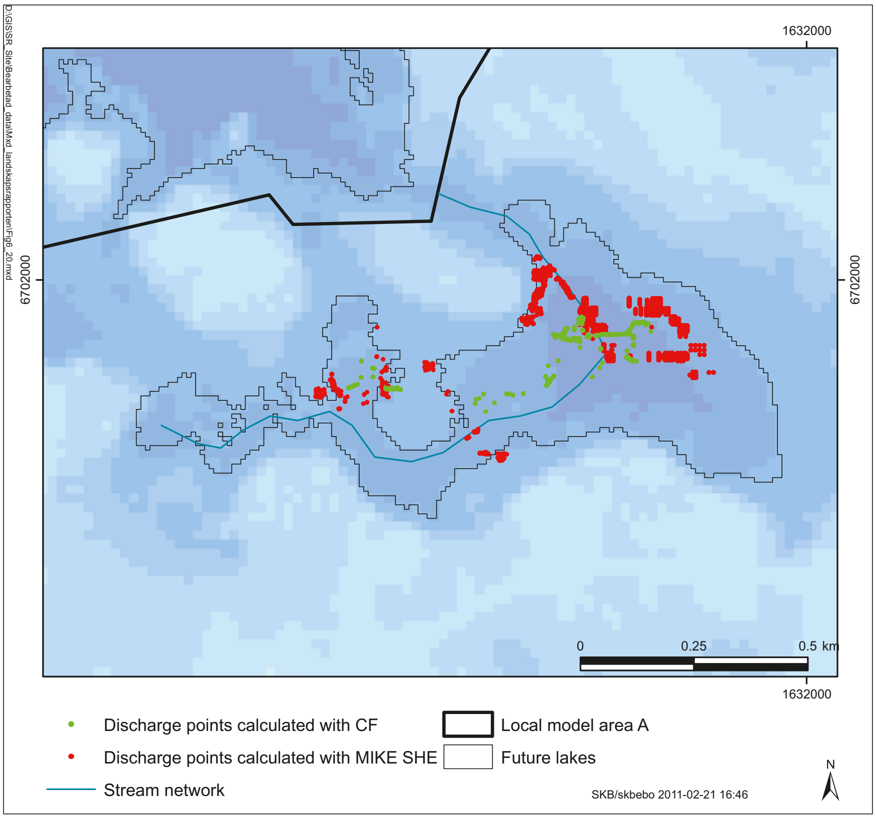


Figure 6-20. *Comparison of discharge points appearing in terrestrialised lake area, calculated with MIKE SHE (red dots) and ConnectFlow (CF, green dots).*

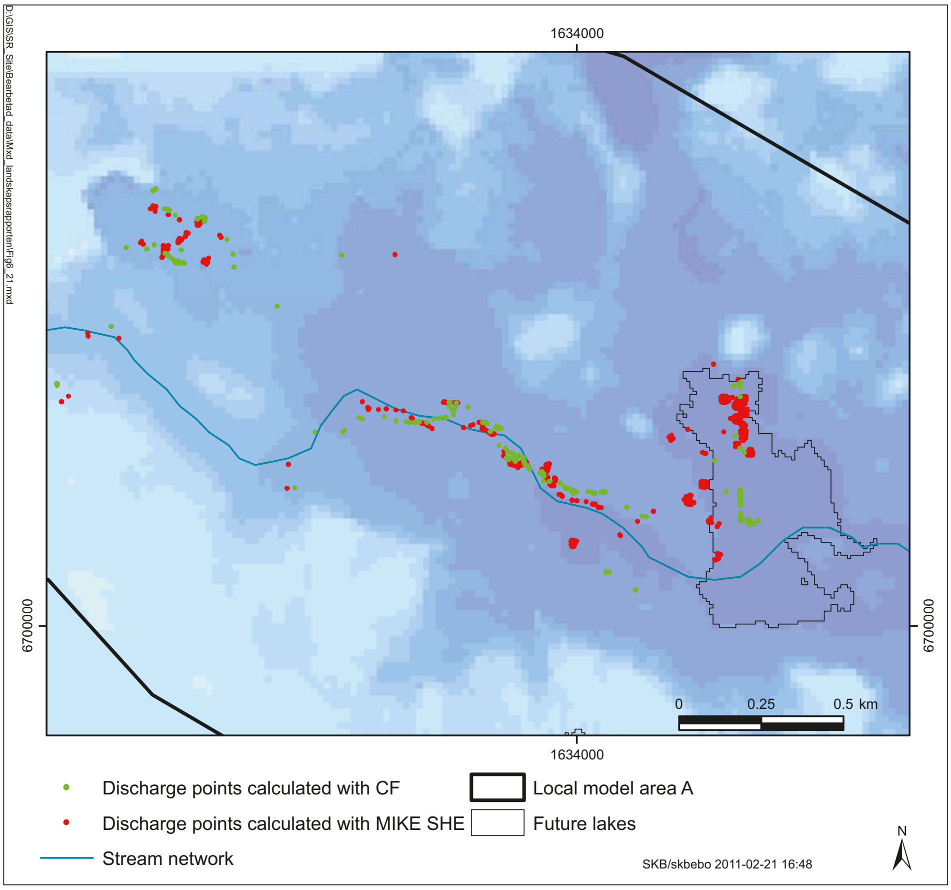


Figure 6-21. *Comparison of discharge point locations in terrestrialised lakes and along a stream, calculated with MIKE SHE (red dots) and ConnectFlow (CF, green dots).*

discharge points are very similar, especially along the stream but also in other parts of the model area. This implies that the more detailed representation of the hydrological processes in the near-surface region provided by MIKE SHE does not lead to significant changes in discharge locations.

As described above, 20% of the particles introduced in the particle-tracking simulation remained in the model volume at the end of the 1,000-year simulation. In order to investigate whether the particle recovery was sensitive to the length of the simulation period, a long-term simulation covering a period of 6,000 years was performed (results not reported in /Bosson et al. 2010/). In this simulation, more detailed reporting of particle end locations and travel times and travel distances was also made.

The results of the long-term simulation showed that 98% of the injected particles reached the regolith during the longer simulation period. However, about 16% of all particles were left in the regolith at the end of the simulation. Thus, the overall recovery of particles increased only marginally (from 80% to 82%) when the simulation was extended from 1,000 to 6,000 years.

One explanation for the relatively large fraction of particles left in the model could be that the flow fields in the two models are not identical (due to differences in discretisation, for instance), such that particles are started in areas from which transport towards the surface is slower in MIKE SHE (or perhaps not directed towards the surface at all). However, the fact that most of the particles left in the model have reached the regolith shows that also other factors contribute. In particular, the results indicate that the particles are transferred from the rock to low-velocity/low-permeability parts of the regolith and remain in the layer where they first enter the regolith.

6.3.2 Advective-dispersive modelling of solute spreading

Sources along all ConnectFlow paths from the repository

This section describes some of the results from an advection-dispersion simulation with local model A, where continuous and constant sources were placed at the same locations along ConnectFlow flow paths as the particles discussed in the preceding section. Thus, the starting positions are the same, whereas the transport processes (dispersion is added) and source type are different (continuous injection at a concentration of 1 g/m^3). Another difference between the particle tracking and advection-dispersion calculations is that particles are removed from the model when they leave the saturated (groundwater) zone, whereas advective-dispersive transport can continue in the unsaturated and overland water parts of the model.

Figure 6-22 shows concentration surface plots for different calculation layers in the advection-dispersion simulation with the shoreline and QD distribution for 10,000 AD. Layer L1 is the uppermost calculation layer, i.e. a QD-layer, and layer L4 is the uppermost bedrock layer. Layer L7 is located at c. –20 m, whereas layer L10 at c. –40 m is the layer in which most of the sources are applied. Layer L14 is located at –85 m to –65 m and layer 17 at between –145 m and –125 m.

The figure illustrates that the solute is mainly transported vertically towards the surface. The solute reaches the surface along surface water streams and in lake areas. Figure 6-22 also shows that in parts of the model domain the solute is transported downwards. Although not fully compatible (cf. above), the advection-dispersion results appear largely similar to the particle-tracking results in the preceding section (Figure 6-19). However, it is seen that the advection-dispersion simulations result in additional areas with solute in the uppermost layer. One reason for this is that solutes are traced further from the saturated zone in the advection-dispersion model. A detailed discussion of the comparison between the two models is provided in /Bosson et al. 2010/.

Results are also shown in two profiles illustrating the differences in transport conditions in different parts of the area. The profile in Figure 6-23 is taken within the target area, just north of the intake canal from south to north (in the left red-coloured area in the L14 panel in Figure 6-22). Figure 6-24 shows a profile taken from west to east in the eastern-most terrestrialised lake within the model area; hence, it illustrates the transport conditions in a future lake area.

Figure 6-23 shows results from the profile from within the target area. After 1 year the solute has started spreading downwards, but a small portion of the solute is also moving horizontally in a layer situated at c. 45 m.b.s.l. After 10 years of simulation, the solute plume has spread further downwards and also horizontally along two distinct layers, at c. –55 m and c. –90 m. After 25 years the solute is mainly moving towards the north along the layer situated at –90 m and this is seen also after 50 years and 100 years of simulation. These results clearly illustrate the effects of the horizontal fractures/sheet joints mentioned in Section 6.1.2.

Figure 6-24 shows the transport pattern below the terrestrialised lake in the eastern part of the model area. Note that only a few source locations from the ConnectFlow model are found in the area. The figure indicates that the solute is mainly transported vertically upwards to the surface and then starts spreading horizontally in the top layers. As the simulation proceeds, the solute that spreads horizontally starts to infiltrate and migrate downwards. However, part of the injected solute mass is transported horizontally just below the source. This plume travels towards east and is moving horizontally only, at least during the 100-year simulation period.

Single source locations along paths from selected deposition holes

In the preceding sections, solute transport has been described based on simultaneous solute injections at all source locations given by the flow paths in the ConnectFlow model that fell within the considered model area. However, this is not a realistic transport scenario in the safety assessment context, where focus is on transport from single canisters. Furthermore, modelling results from simulations with many sources could be somewhat difficult to interpret. For clarity and for better agreement with more realistic transport scenarios, a set of simulations with one source in each simulation was performed. Also in these simulations, the sources were located along flow paths calculated with the ConnectFlow model.

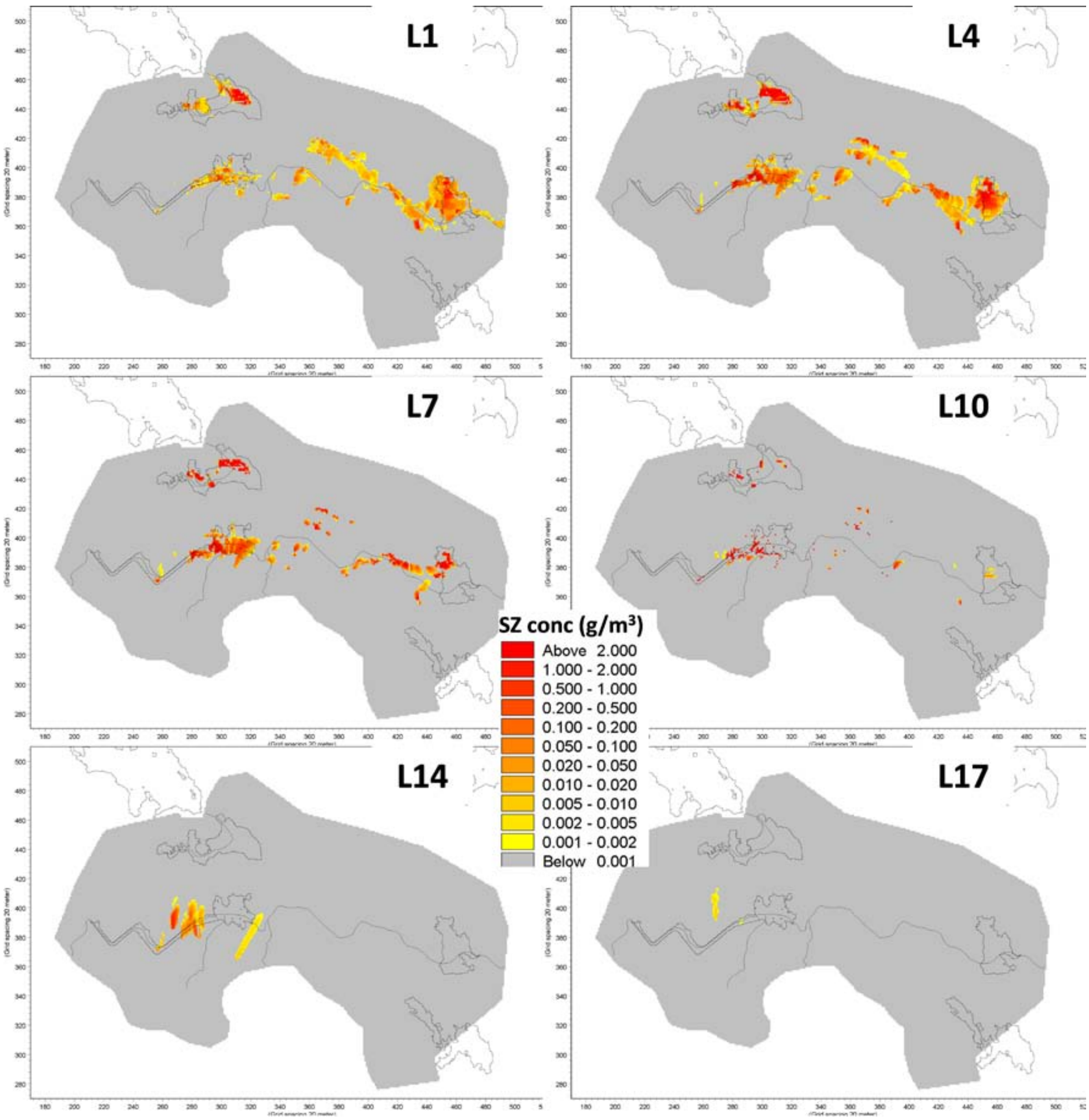


Figure 6-22. *Surface plots of calculated concentrations in different layers (see text) of local model A; all plots show results after 100 years of simulation.*

Based on the calculated discharge points presented in /Joyce et al. 2010/, ten canister positions in the repository with relatively high groundwater flow rates in the deposition holes and relatively short travel times to the ground surface were selected. Of the ten sources considered, seven were located in local model area A and three in model area B. The flow paths from the ten canisters are a subset of the flow paths discussed above. Using the ConnectFlow particle tracking simulations of flow paths from the repository, the positions at –40 m along the flow paths associated with the ten selected deposition holes were identified and then used as source locations in transport modelling with MIKE SHE.

Separate transport simulations were made for each of the ten source locations using the advection-dispersion module in MIKE SHE. The purpose of these simulations was to study near-surface solute transport associated with canister positions and flow paths of particular interest for the safety assessment (i.e. those characterised by large flow rates and short travel times). In the grid cell corresponding to each source location, a continuous and constant concentration source of 1 g/m^3 was set in MIKE SHE. However, since the groundwater flow velocity varies in the model area, the solute mass produced by the sources may differ substantially. Therefore, the results from different sources are not directly comparable and should mainly be taken as an indication of transport directions and patterns in different parts of the area.

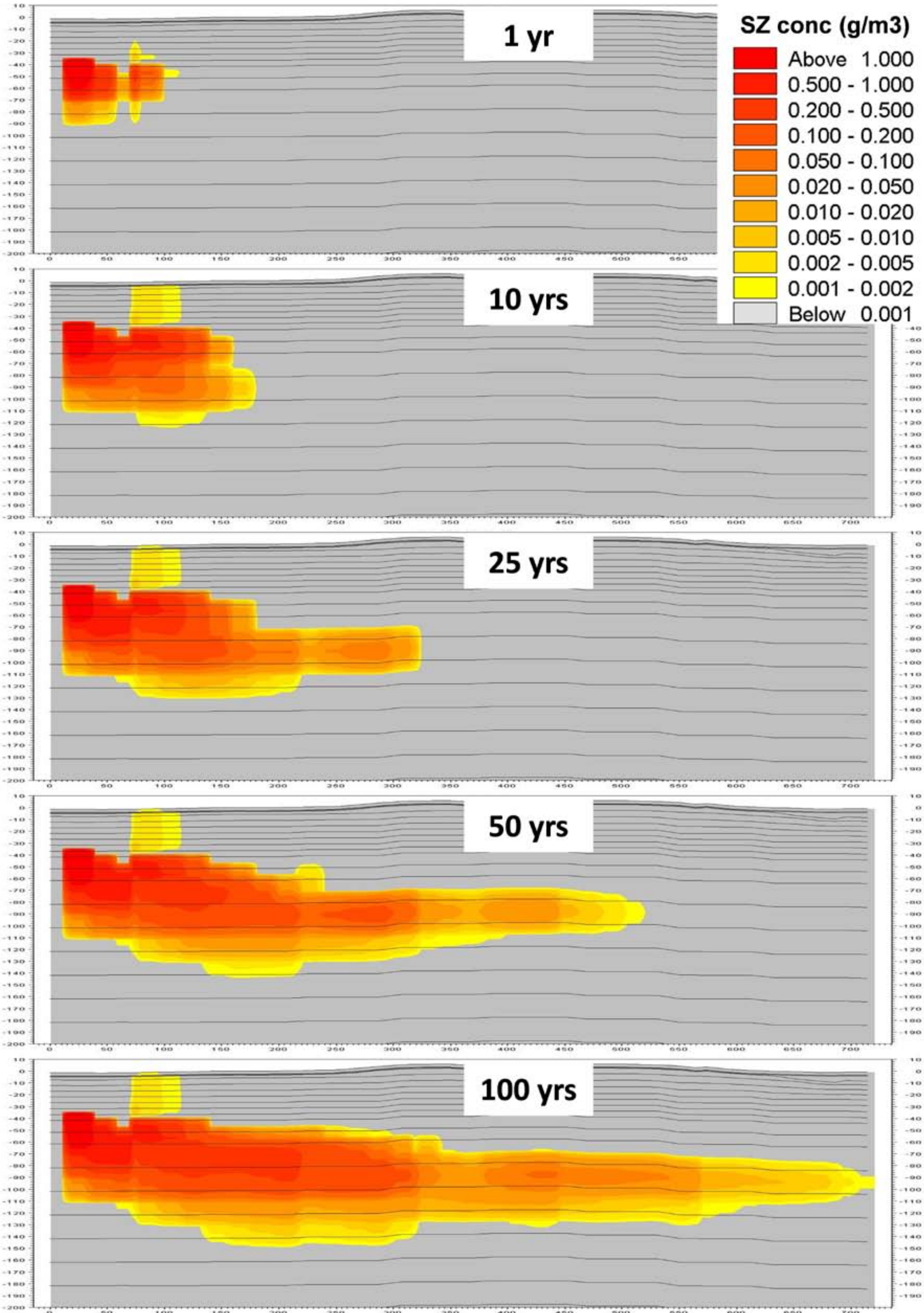


Figure 6-23. *Concentrations along a south-to-north profile within the target area after 1, 10, 25, 50 and 100 years of simulation; vertical scale in metres above sea level.*

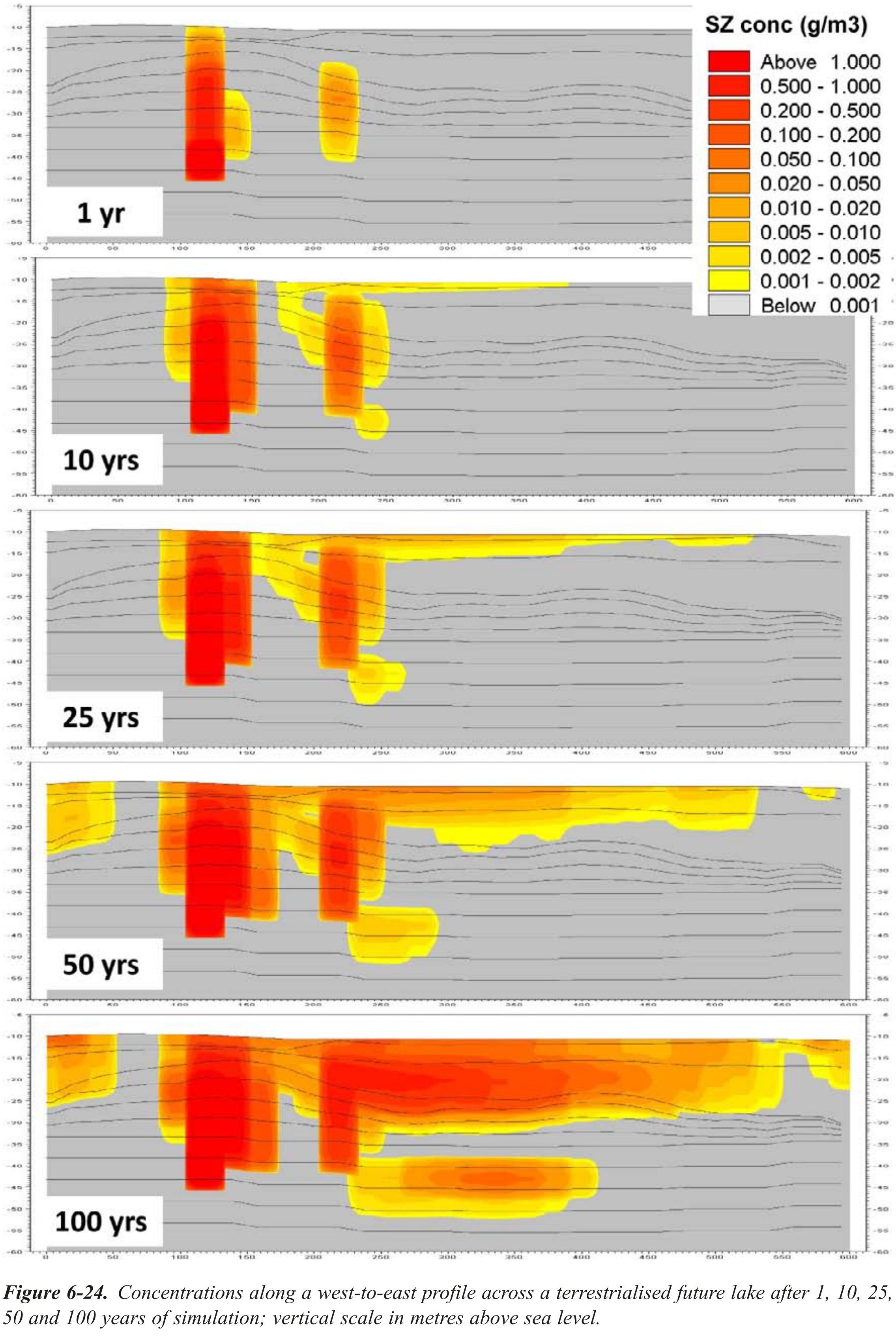


Figure 6-24. Concentrations along a west-to-east profile across a terrestrialised future lake after 1, 10, 25, 50 and 100 years of simulation; vertical scale in metres above sea level.

As the simulations involving transport in several MIKE SHE components are very time-consuming, it was not possible to run the simulations for more than approximately 65 years. For some of the sources, this period was too short for the solute to reach the ground surface or other model boundaries. In some of the simulations, the solute storage in the saturated zone reached steady state, which means that the input from the source was equal to the output to the unsaturated zone, overland water and streams, whereas for other sources conditions were far from steady state at the end of the simulation. The simulations are based on the 10,000 AD shoreline and Quaternary deposits. As explained above, all lakes have been terrestrialised at that time, and the lake contours shown on the maps mark the maximum extents of the lakes.

Figure 6-25 shows a surface plot of calculated concentrations for a source within the terrestrialised lake in the northern part of model area A (see e.g. Figure 6-18). The upper figure shows the location of the source at –40 m and the lower figure shows the extent of the saturated zone concentration plume in the uppermost calculation layer (i.e. in the uppermost QD-layer). The strength of the source is 1 g/m^3 but the concentration in the surface layer is very low except directly above the solute source. In Figure 6-25, all concentrations higher than 10^{-14} g/m^3 are illustrated; the scale is logarithmic. The solute is mainly transported directly to the stream (indicated by the line going through the lake area). However, part of the solute mass is spread horizontally over a larger area.

Figure 6-26 shows the concentration along a profile in the lake area; the concentration scale is the same as in Figure 6-25, where also the location of the profile is illustrated. The concentrations along the profile are illustrated at 1, 10 and 65 years of simulation time. The figures show that the solute is mainly transported vertically upwards to the surface and when it has reached the surface it starts spreading in the horizontal direction in the top layer. From the part of the top layer to which solute first migrates, the solute spreads both horizontally and vertically.

The large concentration interval considered above, i.e. from a lowest displayed concentration of 10^{-14} g/m^3 to the source concentration 1 g/m^3, is useful to indicate transport directions, but exaggerates the area that realistically can be considered affected by transport from the source substantially. For example, Figure 6-25 indicates that the area where solute is present is on the order of 200 m by 500 m (the source has a size of 20 m by 20 m); note that the length scale in the figure is expressed in number of grid cells and that multiplication by 20 (the grid cell size) is needed to obtain distances in metres.

To investigate the sensitivity to the selected minimum concentration and perhaps obtain more relevant quantifications of contaminated areas, a smaller concentration interval with the lowest value at 10^{-5} g/m^3 was investigated. Figure 6-27 shows the resulting solute distributions in the uppermost bedrock layer (bottom) and the uppermost regolith layer (top). Thus, the lower figure shows the size of the area where solute is transferred from rock to regolith, whereas the upper figure shows the resulting solute distribution in the surface layer.

It is seen in Figure 6-27 that the solute occupies an area of about 50 m by 200 m in the surface layer and a slightly smaller area in the upper bedrock layer. Thus the horizontal size of the plume does not increase much when the solute is transported in the Quaternary deposits. The contaminated area is much smaller than that displayed in Figure 6-25, but still much larger than the source size. However, the comparison between the results in Figures 6-25 and 6-27 shows that the definition of the contaminated area (i.e. the concentration interval) could be important when discussing the size of the contaminated area.

Another example of transport from a source located below one of the terrestrialised lakes is shown in Figure 6-28 (concentration distribution in the surface layer) and Figure 6-29 (concentration profile). In this case, the transport simulation concerns local model B and the large lake that forms there (see Figure 4-21) and then is terrestrialised before the time considered in the present modelling (10,000 AD). Furthermore, flow paths from two of the selected deposition holes went through the same cell at –40 m. One source with a total strength of 2 g/m^3 was therefore placed in that cell.

Figure 6-28 shows the surface plot for transport from this source. The red square in the upper figure shows the location of the source at –40 m. The lower figure shows the saturated zone concentration in the uppermost calculation layer after 65 years of simulation. The spreading of the solute appears to be limited to the area close to the surface streams. The reason is that the source is located directly under the surface stream flowing through the terrestrialised lake area. Solute has spread to an area of about 100 m by 300 m in the surface layer when using the 10^{-14} g/m^3 concentration limit.

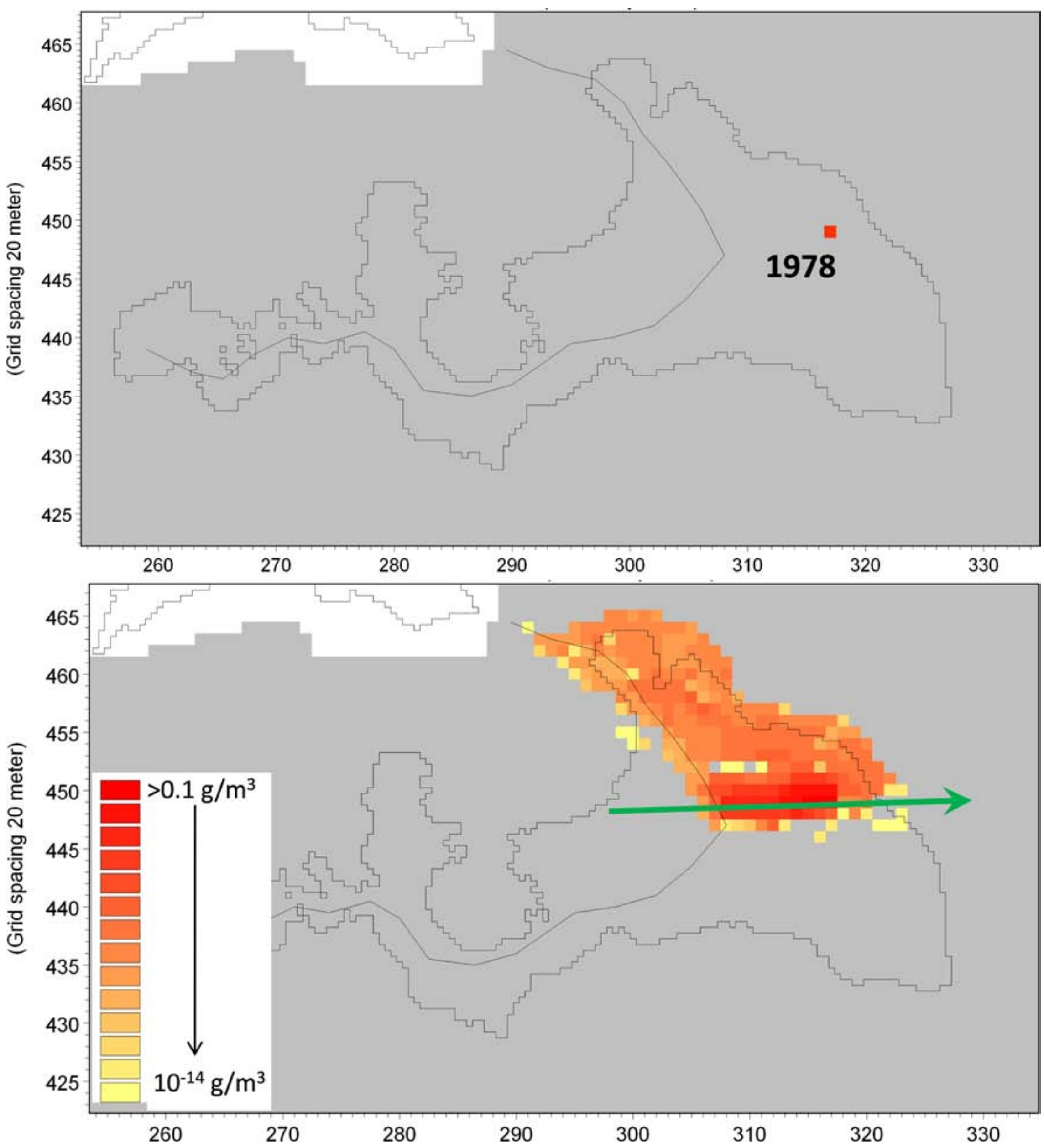


Figure 6-25. Surface plots of a terrestrialised lake in the northern part of local model A. The upper figure shows the location of the source at –40 m (and the corresponding canister number), and the lower figure the solute plume in the uppermost layer after 65 years. The green arrow indicates the location and direction of the profile in Figure 6-26. Note that the spatial scales are in number of grid cells, and should be multiplied by 20 for conversion to metres.

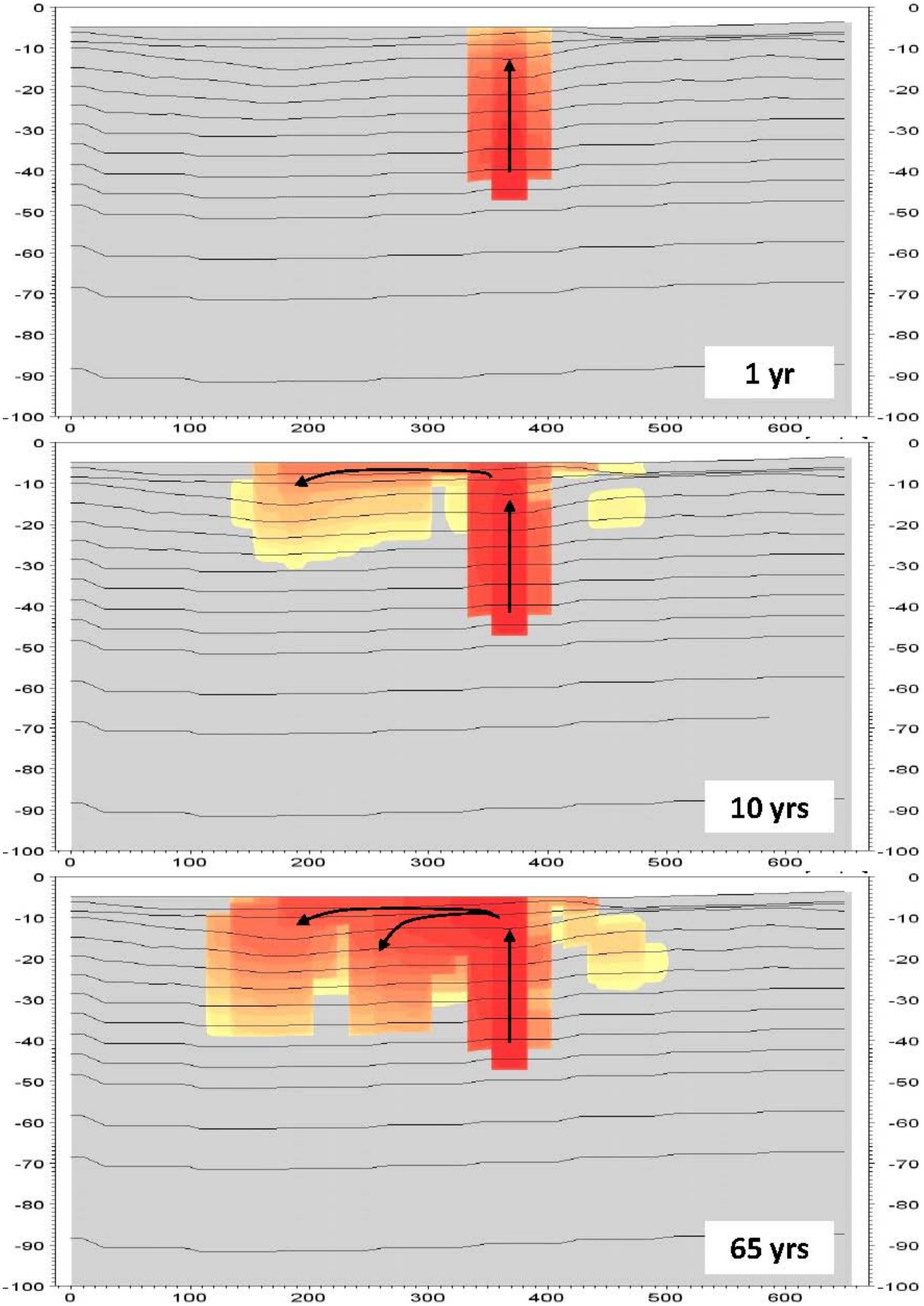


Figure 6-26. *Concentrations along profile indicated in Figure 6-25, results after 1, 10 and 65 years of simulation. Note the different scales on the axes; both are in metres, the vertical scale in metres relative to the sea level.*

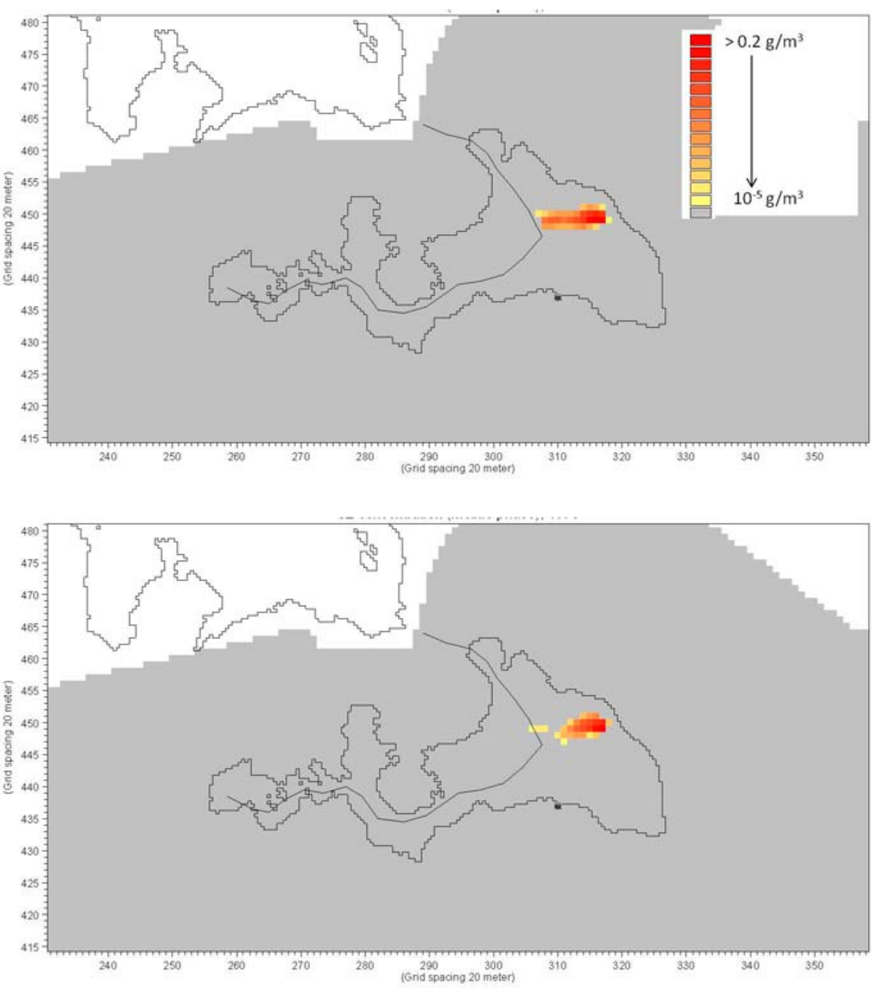


Figure 6-27. *Concentration distributions after 65 years, with 10^{-5} g/m³ as lowest displayed concentration, in the upper regolith layer (top) and the upper bedrock layer (bottom). The location of the source at –40 m is shown in Figure 6-25. Spatial scales are in number of grid cells; multiply by 20 for conversion to metres.*

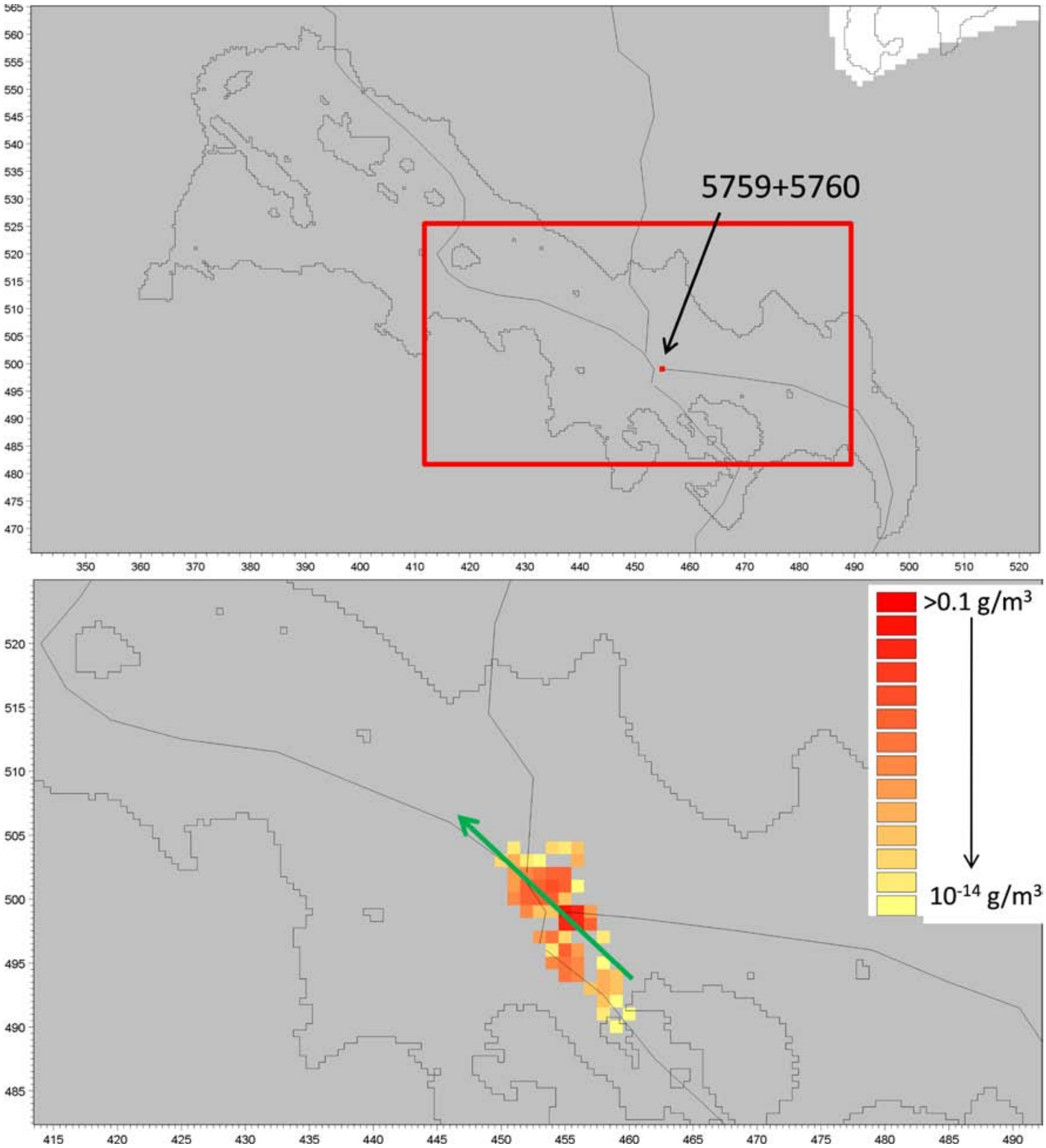


__Figure 6-28.__ Surface plots of a large terrestrialised lake in local model B. The upper figure shows the location of the source at –40 m (and the corresponding canister numbers – flow paths from two canisters go through the same cell), and the lower figure the solute plume in the uppermost layer after 65 years. The green arrow indicates the location and direction of the profile in Figure 6-29. Note that the spatial scales are in number of grid cells, and should be multiplied by 20 for conversion to metres.

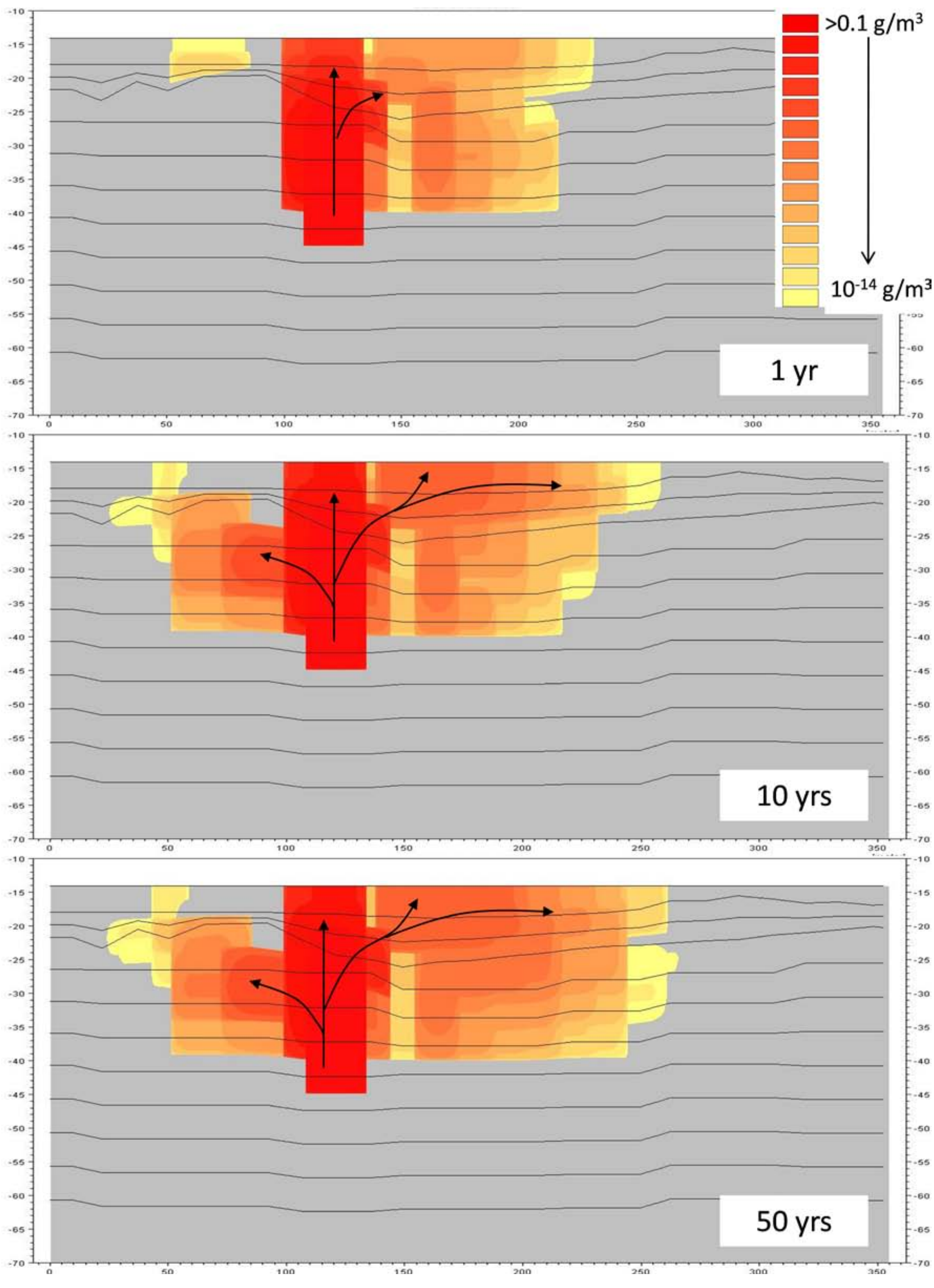


Figure 6-29. *Concentrations along the profile indicated in Figure 6-28, results after 1, 10, and 50 years of simulation. Note the different scales on the axes; both are in metres, the vertical scale in metres relative to the sea level.*

Results for the profile indicated in Figure 6-28 are shown in Figure 6-29; concentration profiles after 1, 10, and 50 years of simulation are illustrated. The solute is moving vertically up towards the streams on the surface. All three profiles are similar because the spreading is fast and does not increase significantly over time. This is also demonstrated by the fact that the mass balance of the saturated zone reaches steady state at an early stage (results not shown). Figures 6-28 and 6-29 also show that the high concentrations are found within a very small area, corresponding to just a few grid cells.

The results presented above emphasise the importance of the remaining surface water, i.e. the stream network, for near-surface transport in the areas of terrestrialised lakes. In the two examples shown, solute mass is transported vertically from the source and then further towards and along streams. In the following, additional examples from single-source simulations are shown, with the aim of illustrating the variations in spreading patterns among the relatively few simulations performed. These variations concern both the spatial distributions in general and the differences between distributions in bedrock and regolith in particular.

Figures 6-30 to 6-32 show results from three source locations within and in the vicinity of the eastern lake area in local model A (see Figures 6-18 and 6-21 for lake location). All results are plotted for the smaller of the concentration intervals used above, i.e. with a lower concentration limit of 10^{-5} g/m^3 (all sources have a constant concentration of 1 g/m^3). The presentation in the figures is similar to that in Figure 6-27, with an upper figure showing the upper regolith layer and a lower one showing the upper layer in the rock.

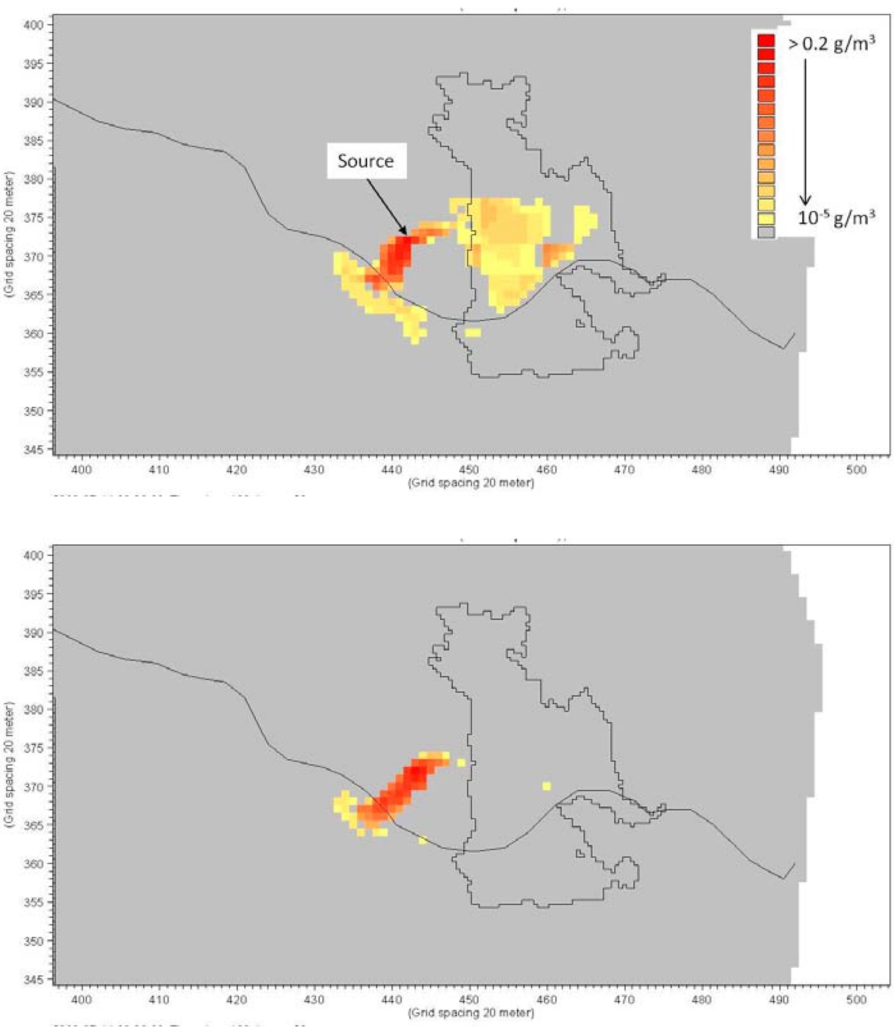


Figure 6-30. *Concentration distributions after 65 years, with 10^{-5} g/m^3 as lowest displayed concentration, in the upper regolith layer (top) and the upper bedrock layer (bottom). The location of the source at –40 m is shown on the upper map. Spatial scales are in number of grid cells; multiply by 20 for conversion to metres.*

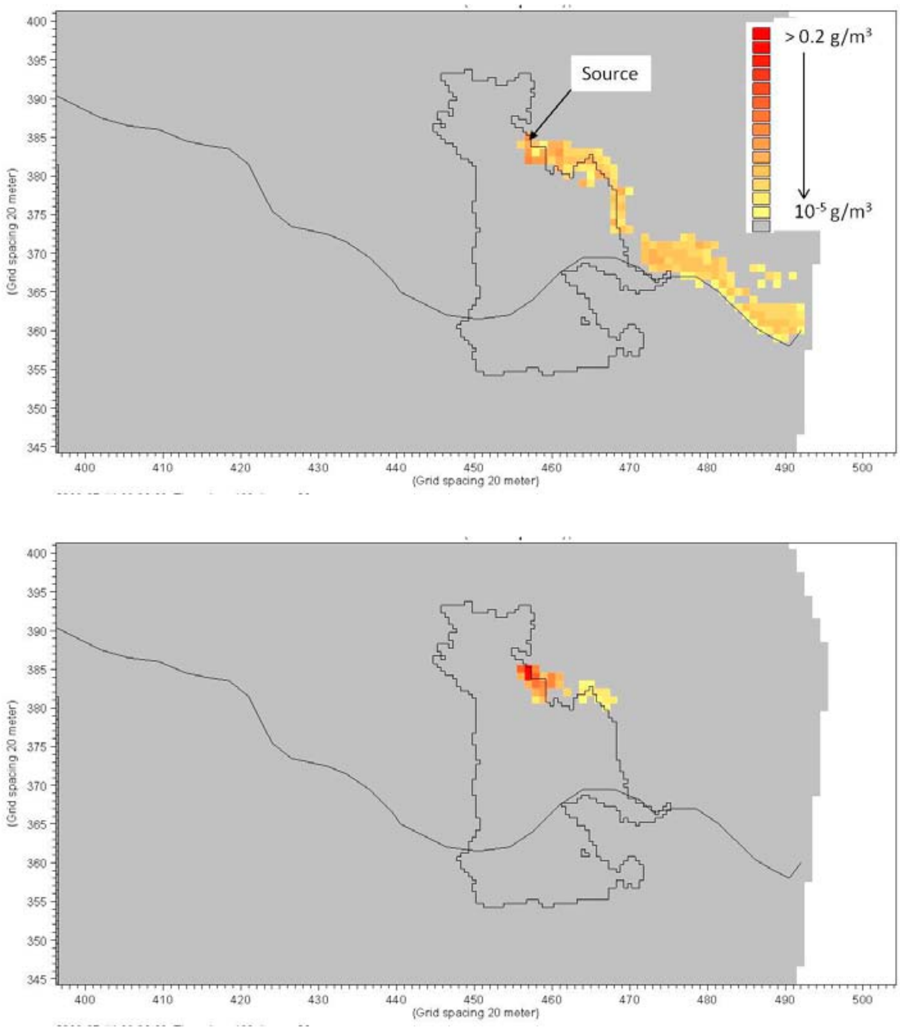


Figure 6-31. *Concentration distributions after 65 years, with 10^{-5} g/m^3 as lowest displayed concentration, in the upper regolith layer (top) and the upper bedrock layer (bottom). The location of the source at –40 m is shown on the upper map. Spatial scales are in number of grid cells; multiply by 20 for conversion to metres.*

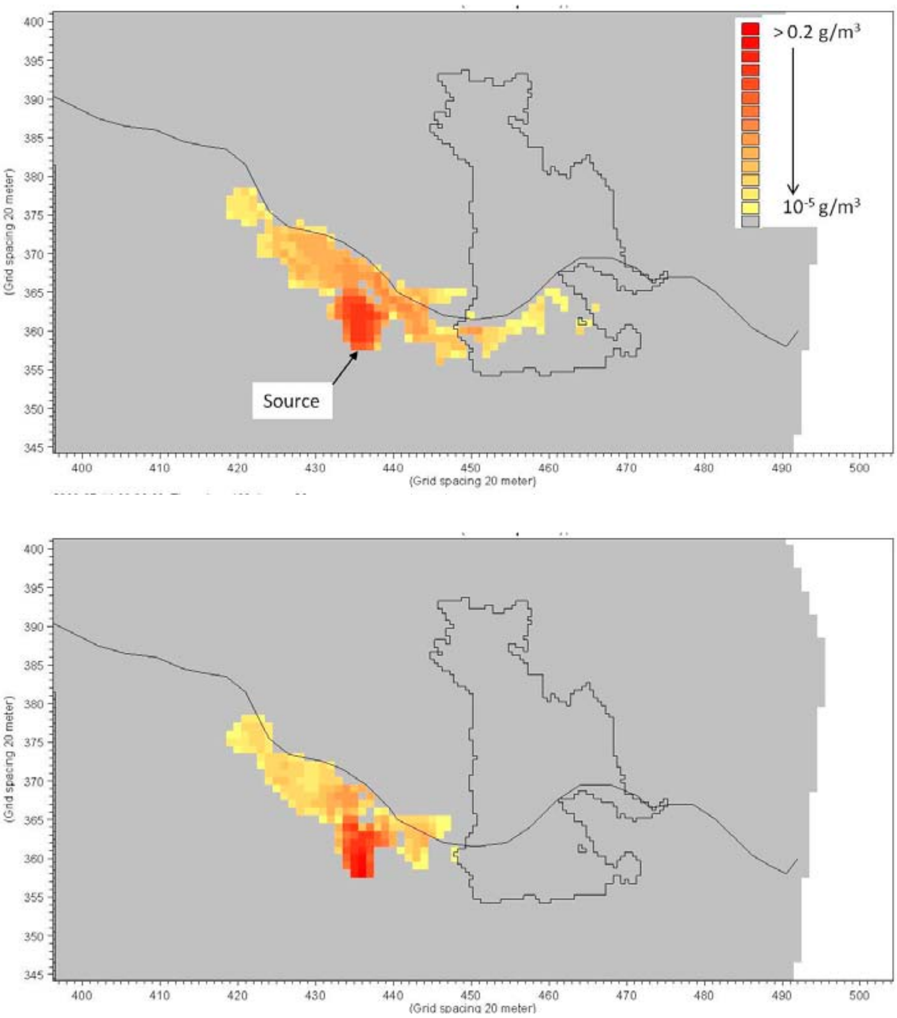


Figure 6-32. Concentration distributions after 65 years, with 10^{-5} g/m³ as lowest displayed concentration, in the upper regolith layer (top) and the upper bedrock layer (bottom). The location of the source at –40 m is shown on the upper map. Spatial scales are in number of grid cells; multiply by 20 for conversion to metres.

In Figure 6-30, results for a source west of the terrestrialised lake are shown. It is seen that the solute distribution in the upper bedrock (lower figure) forms a band (c. 70·300 m) between the source and the stream south of the source. In the uppermost layer in the regolith (upper figure) further spreading has taken place, both along the stream and to a relative large area inside the former lake boundary. However, the concentrations in these areas are in the lower range of the interval plotted.

Figure 6-31 illustrates the transport from a source along the north-eastern part of the former lake perimeter. The area of higher concentrations in the upper bedrock (lower figure) is small (c. 50·100 m), but the spreading in the upper regolith covers a much larger area; it follows the lake perimeter to the stream and then continues along the stream. All concentrations in the surface layer are low.

The results in Figure 6-32 were obtained for a source west of the lake area and south of the stream. In this case, solute appears in more or less the same areas in the upper bedrock and the upper regolith; there is some additional spreading along the stream in the surface layer, but otherwise small differences. This means that most of the horizontal spreading takes place in the rock. It is also seen that the areas with high concentrations are relatively small in both layers, on the order of 100 m by 100 m.

Thus, it can be concluded that there is some variety in the near-surface transport conditions in different parts of the model area. However, the results also show common features, such that the initial transport from the sources is mainly vertical and that high concentrations are found within relatively small areas and usually directly above the sources.

6.4 Radionuclide retention and reactive transport

This section summarises the knowledge gained during the last few years on the expected behaviour of key radionuclides in the Quaternary deposits of the near-surface system at the Forsmark site. This knowledge was generated by means of process-oriented conceptual modelling and subsequent quantitative implementation in reactive transport simulations considering different hypothetical cases of radionuclide releases from the deep repository.

The near-surface system at Forsmark consists of Quaternary deposits that would constitute the last natural barrier for the radionuclides prior to reaching the biosphere. /Grandia et al. 2007, Sena et al. 2008, Sena 2009, Piqué et al. 2010/ evaluated the behaviour of selected long-lived radioactive isotopes of Sr, Ra, U, Cs, C, I, Cl, Nb, Ni, Mo, Se, Tc and Th in Quaternary deposits, including till and lake and wetland sediments, and developed quantitative reactive-transport models of till and glacial clay deposits to assess the retention capacity of such near-surface systems.

6.4.1 Conceptual model of radionuclide behaviour in the near-surface system at Forsmark

General characteristics

The conceptual model of radionuclide behaviour in the Forsmark near-surface Quaternary deposits is presented in this section (from /Grandia et al. 2007, Sena et al. 2008, Piqué et al. 2010/). The most likely retention mechanisms were evaluated taking into account the available data from the site and from other locations in similar environments. This evaluation is done considering that the radionuclides would migrate from the deep bedrock to the surface, and that the near-surface deposits would eventually interact with groundwater carrying these radionuclides, as depicted in Figure 6-33.

The Quaternary deposits in the Forsmark area are divided into: (a) *glacial sediments*, including till, glaciofluvial deposits, clay and silt, with little (or no) organic matter (OM) and high content of $CaCO_3$ (23.4 ± 6.6% in clayey till and an average of 26% in many lakes sediments), and (b) *postglacial sediments*, with OM and re-deposited clay, sand and gravel. Peat sediments occur frequently in wetlands /Hedenström and Sohlenius 2008/. Illite is the dominant clay mineral in till, and glacial and postglacial clay sediments /Sohlenius and Rudmark 2003, Hedenström 2004/.

Forsmark waters, including surface water and shallow groundwater, have pH values mostly between 6.6 and 9.6 and high concentrations of calcium and bicarbonate. Dissolved organic matter (DOC) is present in surface water and shallow groundwater (at mean concentrations of 1.4 and 1.2 mmol/L, respectively). In spring/summer, the whole water column of lakes is under oxidising conditions; these are favourable for the formation of mineral phases able to retain radionuclides (e.g. Fe-Mn oxy-hydroxides). In winter, reducing conditions in the lakes favour the formation of iron sulphides. Shallow groundwater in the till has relatively high dissolved oxygen contents ($9 \cdot 10^{-6}$ to $3 \cdot 10^{-4}$ mmol/L), although there are too few measurements to determine definite trends in this case.

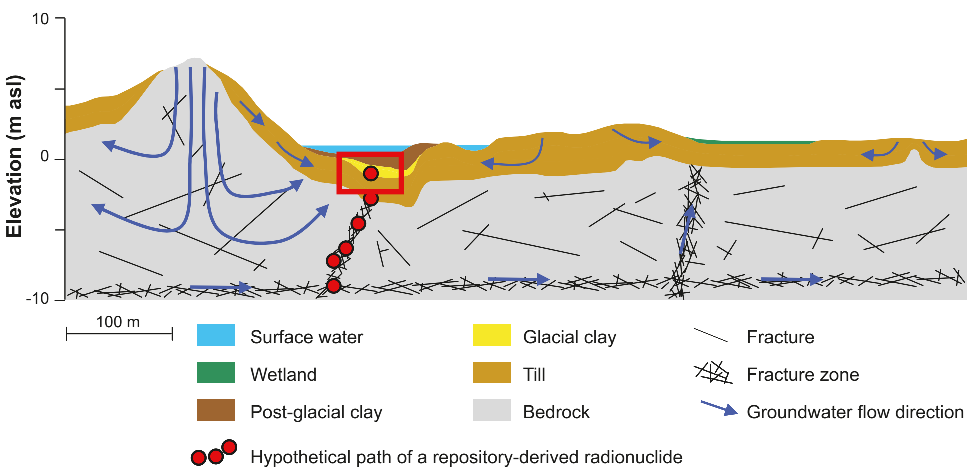


Figure 6-33. *Near-surface hydrogeological conceptual model of Forsmark showing a hypothetical path of radionuclides released from the repository and eventually interacting with the near-surface Quaternary sediments.*

Implications of site conditions for radionuclide retention

In general, the concentration of carbonate in shallow groundwater is controlled by equilibrium with calcite. Precipitation of carbonate minerals may thus be an effective sink for repository-derived C, Sr /Lorens 1981, Tesoriero and Pankow 1996, Bruno et al. 1998/, Se /Lamble et al. 1995, Wang and Liu 2005/ and Ni /Lakshtanov and Stipp 2007/ in these sediments. Other geochemical processes that can effect ^{14}C behaviour are sorption and isotope exchange with the more abundant stable ^{12}C, e.g. /Yim and Caron 2006/. The positive correlation between Sr and Ca both in the till sediments and in the shallow groundwater points to the occurrence of $(Ca,Sr)CO_3$ solid solutions with a relatively constant Sr/Ca ratio, which are considered common solubility limiting phases for Sr /Grandia et al. 2007/.

OM present in organic-rich postglacial deposits, such as wetlands, has a potential for retention of several radionuclides, such as I and Cl. Iodine is mainly found as iodide (I^-) and, under very oxidising conditions, as iodate (IO_3^-). Iodide is the expected major species of I in the Forsmark near-surface groundwater. Iodide can interact with humic substances, especially in the presence of microorganisms /Schmidtz and Aumann 1995, Hou et al. 2003/, although it has less affinity for solid surfaces than IO_3^- (e.g. /Muramatsu et al. 1990, Fukui et al. 1996, Yoshida et al. 1998, Hu et al. 2005, Kodama et al. 2006/.

The observed Kd values of natural I in the Forsmark soils are usually higher than the literature values plus 1 GSD (geometric standard deviation) /Sheppard et al. 2009/. The samples with highest Kd values are those with the highest OM content. According to /Sheppard et al. 2009/, some of the I in the soils may have been incorporated by plants and subsequently incorporated as strongly bound forms in organic matter. The Kd of Cl from Forsmark soils and lake sediments (up to 93 L/kg /Engdahl et al. 2008, Sheppard et al. 2009/) exhibits a positive correlation with OM content, consistent with the observation that OM has a significant effect on Cl^- retention /Öberg 1998, Lee et al. 2001, Ashworth and Shaw 2006/.

OM can form complexes with other repository-derived radionuclides, as it does with natural radioisotopes, such as Ra, Th (e.g. /Langmuir and Herman 1980/, Ni /Zhou et al. 2005, Doig and Liber 2007/, U(VI) /Lenhart et al. 2000, Reiller 2005/, and stable Se /Zhang and Moore 1997, Belzile et al. 2000/. Sorption of Se on organic compounds has long been considered as one of the most significant retention mechanisms for this element. Major cations, especially Ca, will compete with the radioelements for the OM binding sites.

In the Forsmark near-surface groundwater, Th is reasonably well correlated with DOC. This correlation is consistent with the presence of Th organic complexes. The association of Th with humic acids (HA) is strong and an excess concentration of HA may hinder the sorption of Th onto mineral surfaces, e.g. /Reiller et al. 2002, 2003/. The complexation of U with humic acids is favoured at pH below 6, whereas under alkaline conditions carbonate complexes of U will predominate (considering a concentration of humic acids of $5 \cdot 10^{-4}$ M). In this case, the main retention process will be the adsorption of uranium onto inorganic phases (e.g. iron oxy-hydroxides and clays).

In the till sediments, the slightly oxidizing conditions and near-neutral pH of the shallow groundwater favour the precipitation of ferric oxy-hydroxides. These mineral phases can sorb Ni (e.g. /Ticknor 1994, Scheidegger et al. 1997, Green-Pedersen and Pind 2000/), U(VI) /Hsi and Langmuir 1985, Payne et al. 1996, Duff et al. 2002/, Th /Reiller et al. 2005/, Sr /Trivedi and Axe 1999, van Beinum et al. 2005/ and Se (e.g. /Duc et al. 2003, 2006, Templeton et al. 2003, Peak 2006/). The positive correlations of Ni vs. Fe, Th vs. Fe and Nb vs. Fe in the Forsmark surface and near-surface waters suggest that ferric oxy-hydroxides play a major role in their retention. In contrast, at the circumneutral to basic pH of the Forsmark waters, the retention of repository-derived Mo (mainly present as molybdate anions) by iron oxy-hydroxides or OM is not expected to be significant /Bibak and Borggaard 1994/.

In till and clay sediments (either glacial or postglacial), illite, the major clay mineral, can sorb several repository derived radionuclides, such as Th /Bradbury and Baeyens 2009a/, Ni (e.g. /Bradbury and Baeyens 2009b/), Sr (e.g. /Chen and Hayes 1999, Lu and Mason 2001/), U /Turner et al. 1996/, Cs (e.g. /Sawhney 1972/) and Ra /Shahwan and Erten 2004/. Sorption onto illite is considered the major retention process for Cs^+, despite the fact that it competes with the more abundant K^+ and NH_4^+ for sorption sites /Comans et al. 1989, Shaw and Bell 1991, Shenber and Eriksson 1993, Poinssot et al. 1999/.

Some radionuclides are highly mobile in their oxidised forms, such as Mo as molybdate and Tc as pertechnetate. However, if anoxic conditions prevail, e.g. in Forsmark wetlands and lake sediments, the solubility of Tc can be drastically decreased by the reduction of Tc(VII) to Tc(IV) and precipitation of Tc(IV) species /Henrot 1989, Cui and Eriksen 1996, Farrell et al. 1999, Lloyd et al. 1999, 2000, 2001, Abdelouas et al. 2005, Burke et al. 2005/. In anoxic environments, molybdate in the presence of sufficient amounts of H_2S is readily converted to thiomolybdate, which is scavenged by metal-rich (notably Fe) particles, sulphur-rich organic molecules /Helz et al. 1996, Tribovillard et al. 2004/ and iron sulphide /Vorlicek et al. 2004/. Over long time scales, the reduction to Mo(V) followed by adsorption on various substrates, including peat, could be an important retention mechanism /Bertine 1972/.

Under reducing conditions, Th, Se and U(IV) can be retained by precipitation of pure phases. If enough Th is available in the system, the precipitation of amorphous ThO_2 can take place under near neutral to basic pH. Under more acidic pH and in the presence of phosphates, a thorium phosphate can form. U(IV) solid phases are mainly oxides, especially uraninite (or amorphous analogues). Coffinite ($USiO_4 \cdot n(H_2O)$) is a very common U(IV) phase in many U ores although the conditions needed for its formation have long been debated. Direct precipitation from U(IV)-bearing solutions is believed to be kinetically limited since laboratory experiments failed to synthesise it /Robit-Pointeau et al. 2006/. It is likely that a previous U(VI) reduction step is required before coffinite precipitates /Goldhaber et al. 1987/.

Se oxyanions can be reduced and precipitated as native Se, $FeSe_2$ or $Fe_{1.04}Se$. This reduction will be favoured by the presence of bacteria, organic matter and Fe(II)-containing minerals /Zhang and Moore 1996, 1997, Charlet et al. 2007, Bruggeman 2008, Scheinost et al. 2008/. The precipitation of one or another phase of Se is conditioned by the Eh and pH of the water, and the concentrations of dissolved Fe(II) and Se /Howard 1977, Pérez del Villar et al. 2002/. Se^{2-} and Ni^{2+} can be also incorporated into newly formed sulphides, replacing S^{2-} and Fe^{2+}, respectively.

U(VI) solubility limiting phases depend on the chemistry of water. In silica and calcium-rich oxic waters at neutral to alkaline pH, U is commonly precipitated as uranophane ($Ca(UO_2)(SiO_3OH)_2(H_2O)_5$ /Finch and Murakami 1999/). Uranophane can be replaced by soddyite ($(UO_2)_2SiO_4(H_2O)_2$) if pCO_2 is low enough /Finch 1994, Casas et al. 1994/. At low Si concentrations, becquerelite precipitation is favoured ($Ca(UO_2)_6O_4(OH)_6 \cdot 8H_2O$ /Duro et al. 2006a/). Phosphates, such as saléeite ($Mg[(UO_2)(PO_4)]_2(H_2O)_{10}$), can be a sink for U even if the groundwater is, apparently, undersaturated in these phases; /Murakami et al. 1997/ suggested that local release of P adsorbed onto ferrihydrite when this mineral is replaced by other Fe(III) phases (hematite and goethite) could cause uranyl phosphate precipitation.

The co-precipitation of U with iron oxides has been proven to be a very efficient process that controls the U concentration in natural waters (e.g. /Bruno et al. 1998, 2002/). Rough correlations are observed between U and Fe, Mn and P in Forsmark till sediments; however, according to /Grandia et al. 2007/, the decrease of U concentration with depth can indicate that it is progressively incorporated in these sediments via reduction /Grandia et al. 2007/. U distribution in fine-grained sediments shows a marked increase down to depths of 40–50 cm, and a decrease down to 55 cm. These variations could be attributed to changes in the redox conditions.

Nb seems to be strongly retained in Quaternary deposits, based on the available Kd values in till, soils and lake sediments /Engdahl et al. 2008, Sheppard et al. 2009/. However, the processes responsible for this retention have not been ascertained so far. One possibility could be the precipitation of Nb phases. /Charles and Prime 1983/ reported the precipitation of Nb compounds (like niobic acid, niobate, or polymeric hydrous oxide) on silt particles from an area contaminated with spills from radioactive waste. /Åström et al. 2008/ analysed stream waters in the boreal zone of Europe and found that dissolved Nb was correlated with DOC and dissolved Fe (0.45 µm-filtered). The limited data available for Forsmark waters also show a correlation between dissolved Nb and Fe.

Till groundwater in the Forsmark area is very close to barite saturation. Therefore, the precipitation of this mineral could be a sink for repository-derived Ra, which is known to co-precipitate with barite (e.g. /Beaucaire et al. 1987, Sturchio et al. 1993, Grundl and Cape 2006/). The very low concentration of aqueous Ra (from 10^{-14} to 10^{-11} M) in both natural and anthropogenic environments indicates that the solubility of radium is not controlled by pure phases (mainly $RaSO_4$, with expected solubility under these conditions of 10^{-8} to 10^{-7} M). $(Ba,Ra)SO_4$ solid solutions commonly precipitate in oil extraction facilities, in geothermal systems and in uranium mining areas (see /Grandia et al. 2008/ for references).

Selection of main radionuclide retention processes

Based on the conceptual evaluation of radionuclide retention in the Forsmark near-surface environment, the processes identified as affecting radioelement retention are presented in Table 6-1. Processes judged to be relevant in the Quaternary soils and sediments at Forsmark are not shadowed. Dark cells indicate no influence of the process on the retention of the element. Light shadowed cells indicate processes that can actively affect radioelement retention, but not in the Forsmark media. This discrimination partly arises from results obtained from reactive transport simulations under the specific conditions of Forsmark.

The strengths of the different processes likely to retain radioelements can be quantified through association, sorption or equilibrium constants. These parameters are not available for all the relevant processes identified, although this cannot be used as an argument for not discussing the processes from a qualitative perspective. Those processes for which quantification is possible through association/sorption/stability constants have been ticked in red.

Most of the studied radioisotopes have very long half-lives, except for ^{14}C, ^{93}Mo, ^{226}Ra and ^{90}Sr. These four radionuclides will have an important loss of mass in the time framework of a few thousands of years. Taking 3,000 years as time framework to study "stable" geomorphological conditions, losses of 30%, 40%, 77% and 100% are expected for ^{14}C, ^{93}Mo, ^{226}Ra and ^{90}Sr, respectively. On the other hand, it is worth noting that radium is a product of the 4N+2 decay chain (^{238}U), so it will also be produced. Radioactive decay and decay chains have not been implemented in the numerical simulations at the present-day state of model development.

6.4.2 Quantitative modelling of radionuclide migration

Setup of numerical models

The retention capacity of the near-surface Quaternary deposits in Forsmark was evaluated by means of reactive transport simulations, considering two distinct domains /Grandia et al. 2007, Sena et al. 2008, Piqué et al. 2010/:

1. **Quaternary till** overlying the granite bedrock. In this model, deep groundwater containing dissolved radionuclides was assumed to migrate upwards through a fracture in the granite and eventually transfer the radionuclides to the Quaternary deposits. The Quaternary deposits were assumed to be hydraulically connected to a discharge zone (Figure 6-34).
2. **Glacial clay** present at the bottom of a discharge zone (such as a lake or the Baltic Sea), and overlying a till deposit. In order to evaluate the retention capacity of the glacial clay, it was assumed that deep groundwater can flow through a preferential path in the till, which contacts directly with the bottom of the clay layer (Figure 6-35).

Table 6-1. Retention processes that may be relevant under the conditions of the Forsmark near-surface system.

Retention process	^{14}C	^{129}I	^{36}Cl	^{94}Nb	^{59}Ni	^{93}Mo	^{79}Se	^{99}Tc	^{230}Th	^{235}U	^{135}Cs	^{90}Sr	^{226}Ra
Sorption onto organic matter													
Sorption onto Fe-Mn-Al oxyhydroxides					✓		✓			✓			
Sorption onto phyllosilicates					✓				✓	✓	✓	✓	
Precipitation as pure phases	✓			✓	✓	✓	✓	✓	✓	✓			
Association with sulfides													
Association with carbonates												✓	
Incorporation into bacteria													
Association with phosphates													
Association with sulfates													✓

Processes likely to be active in the QD of Forsmark

Processes not likely to be active in the QD of Forsmark

Retention processes not relevant for the indicated element

✓ Available thermodynamic data

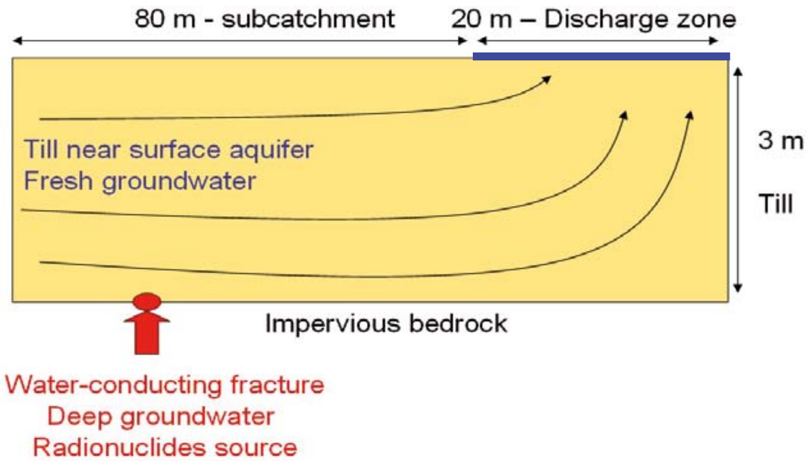


***Figure 6-34.** Sketch of reference case #1, the till system. Blue line indicates the discharge zone for which breakthrough curves were integrated for interpretation.*

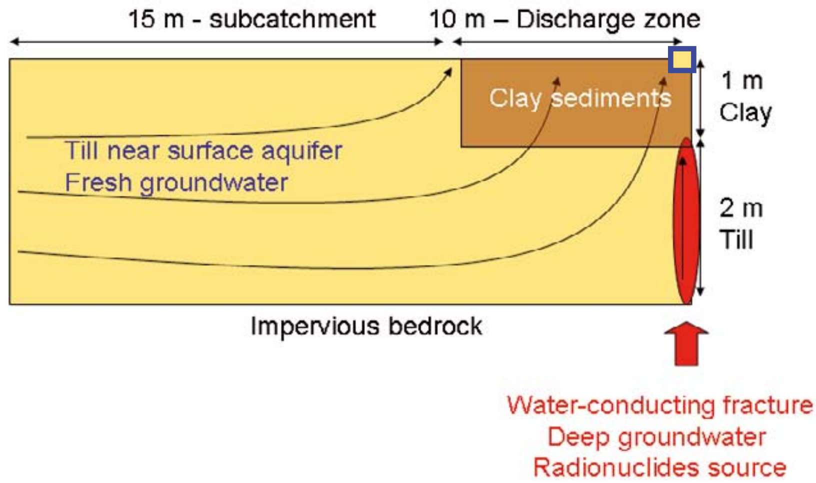


***Figure 6-35.** Sketch of reference case #2, the glacial clay. Computed breakthrough curves were evaluated at the blue and yellow square.*

Reference cases were simulated for a period of 2,700 years, in order to generate consistent initial conditions for the geochemical system prior to the release of repository-derived radionuclides from the bedrock. After this period, the release of radionuclides was simulated over 30,000 years. Such a long time of simulation was used for the determination of effective Kd values for the radionuclides, although the analysis of computed results was undertaken only for the first 3,000 years, assuming this framework as a reasonable time to assume "constant" geomorphological conditions in the near-surface system.

The reactive transport simulations were performed with the code PHAST, version 1.5.1 /Parkhurst et al. 2004/, which is able to simulate multi-component, reactive solute transport in 3D saturated groundwater flow systems. The thermodynamic database used was basically that reported in /Duro et al. 2006b/, with additional incorporations to the database detailed in /Piqué et al. 2010/. In reference case #2 (the clay system) dissolved humic acids were included to simulate U and Th complexation in waters with high concentrations of organic compounds.

Chemical input data

In both reference cases, the major reactive minerals considered in the models were calcite and illite. Calcite was considered to contain trace amounts of strontium, forming a solid solution. Dissolution of illite was not considered, and this mineral participated only as a charged surface for cation exchange. Fe(III)-hydroxide (ferrihydrite) was thought to be the redox-controlling phase of the till porewater, and an initial concentration of 0.1 wt% of ferrihydrite was arbitrarily considered (due to the lack of field data). For the clay domain, an initial concentration of approximately 1.5 wt% of pyrite was considered in order to ensure relatively reducing conditions. The initial compositions of till and clay porewaters and the composition of the deep groundwater before and after the radionuclide release from repository are presented in /Piqué et al. 2010/.

Due to the geochemical variability of the modelled Quaternary deposits, a sensitivity analysis was developed in order to estimate the impact of considering distinct values for the most important geochemical parameters. The sensitivity analysis focused on the following geochemical features: $(Ca,Sr)CO_3$ solid solution, isotopic fractionation of carbon, cation exchange capacity (CEC) and complexation sites on illite, and amount of dissolved humic acids. For details on the hydrodynamic parameters, groundwater selection, hydrological and hydrogeochemical initial conditions, calculation of initial concentrations of repository derived radionuclides, and spatial and time discretisations of the numerical models, the reader is referred to the report by /Piqué et al. 2010/.

Retention processes in the numerical models

The retention processes included in the numerical modelling are summarised in Table 6-2. In the till domain (reference case #1), sorption was assumed to take place onto illite and iron oxy-hydroxides. In the glacial clay domain (reference case #2), only sorption onto illite was considered. In both reference cases, the phases allowed to precipitate if saturation was reached were: $(Ca,Sr)CO_3$, Nb_2O_5, Se(0), $FeSe_2$, $Fe_{1.04}Se$, $TcO_2{\cdot}1.6H_2O$, $UO_2{\cdot}2H_2O$, schoepite, soddyite, uranophane, becquerelite and radiobarite.

Complexation with OM was not simulated because scarce thermodynamic data are available and there is too much uncertainty with the related parameters required for modelling. Moreover, the simulated till and glacial clay domains correspond to glacial sediments with relatively low contents of OM. Therefore, I and Cl, which can sorb onto OM, were considered as conservative in the numerical modelling even though we know that may sorb onto OM. Mo was not implemented in the modelling due to the lack of conceptual understanding and related data.

6.4.3 Results and discussion

Breakthrough curves

The repository derived radionuclides that behave conservatively (e.g. ^{129}I and ^{36}Cl) are expected to discharge very quickly to the surface water both in the till (Figure 6-36) and clay system (Figure 6-37). It must be emphasised that the concentration steady state for conservative radionuclides is reached approximately 500 years later in the clay system than in the till, due to the contrasting hydrogeological properties of the media. Hydraulic conductivity is two to three orders of magnitude higher in the till than in the clay system. As a result, advection and dispersion are the dominant transport processes in the till system whereas in the clay system (low permeability medium) diffusion plays a more important role.

The quantitative modelling exercise showed that, besides repository-derived Cl and I, also ^{94}Nb and ^{99}Tc behave almost conservatively in the till and clay systems, and the same can be observed for ^{79}Se in the clay. It is worth noting that only the precipitation of pure phases was considered as a process able to retain Nb, Se and Tc. Under the (assumed) Forsmark conditions, Nb and Tc solids are far from saturation, and the same happens with Se in the clay sediments.

According to the reported Kd values for Forsmark sediments, Nb has a high affinity for the solid phase /Engdahl et al. 2008, Sheppard et al. 2009/. However, the model predicts no retention of Nb (natural + repository derived) because the saturation of Nb_2O_5 is not reached at any point and at any time. In the natural system, Nb could be partially retained by sorption onto sediment particles, which could explain the high Kd values reported for Nb based on the in situ measurements.

Table 6-2. Retention processes implemented in the numerical modelling.

Retention process	^{14}C	^{94}Nb	^{59}Ni	^{79}Se	^{99}Tc	^{230}Th	^{235}U	^{135}Cs	^{90}Sr	^{226}Ra
Sorption onto Fe oxyhydroxides			■				■			
Sorption onto illite			■			■	■	■	■	■
Precipitation as pure phases	■	■		■	■	■	■			
Association with carbonates									■	
Association with sulfates										■

■ Processes modelled

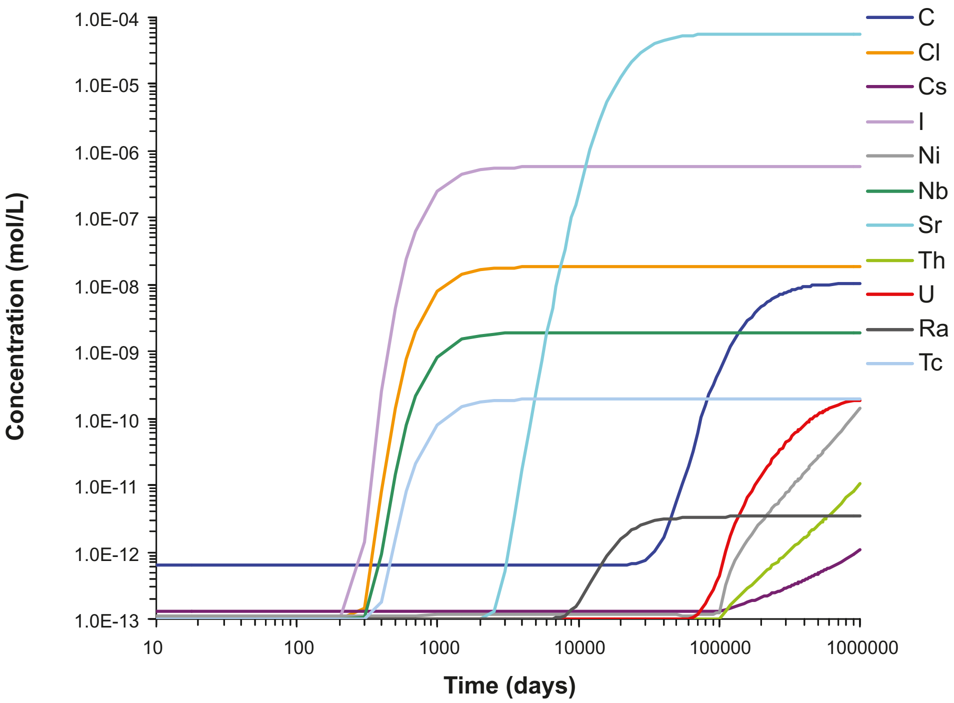


Figure 6-36. *Integrated breakthrough curves of repository-derived radionuclide concentrations at the discharge area of the till domain (see Figure 6-34 for location).*

Tc also behaves conservatively in the numerical modelling. For the case of the till system, this is consistent with the fact that under oxidising conditions the main Tc(VII) aqueous complexes are TcO_4^-, i.e. anions. For the case of the clay system, the more reducing environment favours the stability of Tc(IV) species, although in the modelled domains the concentration of Tc in solution was too low for the precipitation of TcO_2. Reported Kd values for Tc reveal that this element is poorly retained in soils /Sheppard et al. 1990/.

For the case of Se, the simulation of the clay system shows that no solid phases will precipitate in the whole domain. The precipitation of pure phases is not the only mechanism that can potentially retain Se, although it was the only one considered in the simulations. In the real case, the concentration of dissolved selenium in the clay system could decrease, for example by its sorption onto organic matter or by its incorporation in newly formed sulphides. These processes were not implemented in the numerical models due to the lack of reliable parameters for their quantification, but the reported Kd values for Se in Forsmark lake sediments (9,500 to 100,000 L/kg; /Engdahl et al. 2008/) confirm that this element is effectively retained in these environments.

In the till domain, the Eh-pH conditions and the concentration of dissolved Se (in the order of $1{\cdot}10^{-15}$ to $1.6{\cdot}10^{-15}$ mol/L) favour the precipitation of native selenium. The release of this radionuclide to the discharge area of the till domain is completely prevented (i.e. zero concentration in the discharging

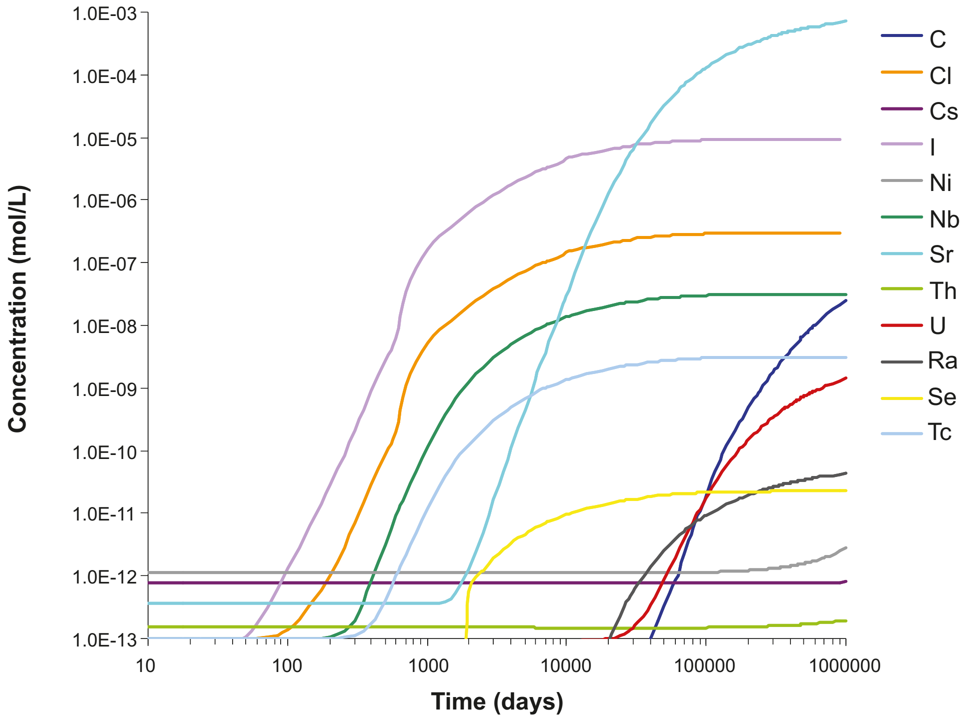


Figure 6-37. *Simulated breakthrough curves of repository-derived radionuclide concentrations at the observation point of the discharge area in the clay domain (see location in Figure 6-35).*

water). It should be emphasised that the stability field of native selenium under the conditions of interest is very narrow, and a slight change in Eh and/or pH would prevent the precipitation of native selenium (Figure 6-38).

The next radioelements discharging in both domains are ^{90}Sr and ^{226}Ra. ^{14}C and U will follow, while ^{135}Cs, ^{230}Th and ^{59}Ni are the radionuclides showing the strongest retardation (Figure 6-36 and Figure 6-37). Conversely to Nb and Se, all the significant processes that could apparently retain Sr in the till and clay domains were included in the simulations. The numerical modelling computes that the till system is not efficient in retaining ^{90}Sr, which is only partially retained by cation exchange onto illite and, close to the deep groundwater discharge point, in (Ca,Sr)CO_3 solid solution.

The clay system also shows a decreasing capacity to retain ^{90}Sr with time. In fact, at the end of the simulation period (~3,000 years), the maximum ^{90}Sr concentration at the discharge area is only 25% lower than in the corresponding conservative transport simulation. The sensitivity analysis shows that the arrival of ^{90}Sr at the discharge area is controlled by the amount of cation exchange sites, indicating that the slight retention of ^{90}Sr is mainly due to sorption onto illite.

Retention efficiency and retardation factor

The "retention efficiency", E (%), is a time-dependent measure of the relation between the concentration of the radionuclide and that of a corresponding non-reactive solute in the discharging groundwater; an E value of 100% corresponds to a zero concentration of the reactive radionuclide, whereas E=0 implies no concentration reduction due to retention processes (see /Piqué et al. 2010/ for details). Calculated retention efficiencies after 2,700 years of simulation time are summarised in Table 6-3, together with other measures of retention.

Ra is partially retained by cation exchange in both till and clay sediments, but it also scavenged from solution by the precipitation of (Ba,Ra)SO_4 in the conditions of the till. The retention efficiency for Ra in the till system drops very fast to almost zero, whereas such a decrease is more gradual in the clay domain, down to 20% after almost 3,000 years of simulation. This indicates that the maximum retention capacity of illite is reached and no more Ra can be accommodated in the case of the till. It is worth noting that slight changes in groundwater composition could preclude the precipitation of

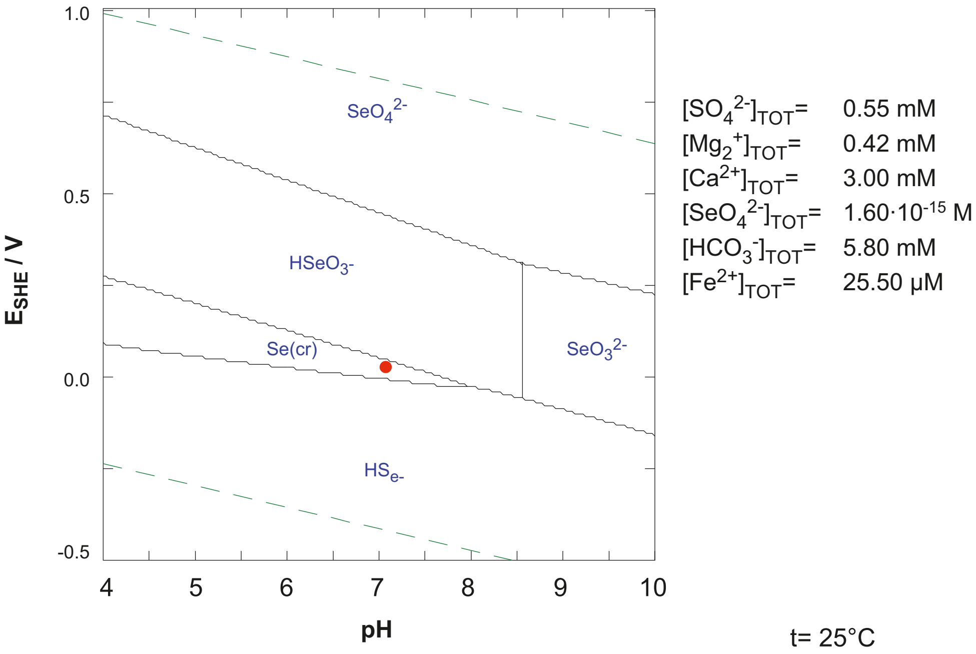


Figure 6-38. *Eh-pH diagram of Se species, for a groundwater from the till domain, close to the deep groundwater inflow point. The red point indicates the (very narrow) pH-Eh range in the simulated till domain after repository release (Se(cr) stands for native (elemental) Se).*

Table 6-3. Retention efficiency (E) after 2,700 years of simulated repository release, retardation factor (R), arrival time of 1% concentration and effective Kd (Kd_e) at the discharge area of the simulated domains; see below for definitions of R and Kd_e.

Element	E (2700 y) Till	E (2700 y) Clay	Arrival 1% Till	Arrival 1% Clay	R Till	R Clay	Kd_e Till	Kd_e Clay
^{14}C	0.83%	85%	205 y	810 y	196	291	7.89	29
^{36}Cl	0%	0%	1.4 y	4 y	1	1	0	0
^{135}Cs	100%	100%	9500 y	>> 33000 y	-	-	-	-
^{129}I	0%	0%	1.4 y	4 y	1	1	0	0
^{94}Nb	0%	0%	1.4 y	4 y	1	1	0	0
^{59}Ni	99.2%	100%	2500 y	32000 y	6035	-	244.1	-
^{90}Sr	0.02%	23.6%	29 y	94 y	24	30	0.93	2.9
^{230}Th	99.8%	100%	4300 y	>> 33000 y	11819	-	478.2	-
^{235}U	7.62%	57.1%	340 y	329 y	402	>158	16.2	>15.7
^{226}Ra	2.98%	21.2%	23 y	82 y	20	27	0.77	2.6
^{79}Se	100%	0%	>> 33000 y	4 y	-	1	-	0
^{99}Tc	0%	0%	1.4 y	4 y	1	1	0	0

radiobarite and radium uptake in the till. The sensitivity analysis indicated that if less sorption sites are available on illite (a ten-fold decrease), the arrival of Ra at the discharge areas takes place earlier.

For repository-derived radiocarbon, the main retention mechanism considered in the Forsmark near-surface system is carbonate precipitation. In the numerical simulations, radiocarbon was allowed to incorporate in newly formed calcite (Figure 6-39). The models predict that ^{14}C could be efficiently retained in the clay system. After 2,700 years of repository release, ^{14}C concentration at the discharge area of the clay system is one order of magnitude lower in the reactive transport simulation than in the conservative simulation. On the contrary, in the till system the retention efficiency of ^{14}C drops very fast, and radiocarbon behaves conservatively during most of the simulation time. The sensitivity analysis at 5, 15 and 25ºC did not show significant differences in the retention of radiocarbon due to isotopic fractionation processes.

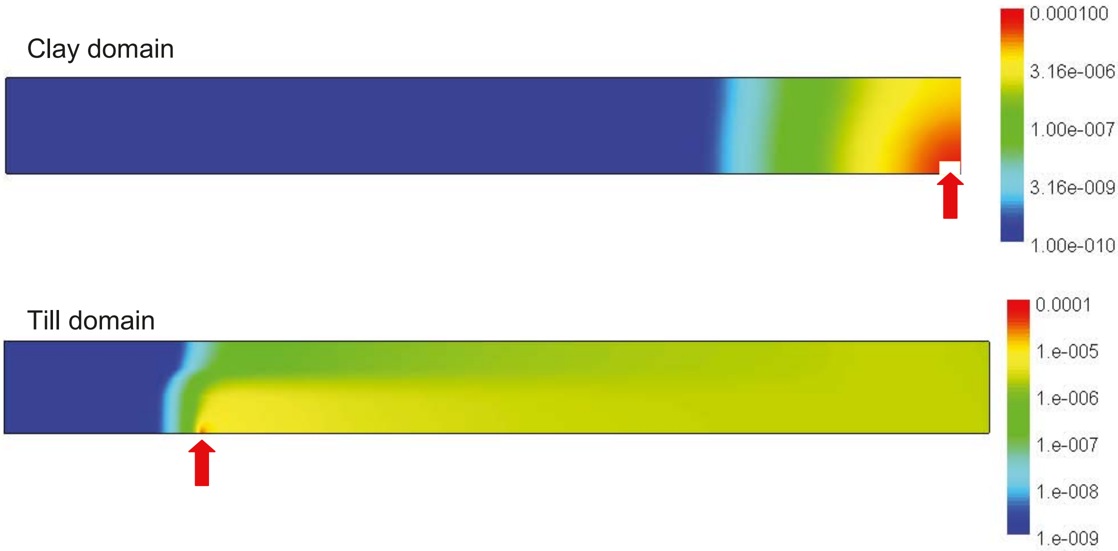


Figure 6-39. *Simulated concentration of ^{14}C (in mol/L) retained in $(Ca,Sr)CO_3$ after 2,700 years of radionuclide-bearing deep groundwater inflow (red arrows) in the till and clay domains.*

Repository-derived uranium is another of the simulated elements that is only partially retained in the till and clay systems. For the till system, the numerical modelling simulates that the retention efficiency maximum will be at the beginning of the repository release, but it will significantly decrease with time and at the end of the simulation (2,700 years) the uranium concentration will not be affected by retention processes (Table 6-3).

In the till domain, sensitivity analyses show that a smaller amount of sorption sites does not affect the concentration of uranium in solution, since it is mostly retained by iron hydroxide. In the clay domain, U will be retained due to the precipitation of amorphous uraninite and to the sorption onto illite. The sensitivity analysis for the clay domain shows that an increase of one order of magnitude in the concentration of dissolved humic acids does not change the concentration of dissolved uranium significantly.

The more strongly retarded radionuclides in the modelled domains are ^{135}Cs, ^{59}Ni and ^{230}Th. The computed retention efficiency for these radionuclides at the end of the simulations of the till and clay domains is 100% (Table 6-3). In the clay system, these elements are very efficiently retained by illite due to the high affinity of these elements for the illite surface (Figure 6-40). In the till domain, Ni is also retained by ferrihydrite, although to much lesser extent than by illite.

The sensitivity analysis of the clay system shows that a decrease of one order of magnitude in illite sorption sites produces an increase of one order of magnitude of ^{230}Th and ^{135}Cs in solution and of two orders for ^{59}Ni. In the till system, the increase in concentrations due to the same change in sorption sites is two orders of magnitude for ^{230}Th and ^{135}Cs and one order of magnitude for ^{59}Ni. As expected, the decrease in sorption sites produces also a decrease in the corresponding retardation factors of these radionuclides (Table 6-4).

The arrival times of 1% of repository-derived radionuclide concentration at the discharge area of the till and clay systems are in agreement with the calculated retention efficiency (Table 6-3). The fastest arrival corresponds to radionuclides that behave conservatively, whereas for other radionuclides the arrival time is over 33,000 years. The retardation factor is another parameter that indicates which radionuclides are better retained in the till and clay sediments. The retardation factor (R) of a given reactive solute can be calculated from the following equation:

$$R = \frac{T_{1/2}^{R}}{T_{1/2}^{C}}$$

where $T^R_{1/2}$ is the advective travel time of the reactive solute in the reactive transport simulation, and $T^C_{1/2}$ is the advective travel time of the same solute in the conservative transport simulation (see /Piqué et al. 2010/).

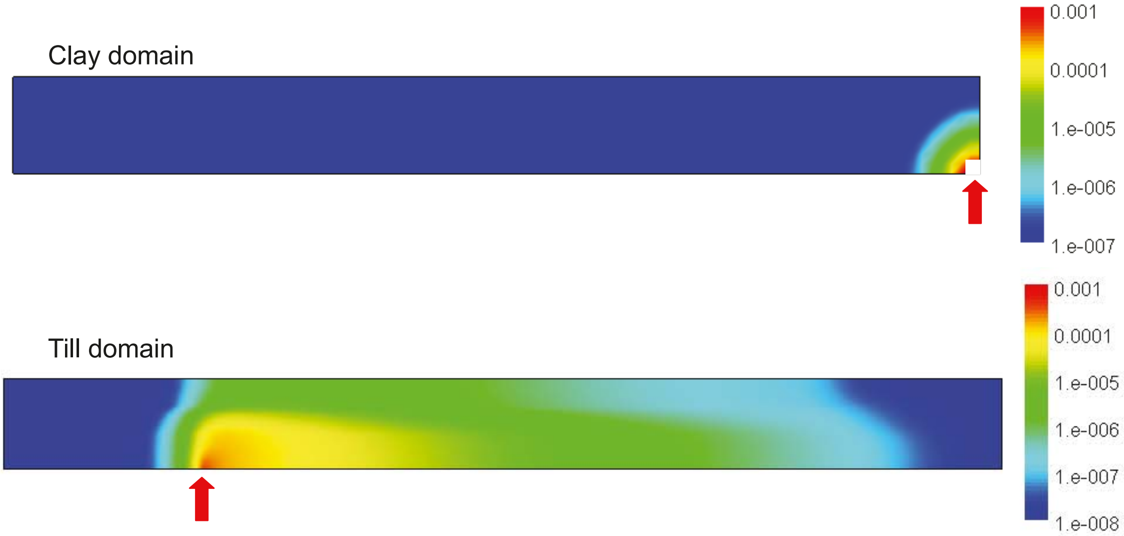


Figure 6-40. *Concentration of Cs (in mol/L) retained in illite fried edge sites (FES), after 2,700 years of radionuclide-bearing deep groundwater input (red arrows) in the till and clay domains.*

Table 6-4. Retardation factor (R) and effective Kd (Kd_e) for the sensitivity analysis with less illite sorption sites (lss) and the base case (bc). Lss simulation run up to 2,700 years and bc simulation up to 33,000 years. (R and Kd_e could not be computed for Ni and Cs in the lss simulation.)

Element	$R_{(bc)}$ Till	$R_{(lss)}$ Till	$R_{(bc)}$ Clay	$R_{(lss)}$ Clay	$Kd_{e\ (bc)}$ Till	$Kd_{e\ (lss)}$ Till	$Kd_{e\ (bc)}$ Clay	$Kd_{e\ (lss)}$ Clay
^{90}Sr	24	9	30	5.4	0.93	0.32	2.9	0.44
^{230}Th	11819	1000	-	-	478.2	40.4	-	-
^{235}U	402	390	>158	n.c	16.2	15.7	>15.7	n.c.
^{226}Ra	20	n.s.	27	3.33	0.77	n.c.	2.6	0.23

Calculated R from breakthrough curves are reported in Table 6-3 and Table 6-4. R is 1 for the conservative radionuclides and it reaches values up to 11,800 for ^{230}Th in the clay system. In some cases the delay was so high that R could not be computed. That was the case for ^{135}Cs, ^{59}Ni and ^{230}Th in the clay domain and for ^{135}Cs and ^{79}Se in the till domain. The sensitivity analysis revealed that R values are correlated with the amount of sorption sites for those radionuclides that are mainly retained on illite (Table 6-4). When the amount of sorption sites is reduced by one order of magnitude, R decreases by up to one order of magnitude for ^{230}Th and ^{226}Ra (Table 6-4). In the cases of ^{235}U and ^{90}Sr in the till, the reductions of R are not so significant because other processes are also involved in their retention (sorption onto ferrihydrite and precipitation of carbonate solid solution, respectively).

Computed effective Kd versus Kd derived from in situ observations

Effective Kd can be calculated based on computed retardations by using the equation:

$$Kd_e = (R-1)\frac{\varphi_e}{\rho_b}$$

where φ_e is the effective porosity and ρ_b is the dry bulk density of the sediment (M L^{-3}). To calculate Kd_e one must give a single value of effective porosity, which is not the case for the modelled till system. A value of 0.0789 for the effective porosity in the till was used to calculate Kd_e. This value was obtained by /Sena 2009/ from a calibration of a conservative transport model. The porosity in the clay system was 0.2. The dry bulk density was 1.95 kg/L in the till and 2.0 kg/L in the clay system. The calculated Kd_e values at the monitoring points are reported in Table 6-3 and Table 6-4.

Furthermore, a Kd mapping, of the whole simulated till and clay domains was carried out (Figure 6-41); the Kd maps were obtained by plotting calculated ratios of retained and aqueous concentrations in each cell in the numerical grids, after conversion to appropriate units. It is important to note that the computed Kd of each natural isotope is equal to that of the corresponding repository-derived radionuclide /Sena 2009/, with the exception of natural carbon and repository-derived carbon, for which slight, but not significant, differences in Kd are observed due to isotopic fractionation processes.

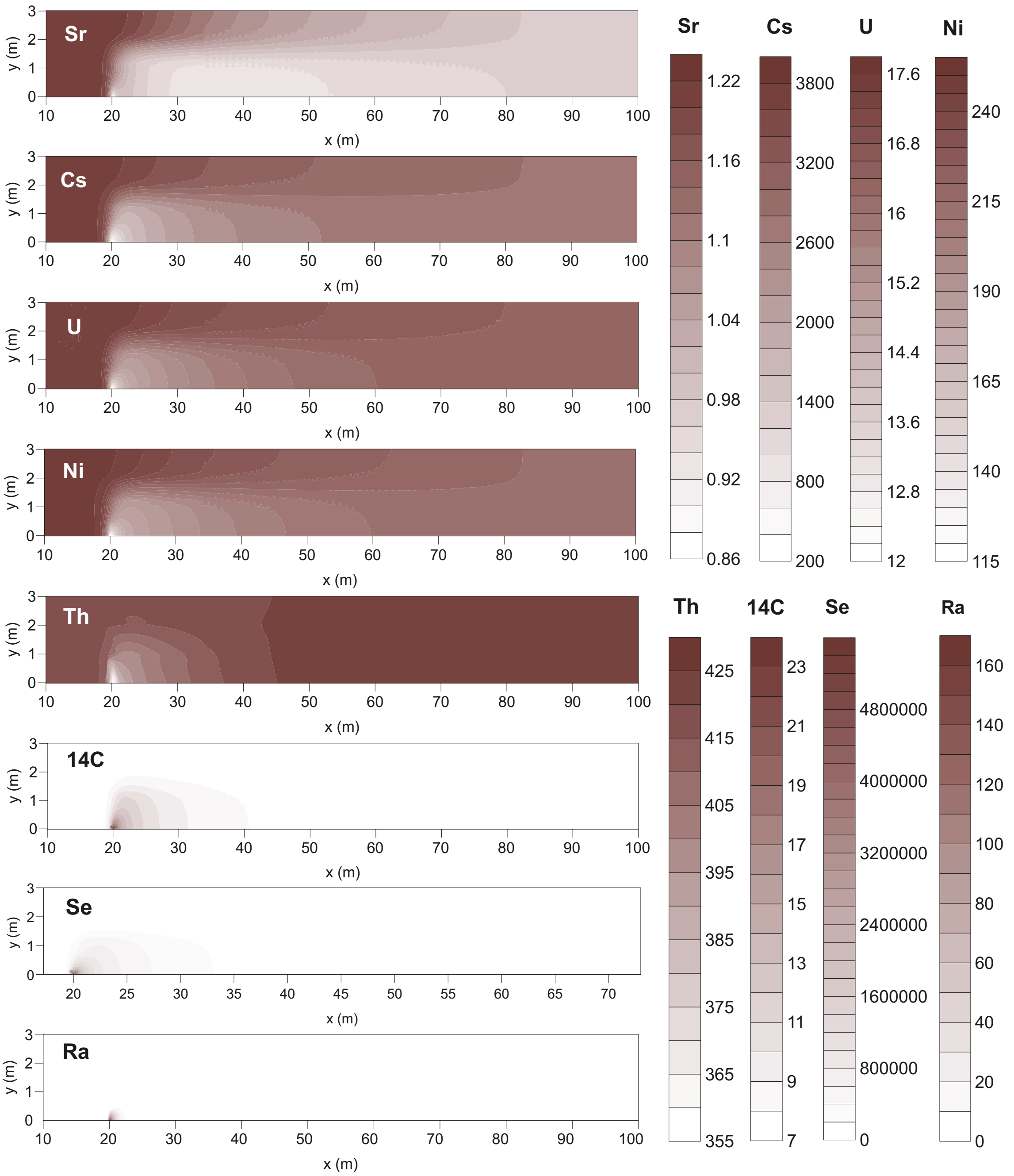


Figure 6-41. *Distribution map of Kd (L/kg) for selected elements in the till domain after 2,700 years of radionuclide release (inflow point X = 20 m; Y = 0 m).*

As pointed out by /Sena 2009/, once the geochemical quasi-steady state has been approached, the Kd of the selected radionuclides is relatively stable in time, but it is not homogeneous in space. In the till domain, the radionuclides that are mostly retained by sorption onto clay and Fe hydroxide (namely ^{90}Sr, ^{135}Cs, ^{235}U, ^{59}Ni, ^{230}Th) show a decrease in the Kd in the area affected by the deep groundwater (Figure 6-41). For the case of ^{79}Se, ^{14}C and ^{226}Ra, the maximum Kd values are reached at the vicinity of the deep groundwater inflow point, where native Se, $(Ca,Sr)CO_3$ and radiobarite precipitate. In the clay system, a decrease in Kd is also computed in the area affected by the deep groundwater, for all those elements that are retained either by sorption onto illite and/or incorporation in solid phases (Sr, Cs, U, Ni, Th, C and Ra).

As expected, the computed Kd values are not equal in the till and clay domains. In general, they are up to one order of magnitude higher in the clay domain for Sr and Cs and up to two orders of magnitude higher for Ni and Th (Table 6-5). The higher retention of these elements in the clay domain is explained by the higher amount of illite, and therefore of available sorption sites. C shows a higher Kd value in the clay domain, but in the same order of magnitude as in the till (Table 6-5). In contrast, Kd values of Ra are up to two orders of magnitude higher in the till domain than in the clay (Table 6-5), due to the precipitation of radiobarite. U shows Kd values in the same order of magnitude in both systems, but slightly higher in the till.

According to the computed Kd values, the most retained radionuclides in the till system are Se and Cs, followed by Th and Ni, with U, Sr, C and Ra much less well retained. The computed Kd values for Ni, Cs, and U are one order of magnitude lower than desorption Kd values reported for till soils in Forsmark, and two to three orders of magnitude lower for Th (Table 6-5). Desorption Kd values in /Sheppard et al. 2009/ were obtained after partial extraction with *Aqua Regia*. Therefore the elements present in non-reactive silicates were not considered in the Kd calculation. Direct comparisons between soil Kd values and those of the deep till should be made with caution, since the environmental conditions and parameters that influence Kd could differ. In addition, OM in the soil could also be a sink for some of the considered radionuclides, such as Ni, U and Th, and this process was not simulated in the model.

Selenium is an interesting exception because the model computes that it is highly retained in the till system, whereas the reported Kd values reveal that Se is poorly retained in Forsmark till soils (Table 6-5). As already mentioned, the predicted Eh-pH conditions are favourable to native Se precipitation in the simulated till domain, but this process is very sensitive to small changes in the groundwater Eh/pH, so this effect may not occur in other contexts.

Table 6-5. Range of Kd (L/kg) in the simulated till and clay domains after 2,700 years of repository release (base case simulations), and reported Kd in Forsmark soils and sediments (a: /Sheppard et al. 2009/, b: /Engdahl et al. 2008/).

Element	Calculated Kd range		Measured Kd range	
	Till	Clay	Till soils[a]	Lake seds.[b]
C	7 - 24	26 - 42		
Cl	0	0	4.4 - 37	7 - 93
Cs	200 - 4000	$6000 - 4.8·10^4$	$2.8·10^4$; $1.2·10^5$	$6857 - 1.1·10^5$
I	0	0	>90 - >210	302 - 2471
Nb	0	0	$3.6·10^4$	$8.1·10^4 - 2.7·10^5$
Ni	115 - 255	$1000 - 1.9·10^4$	3000; 3800	$9375 - 3.1·10^4$
Sr	0.86 - 1.24	2-40		214 - 389
Th	355 - 430	$1.0·10^4 - 1.6·10^4$	$3.1·10^4 - 2.5·10^5$	$1.3·10^5 - 2.9·10^5$
U	12 - 17.8	>15.7	610 - 3300	1435 - 5200
Ra	0 - 170	2 - 10		
Se	$0 - 5.6·10^6$	0	10-14	$9545 - 1.0·10^5$
Tc	0	0		

For the case of the clay system, computed Kd values show that Cs, Ni and Th will be highly retained, whereas Sr, U, C and Ra will be less retained (Table 6-3). Kd values for Ni and Cs are in the range of those reported by /Engdahl et al. 2008/ for Forsmark lake sediments, whereas computed Kd values for Th and Sr are one order of magnitude lower and two orders of magnitude lower in the case of U (Table 6-5). One explanation for the lower computed Kd values of Th, U and Sr can be that /Engdahl et al. 2008/ used an extraction method that leads to total dissolution of these sediments. Therefore, their reported Kd values do not describe only the exchangeable fraction of the solid phase, but also the fraction present in silicates assumed non-reactive in the simulated time framework. The fact that sorption onto OM is not considered, could also explain the lower computed Kd values for Th and U.

Effective Kd values for Ra are below 3 L/kg in the simulated till and clay domains. No Kd data for Ra were available from Forsmark at the time for the analysis reported in /Piqué et al. 2010/. However, /Sheppard et al. 2009/ predicted Kd values for Ra in Forsmark samples by applying a stepwise regression of data from the literature. Predicted Kd values for Forsmark soils cover a very wide range when taking uncertainties into account. /Sheppard et al. 2009/ also combined data from several sources to develop a new regression equation, which yielded predicted Kd values of 73 L/kg and 130 L/kg for the two Forsmark clayey till samples included in the study. The effective Kd obtained in the present simulations is therefore closer to the lower values predicted for Ra in the Forsmark soils.

Despite the fact that computed Kd and experimentally determined Kd differ in most cases, the general trend observed in the Forsmark till soils and lake sediments is relatively consistent. Computed and experimental values agree in that the most retained elements are Th, Cs and Ni, followed by U and Sr. Se is an exception because no retention is computed in the clay and a high retention is computed in the till, whereas experimental Kd values show the opposite behaviour. Nb is another exception because it is highly retained according to "measured" Kd but almost not retained in the modelling results.

An interesting point is that Kd values estimated from in situ measurements are usually taken as constant for a given site and sediment type, but computed results show clearly that Kd values are heterogeneous in space. However, the effective Kd values are determined directly from the breakthrough curve in the discharge area of the model, so they represent a kind of "upscaled" Kd value for the whole domain. In this sense, effective Kd computed by reactive transport simulations will constitute an appropriate way to simulate mass transfers in simplified box models often used for performance assessment and dose calculations. The theoretical relation that must exist between the heterogeneous spatial distribution of Kd values and the effective Kd determined by breakthrough curves is not known to the best of our knowledge.

6.4.4 Summary and conclusions

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

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

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

The reported Kd values in Forsmark soils and sediments, although not directly comparable to the calculated effective Kds, show a similar general trend (i.e. the most strongly retained elements are Th, Cs and Ni, followed by U and Sr). The computed behaviour of Se and Nb are the two exceptions that do not agree with reported Kd values. It needs to be recalled that not all the possible retention processes considered in the conceptual model were included in the simulation, due to either the lack of reliable knowledge and/or the scarcity of thermodynamic data.

Besides the retention mechanisms, other processes that produce attenuation of radionuclide concentration are dilution of the radionuclide-bearing deep groundwater, which applies to all elements, and decay, as we are dealing with radionuclides. The radionuclides that will be more significantly reduced by decay are ^{226}Ra and ^{90}Sr, although it should be noted that ^{226}Ra is a continuing product of the decay of ^{238}U. In this sense, if one considers the possibility that carbonate will be dissolved in a future evolution of the simulated domains, the release into water of the previously retained Sr will not be of significance, whereas for the case of ^{14}C, due to its longer half-life, it could be still present in the system and contribute to increase the radiation dose received.

6.5 Evaluation and concluding remarks

6.5.1 Uncertainties in calculated discharge points

The effects of model scale in the hydrogeological modelling providing the discharge points have been studied by comparing results from site-scale and repository-scale models. This comparison shows that differences can be observed, but these differences are judged not to affect the identification of biosphere objects in the landscape modelling. The same conclusion was reached also when comparing the discharge points calculated in different stochastic realisations and parameter sensitivity cases, see /Joyce et al. 2010/.

In the bedrock hydrogeology modelling reported in /Joyce et al. 2010/ it was noted that discharge points did not vary significantly between different stochastic realisations. However, the sensitivity analysis performed as a part of the modelling suggested that the description of recharge and discharge depends on the flow modelling concept, where the DFN approach results in more localised flow cells and therefore a larger proportion of discharge points closer to the repository. Thus, due to the CPM representation of the region outside the repository area, the discharge locations tend to be dominated by the location of the shoreline. For a DFN or ECPM representation, the discharge locations could have been more influenced by outcropping deformation zones or fractures.

The comparison between discharge points obtained from the ConnectFlow (bedrock) modelling and the MIKE SHE (near-surface) modelling showed that the results are similar in terms of the overall discharge pattern and regarding objects receiving particles, whereas there are some differences in the detailed discharge locations. In the areas of the terrestrialised lakes, the discharge points in the MIKE SHE model tend to be more concentrated along the former shorelines of the lakes, whereas the particles in the ConnectFlow model to larger extent appear in the central parts of the lakes. For the particles going directly to surface streams, the differences between the results from the two models are very small.

6.5.2 Transport conditions in near-surface systems

MIKE SHE simulations with particle releases (particle tracking) or concentration sources (advection-dispersion modelling) at –40 m along flow paths obtained from the ConnectFlow bedrock hydrogeology model showed that transport is directed more or less vertically up to the Quaternary deposits, where horizontal spreading could take place. Discharge locations were concentrated to the surface streams and the terrestrialised lakes. In particular, the particle tracking yielded discharge points along the former lake shorelines, rather than in the central parts of the lakes. One reason for this is probably that the relatively low hydraulic conductivities of the lake sediments make the particles move towards the shorelines instead of through the sediments.

The transport modelling results illustrate the differences between the target area, where horizontal structures (sheet joints) are present in the upper part of the bedrock, and other parts of the future land and lake areas at Forsmark. The sheet joints have a large influence on flow and solute transport from the deeper bedrock and from the surface. They act as drains for water coming both from above and below. Once the solute-bearing water enters a layer with structures of high horizontal conductivity, it is transported horizontally towards the northern part of the model area where discharge could occur.

The results of the advection-dispersion simulations show that solute spreading in some cases leads to relatively large areas with solute in the surface layer, even if the sources are small and relatively close to the surface. In some of the simulation cases, extensive spreading takes place already in the bedrock, whereas others show large differences between contaminated areas in upper rock and regolith. Hence, one interpretation could be that there is no such thing as a typical pattern of near-surface solute spreading. However, solute transport is generally directed towards the remaining part of the surface water system, i.e. the stream network on the surface. Furthermore, it is noted that the notion of a contaminated area is a matter of definition, since different concentration intervals give different impressions of the degree of spreading and the area affected.

Concerning radionuclide retention and reactive transport, the results of conceptual and numerical modelling show that cation exchange and surface complexation on illite are active processes for the retention of several radionuclides (i.e. the isotopes of U, Th, Ni, Cs and Sr). Surface complexation on iron hydroxides is an active process in the till system, which is able to effectively retain U and Ni. Another retention process of importance is the incorporation of the radionuclides into mineral phases, either by the precipitation of pure phases or in solid solutions.

The radionuclides that are most significantly retarded are Th, Ni and Cs, mainly through sorption onto illite. The strong retardation predicted for these elements is in good agreement with reported Kd values for Forsmark till and lake sediments. According to the model results, Cs, Th and Ni are strongly retained, whereas C, U, Sr and Ra are more mobile. The reported Kd values in Forsmark soils and sediments, although not directly comparable to the calculated effective Kd values, show a similar general trend.

The computed behaviour of Se and Nb provides the two exceptions that do not agree with reported Kd values. In this context, it should be recalled that some of the processes included in the conceptual model were not considered in the numerical model, due to lack of reliable knowledge and/or scarcity of thermodynamic data. Finally, it should be noted that radioactive decay has not been taken into account in the reactive transport modelling discussed here. This process would act to reduce concentrations of some radionuclides. In particular, the radionuclides that will be significantly reduced by decay are ^{226}Ra and ^{90}Sr. However, there are also decay chains producing radionuclides of interest for the safety assessment, primarily ^{226}Ra.

7 The landscape model

The landscape model examines the biosphere objects in the landscape through time. This chapter describes how the objects are delimited and how the different geometric properties that constitute the objects are identified. Further, the discharge areas (see Chapter 6) are analysed and used to locate the biosphere objects of interest. Finally, the resulting model is presented showing the biosphere objects in the landscape during an interglacial and the output parameters are described.

7.1 Biosphere objects

A biosphere object is an area in the landscape that potentially, at any time during the considered period, will receive discharge from deep groundwater associated with the repository volume. The object is used to extract data used in the biosphere radionuclide model. The succession in time is described for the biosphere object using the landscape development model described in Chapter 5.

The landscape model is based on three different geometric features or areas; watersheds, basins and sub-catchments. The three areas are partly overlapping, and used for different tasks in the biosphere radionuclide model. The basin is the main feature which most of the output parameters are based upon.

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

The *watershed area* is defined as the portion of the watershed that is land. The watershed area is in Forsmark successively increasing over time. The area is zero until land emerges within the watershed and reaches its maximum when the lake is isolated.

The *basin* is defined as the catchment for an outlet from a lake minus the catchment for the outlet of next upstream lake. If a basin has two or more major streams, the basin is defined as the actual lake catchment minus all upstream lake catchments. The basin area is constant over time and always smaller than the maximum watershed area. Figure 7-2 shows the basin of the hypothetical lake.

The geometric object *sub-catchment* is defined as the catchment of the outlet of a lake minus the catchment of the inlet of the same lake. The sub-catchment is used in the biosphere radionuclide model for calculation of diffuse discharge of water into the lake, i.e. inflow of water not included in the major stream discharge. The sub-catchment area is a constant (only used in the biosphere radionuclide model during the lake phase) and always smaller than the basin area. The sub-catchment to the hypothetical lake is shown in Figure 7-3. The sub-catchment areas are identical to basin areas for basins situated on the water divide and only small differences in area are seen where two linked lakes are situated close to each other, see Figure 7-3.

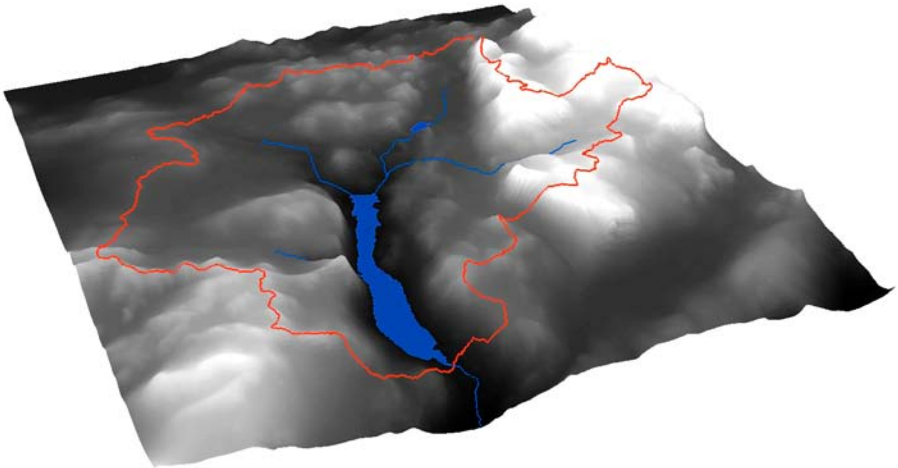


Figure 7-1. The extent of the watershed for a hypothetical lake is illustrated with a red line and the lake in blue. Note that the watershed area, as defined in the present model, does not include the lake itself.

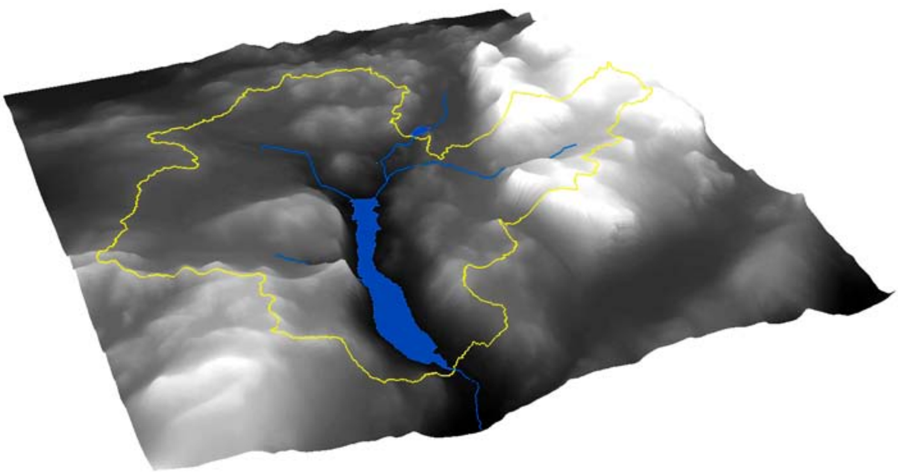


Figure 7-2. The extent of the basin for the hypothetical lake (blue) shown in yellow. The upstream lake is small but the upstream lake catchment delimits the basin.

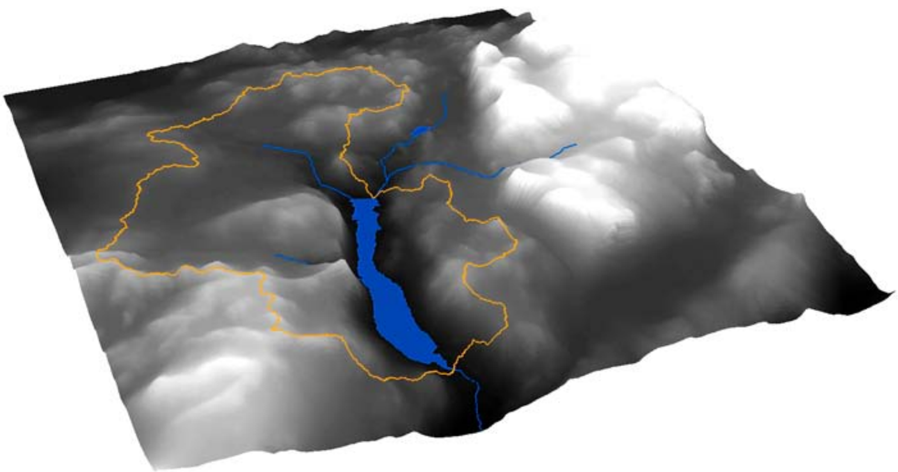


Figure 7-3. The extent of a sub-catchment for a hypothetical lake (blue) is shown in brown. The sub-catchment is the catchment for the outlet of the lake minus the catchment for the inlet of the same lake. The extents of the basin (Figure 7-2) and Sub-catchment are almost the same in this example. Only a small area between outlet from the upstream lake and inlet to the downstream lake is missing in the sub-catchment in this example.

7.2 Methods and input data

7.2.1 Delineating basins

The landscape was divided into basins as described above (Figure 7-4). Each basin holds one single lake (existing or future) and the basins are defined as the catchment of the outlet of the lake minus the catchment of the outlet of the next upstream lake. When the basin is below sea level, the basin equals the extent of the biosphere object during submerged conditions. The extents of the basins are established by mapping the water divides on the part of the landscape that is currently land /Brunberg et al. 2004/ and by modelling with GIS using the DEM for the part that, at present, is situated under the sea /Brydsten 2006/.

Only basins that are of significance for the biosphere radionuclide model are further used in the work describing the landscape model biosphere objects. Figure 7-5 shows the basins linked together by the present and future stream network. The basins can be grouped into two major branches, a northern branch with 6 basins and a southern branch with 25 basins.

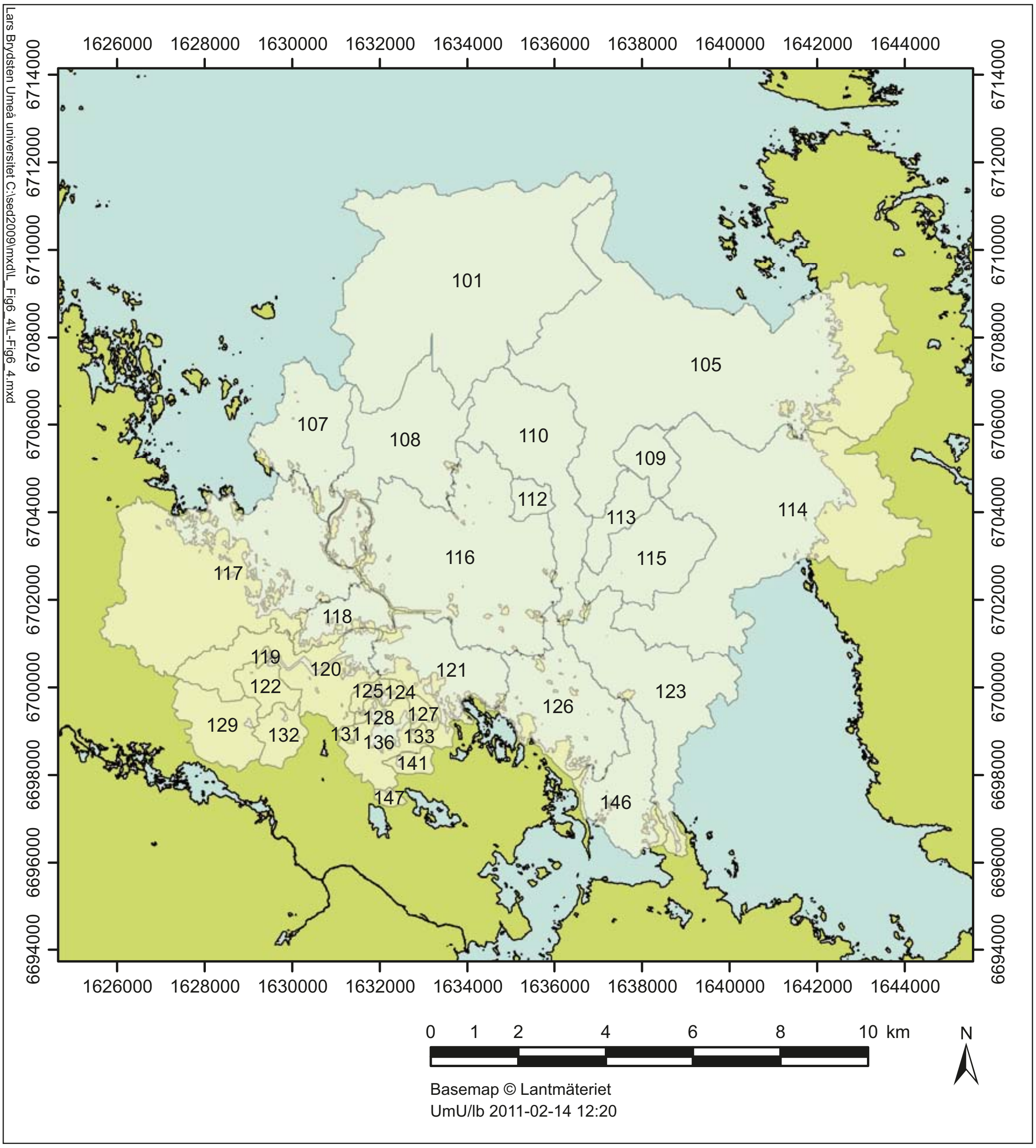


Figure 7-4. Basins identified in /Brunberg et al. 2004/ and /Brydsten 2006/. Present land is displayed in green and basins located on land are displayed in yellow. The identification number used in SR-Site is shown for each basin.

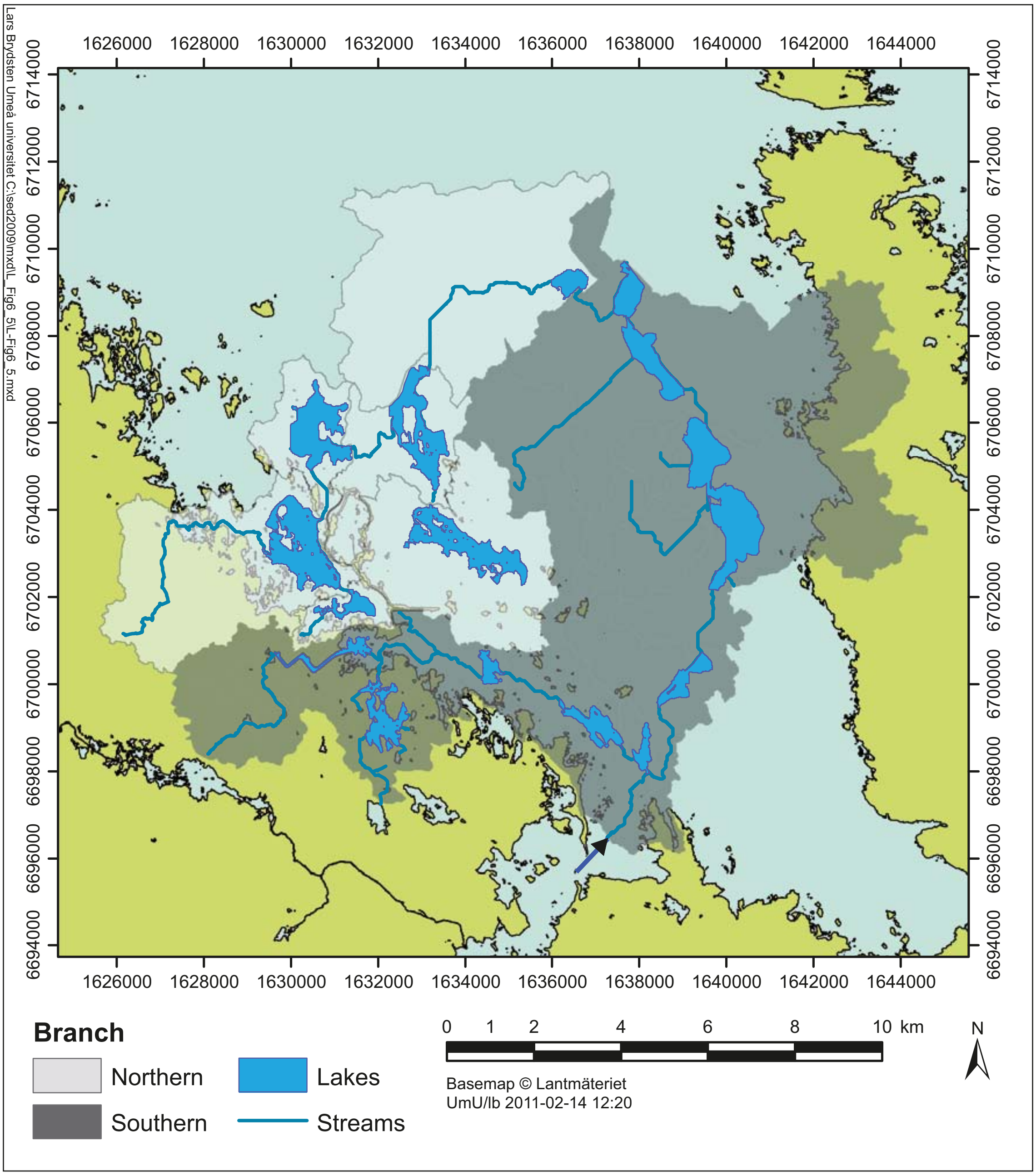


Figure 7-5. *The hydrological network in the landscape model area. The southern branch has a large input of surface water from the combined catchments of Forsmarksån and Olandsån (blue arrow).*

7.2.2 Discharge points

The hydrogeological models are used to simulate the transport of water from each canister through the bedrock and soils up to the land surface (see Chapter 6). The positions where the traces reach the surface are called "discharge points". There are three data sets with discharge points, two covering the whole model area and one for the area close to the repository with presumed high impact on the environment. The different data sets are based on different hydrogeological models. The differences in traces between the models are small.

The modelled discharge points have been used for the selection of basins treated in the landscape model. The data set holds 89,908 records. Many of the traces never reach the surface and many enter the surface when the Forsmark area will be covered by an ice sheet, so these records were deleted from the data set. The numbers of records left after deletion was 20,802. The spatial distribution of the discharge points from the hydrogeological modelling is shown in Figure 7-6.

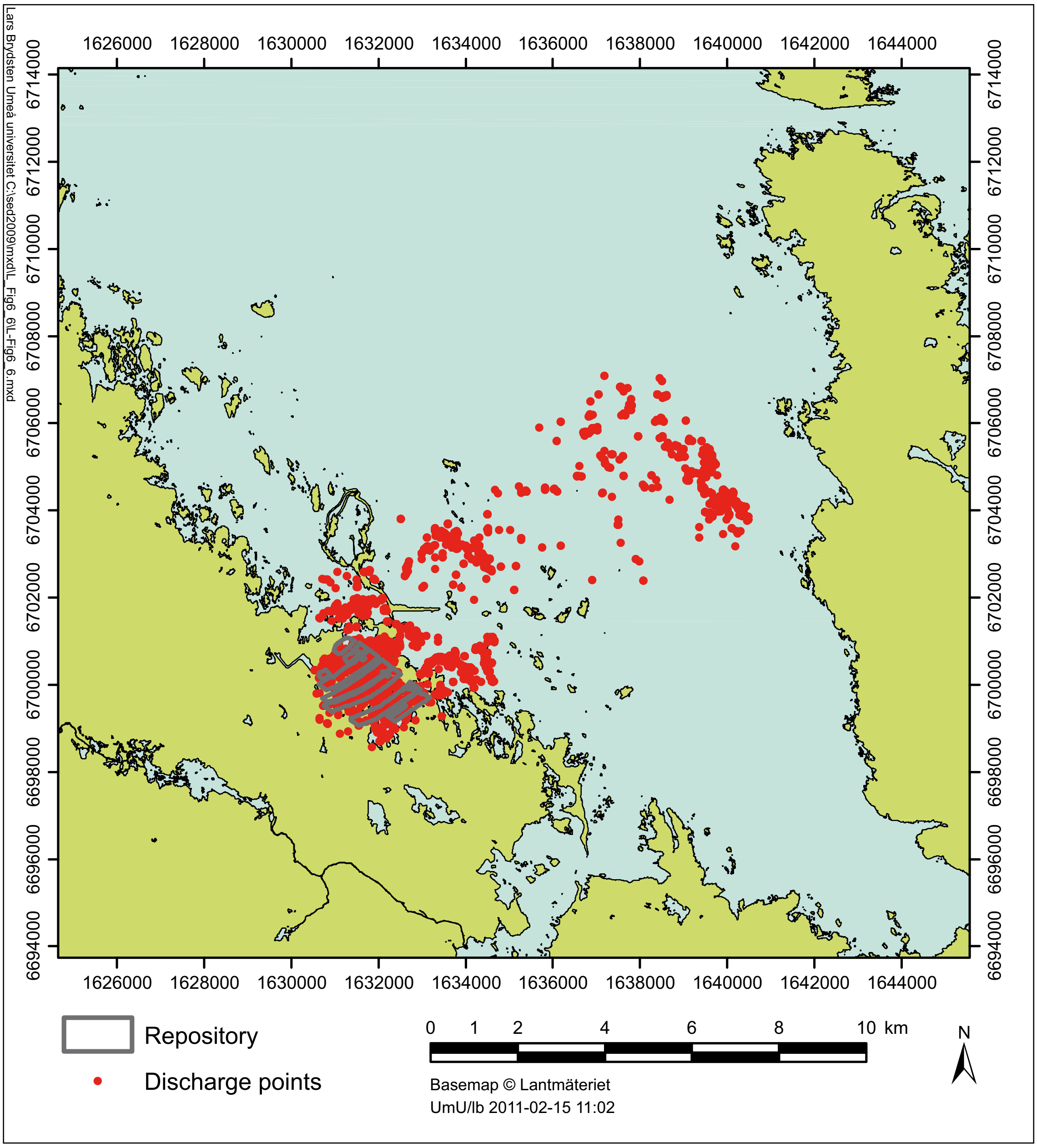


__Figure 7-6.__ Distribution of discharge points from the hydrogeological model. The site for the proposed repository is marked with a grey lines. The shoreline in this figure represents the present day situation and is not valid for the total time frame used for the discharge simulations presented.

The majority of the discharge points are found close to the repository and a minority are displaced in a NE direction, following the shoreline as it moves due to shoreline displacement. The most distant points are displaced approximately 10 km (Figure 7-7). The distribution of travel distances (calculated as the straight-line distance between canister and discharge positions) is bimodal with local extrema at c. 750 and 9,250 m. Travel distances between 5,000 and 8,000 m are few and this is probably an effect of the landscape geometry. Note that more than 500 traces are less than 500 m in travel distance although the vertical distances alone are almost 500 m, so these water particles travel straight up from the repository volume through the bedrock to the surface.

Approximately 42% of the discharge points are in the northern and 58% in the southern branch (all canisters are situated in the southern branch). The distribution of discharge points between basins is shown in Table 7-1.

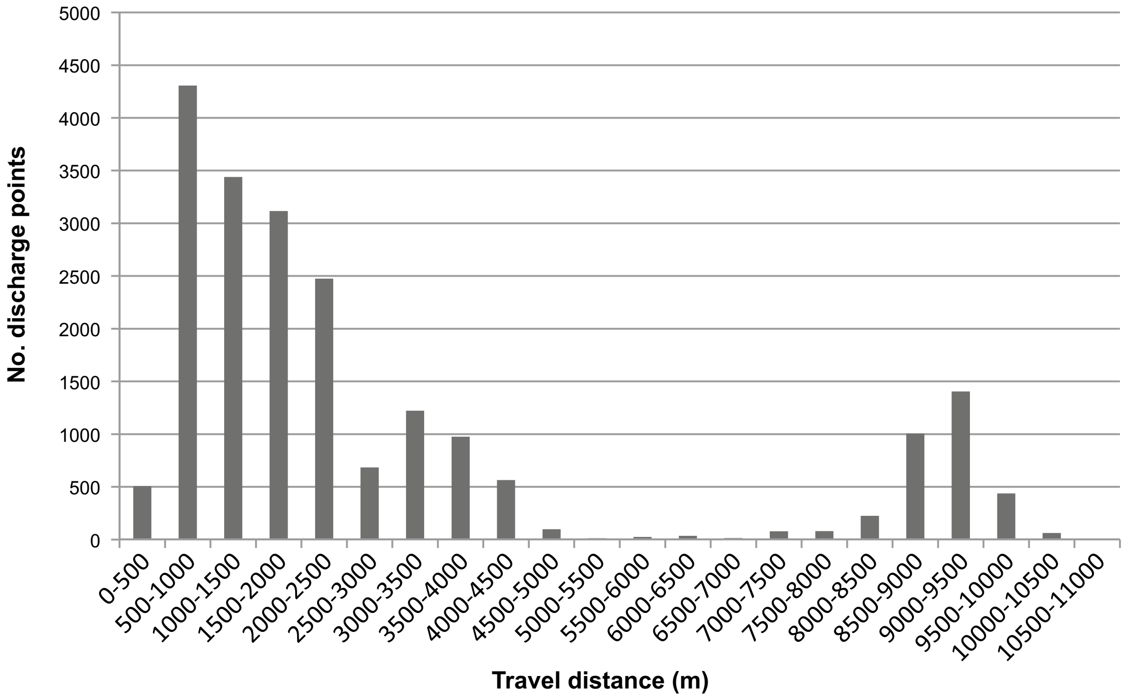


Figure 7-7. *The distribution of distances (in a straight line) between the canister and discharge positions. Two populations exist, a large group close to the repository and a smaller group further away. The time dependency due to changes in the landscape during the travel time is not taken into account.*

Table 7-1. Number of discharge points and discharge density by basin normalised by area.

Basin	No. discharge	No. discharge km^{-2}
101	0	0
105	369	13
107	0	0
108	0	0
109	85	56
110	19	3
112	28	40
113	29	18
114	2,842	150
115	12	3
116	2,940	208
117	14	1
118	5,892	2,939
119	0	0
120	4,511	865
121	3,279	644
122	0	0
123	0	0
124	290	1,189
125	157	449
126	0	0
127	1	3
128	13	182
129	0	0
131	0	0
132	0	0
133	0	0
136	321	143
141	0	0
146	0	0
147	0	0

Five of the basins are associated with 94% of the discharge points (Table 7-1). Two basins (118 and 124) show high values after normalisation by area. As many as 14 basins have no discharge points and 8 basins have less than 100 discharge points. The discharge points are mostly situated at low-points in the landscape (groundwater discharge areas) and more than 70% of the points are in consequence situated in lakes (Table 7-2).

Table 7-2. Number of discharge points in lakes (total number and normalised to area). Lakes with high numbers of discharge points are the inlet canal and Lake 118 situated north of the repository.

		Lake		Basin		
Lake	Basin	No. Discharge	No. Discharge km^{-2}	No. Discharge	No. Discharge km^{-2}	% Lake
Future lake	105	26	19	416	15	6
Future lake	114	2,416	910	2,968	156	81
Future lake	116	2,576	1,608	2,940	208	88
Future lake	117	10	5	14	1	71
Future lake	118	5,509	15,311	5,892	2,939	93
Inlet canal	120	2,430	8,070	4,511	865	54
Future lake	121	1,396	5,858	3,279	644	43
Puttan	124	129	1,559	290	1,189	44
Norra Bassängen	125	26	342	170	449	15
Bolundsfjärden	136	183	299	322	143	57

7.3 Basins in the Forsmark landscape

As mentioned earlier, basins treated in the landscape model are only those significant for the biosphere radionuclide model. By significant we mean areas affected by discharge (primary basins) or areas downstream of affected areas (secondary basins). Basins not receiving any discharge and located upstream of primary basins (tertiary basins) are merged into the primary basins (Figure 7-8). Basins 127, 131, 133, 141 and 142 are merged into basin 136 and basins 119, 122, 129 and 132 are merged into basin 120 and finally basin 128 is merged into basin 125.

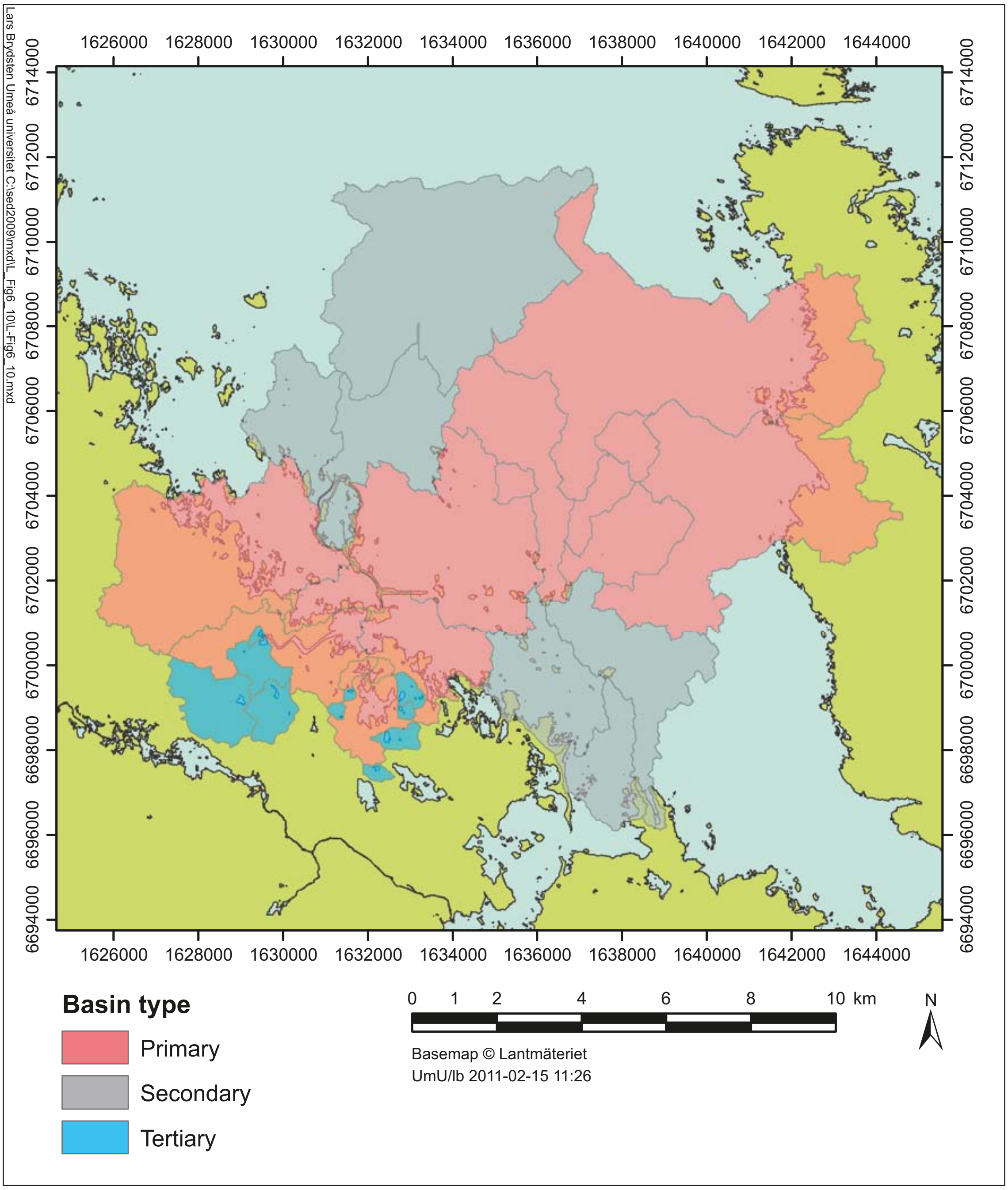


Figure 7-8. The types of basins used to build the landscape model. Primary basins receive discharge, secondary basins are located downstream of a primary basin and tertiary basins are not affected by discharge and are found upstream of primary basins.

Small primary basins with few discharge points are also merged with adjacent downstream primary basins in order to simplify the landscape model. Basins 109, 113 and 115 are merged into basin 114 and basins 110 and 112 are merged into basin 105. These small primary basins are all situated east of basin 116.

In some basins there are discharge points that appear to discharge close to streams. This is particularly distinct in Basin 121 (Figure 7-9). In order to have one well-defined example of stream object in the landscape model, basin 121 was split into three sub-basins. The split was made at the stream outlets from two small wetlands in the central part of the basin (yellow dots in Figure 7-9). The new divided basins are named 121_1 (the most downstream basin with the lake), 121_2 (northern basin with the Forsmark harbour) and 121_3 (the basin that links to the inlet canal).

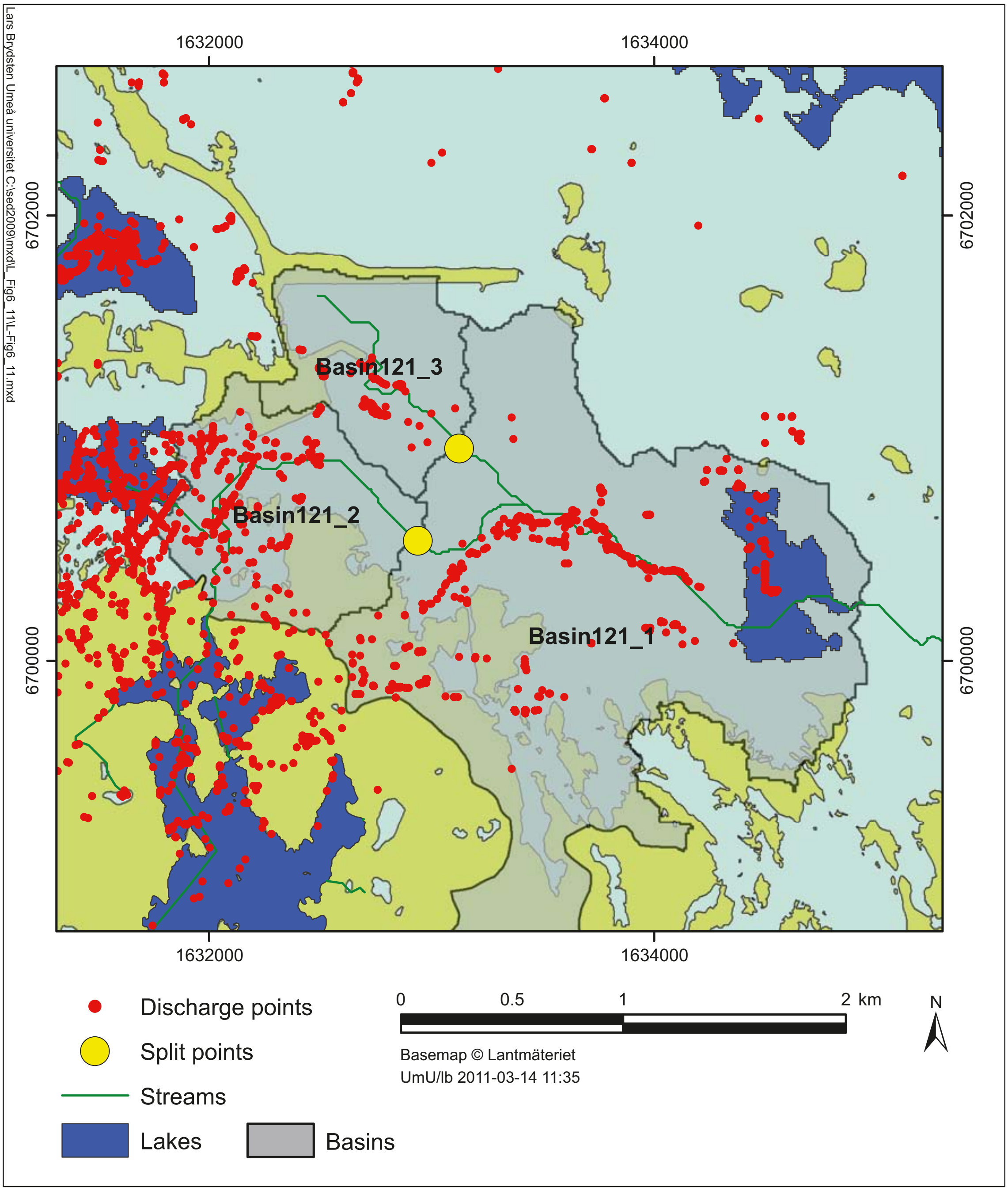


Figure 7-9. *The present-day conditions in the sea area north-east of Lake Bolundsfjärden with discharge points displayed. Note that the displayed discharge points apply at different times and the discharge areas do not correspond to the present-day situation. Many of the discharge points are situated close to streams. In order to show the effects of having a stream object and a small object upstream close to the water divide, basin 121 was split into three sub-basins. The split was performed at the outlets of two small future wetlands (yellow dots).*

After the merging and splitting procedures described above there are 18 basins left, see Figure 7-10. A more detailed illustration of Basin 121 and the sub basins is shown in Figure 7-11. When displaying the simulated discharge points from the hydrogeological model on the developing landscape, a pattern in space and time is seen (Figure 7-12). The discharge points cluster in the landscape in typical areas such as lakes, wetlands, streams and by the sea shore. By using these clusters as evidence for a discharge area, the biosphere objects are identified. During the landscape succession these areas are represented by different ecosystems. This is further described in Section 7.5 below.

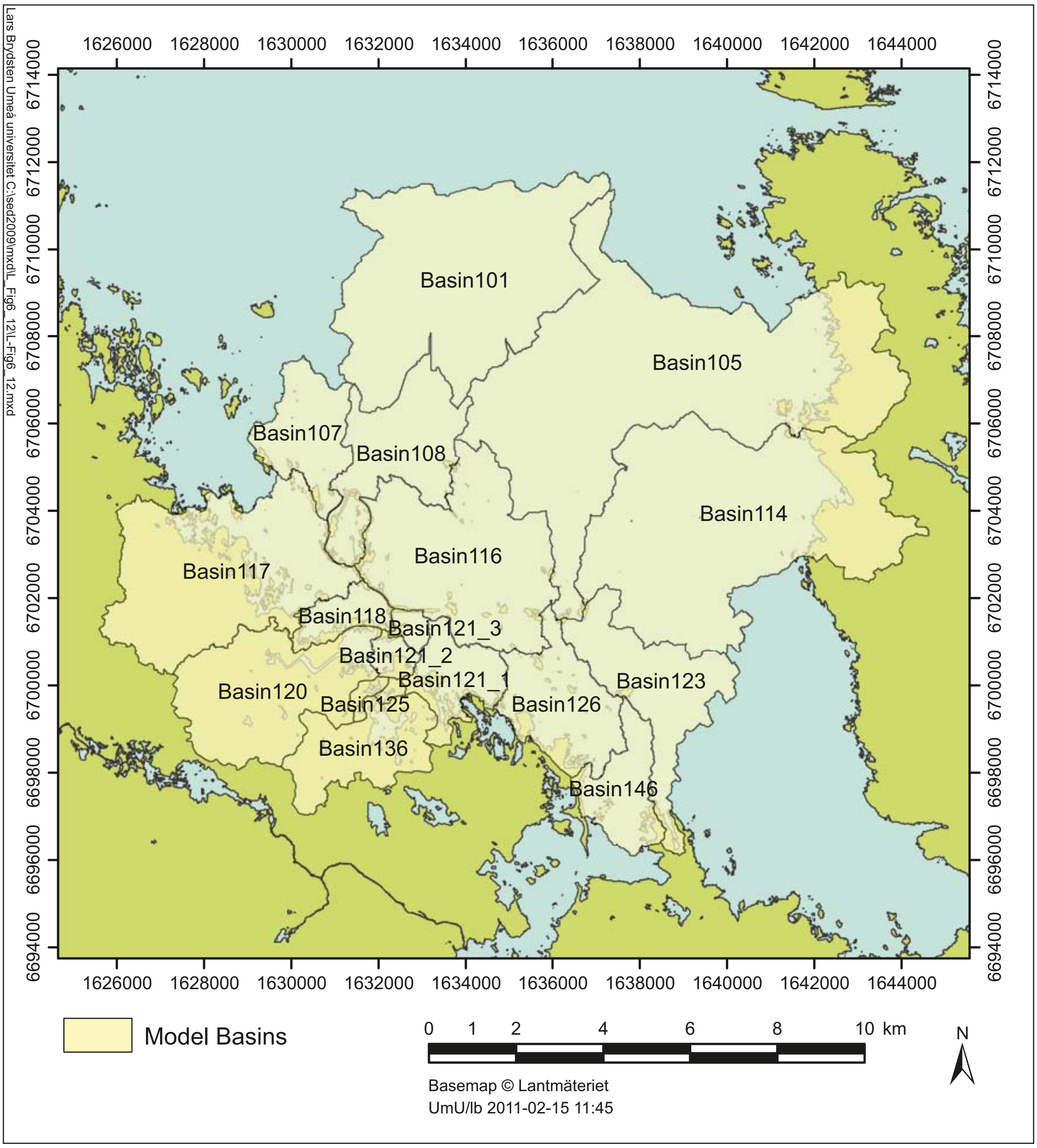


Figure 7-10. *The location and extent of basins after the splitting and merging procedure.*

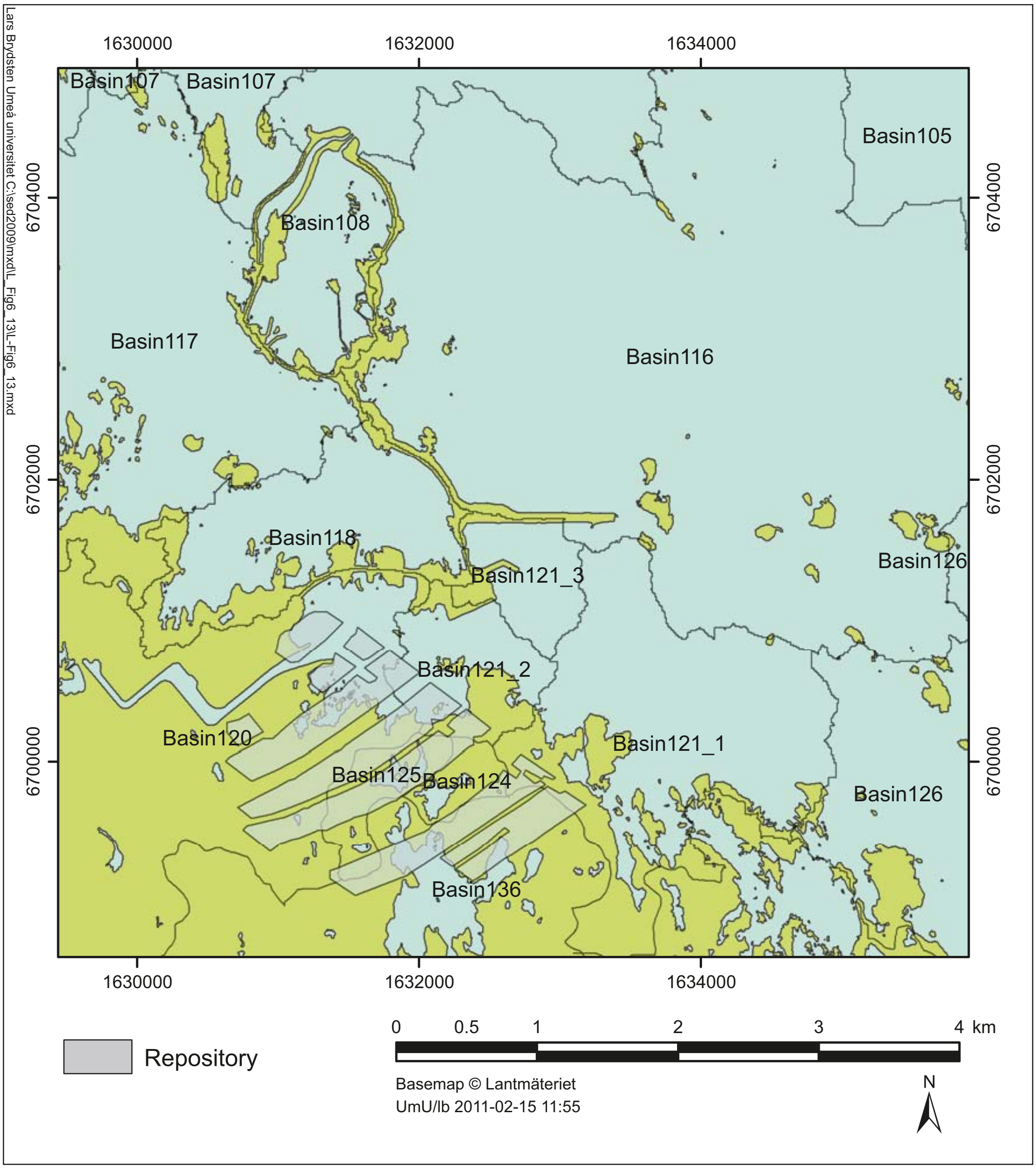


***Figure 7-11.** An enlarged map of the basins situated close to the proposed repository (grey).*

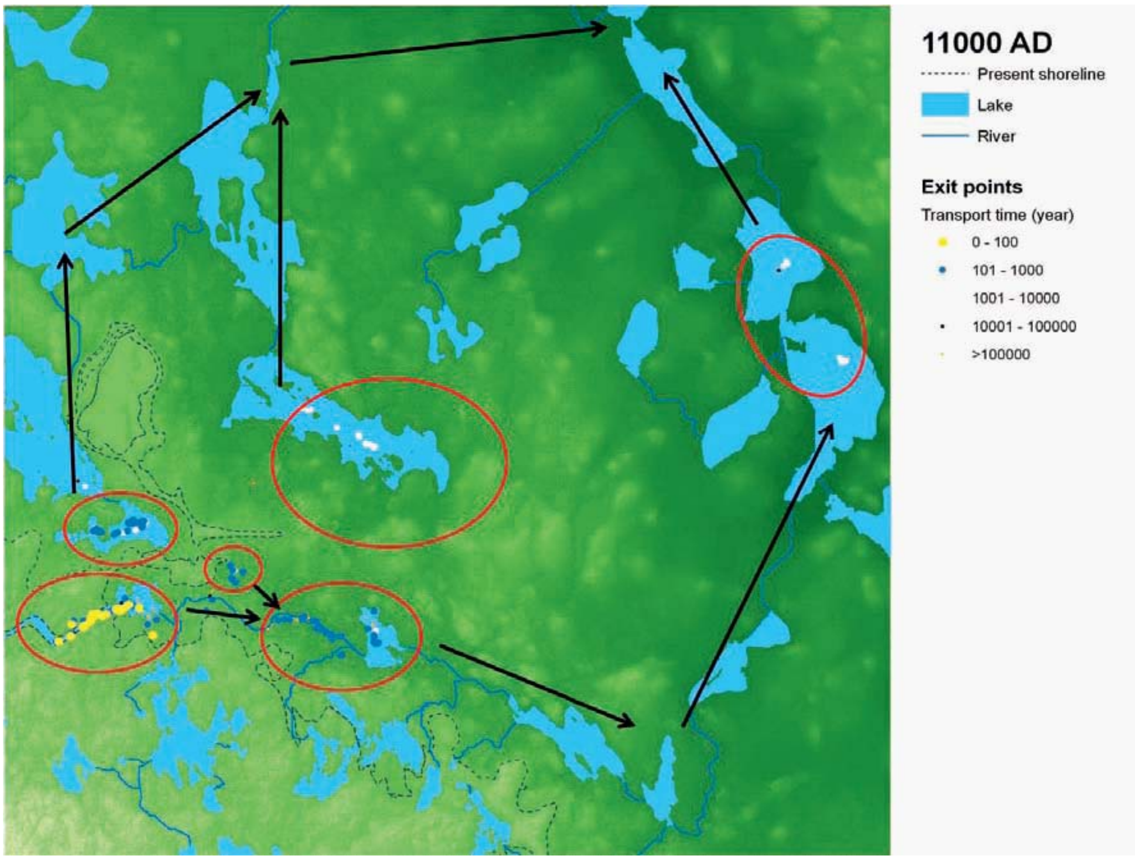


***Figure 7-12.** Illustration of the identification of biosphere objects. The discharge points are displayed on the landscape development model (here shown without sediment dynamics, lake infilling and vegetation type/land-use) for a specific time step (here: 11,000 AD). The discharge clusters are encircled in red where the biosphere objects were identified and the black arrows indicate the surface water flow paths.*

7.4 Lakes and lake isolation processes

Due to the positive shoreline displacement, the local depressions in the landscape are transformed into lakes when the depression thresholds are lifted up above the sea surface levels. Lake isolation is a gradual process because of transient sea level changes. The tide in the Baltic Sea is only a few centimetres so the transient sea level variation is mainly caused by wind and air pressure variations. High sea levels in the Forsmark area are associated with strong and persistent wind from the north in combination with low air pressure.

The sea level at Forsmark is monitored at several places but data from Björns Lighthouse, situated close to the northern model area border, is judged to best represent the whole model area. Based on sea levels measured at Björns Lighthouse (unpublished data) and the present shoreline displacement rate (0.644 mm y^{-1}) a lake isolation period will be c. 430 years, i.e. from the first time the lake is isolated from the sea at extreme low sea level until the last time when brackish water is flowing in to the lake at extreme high sea level.

Assuming that these extreme sea levels are constant over time, it is possible to use the shoreline displacement equation to calculate the isolation period for each lake (current and future). However, the weather extremes (e.g. wind speeds and air pressure) have not been constant over time. Presumably the extremes have been larger in the past (at least soon after deglaciation) and will be more extreme in the future (due to global climate change), so the lengths of the calculated isolation periods (Table 7-3) are probably underestimated. Since the shoreline displacement rate in the Forsmark area is continuously decreasing in time, the lake isolation durations are shorter for lakes isolated early during an interglacial.

Table 7-3. Summary of significant dates for lakes treated in the landscape model. The start parameter is the time the lake is isolated from the sea, the isolation parameter is the time when the lake threshold is at the mean sea level and the stop parameter is the last time when brackish water is flowing into the lake. The Ter-parameters are dates for successive infill values where Ter 100% is the date for a fully developed wetland.

Basin	Lake	Start (AD)	Isolation (AD)	Stop (AD)	Ter 50%	Ter 75%	Ter 90%	Ter 100%
101	Future lake	7480	8020	8380	–	–	–	8,380
105	Future lake	10,450	11,160	11,630	12,700	15,400	18,700	36,000
107	Future lake	3160	3500	3730	3,500	5,250	6,300	9,300
108	Future lake	4610	5010	5280	5,200	7,300	9,400	13,400
109	Future lake	6630	6940	7450	7,000	9,000	11,600	17,100
110	Future lake	5660	5490	6400	5,500	6,900	7,700	8,300
112	Future lake	4080	4330	4710	–	5,200	5,800	6,200
113	Future lake	5180	5450	5880	–	6,450	7,100	10,500
114	Future lake	7980	8550	8920	13,300	17,100	20,100	34,300
115	Future lake	6300	6600	7090	7,300	8,950	11,600	16,900
116	Future lake	4390	4780	5040	4,900	6,650	7,700	8,500
117	Future lake	2680	3000	3210	3,600	5,500	6,650	8,900
118	Future lake	2530	2850	3060	–	4,000	4,700	5,200
120	Future lake	2210	2410	2720	–	4,000	6,600	15,100
121	Future lake	3770	4000	4380	–	4,600	5,200	5,600
124	Puttan	1600	1890	2080	–	2,100	2,350	2,600
125	Norra Bassängen	1620	1900	2090	–	2,100	2,350	2,600
126	Future lake	4010	4380	4630	–	5,500	6,300	6,900
129	Gunnarsboträsket	860	1020	1290	–	1,100	1,400	1,600
134	Future lake	2010	2200	2510	2,300	3,700	4,900	8,700
136	Bolundsfjärden	1610	1900	2090	–	3,350	4,200	4,800
142	Gällsboträsket	1480	1660	1950	–	2,300	2,800	3,200
144	Bredviken	1710	1890	2190	–	2,200	2,500	3,300
148	Fiskarfjärden	1690	1870	2170	2,000	3,500	4,500	9,300
149	Eckarfjärden	930	1100	1370	–	3,500	5,200	7,400
150	Future lake	3230	3450	3800	–	5,100	7,200	11,000

Only one lake in each basin is treated in the landscape model. For merged basins this is the most downstream lake. The extents of existing lakes have been mapped in the field by GPS /Brunberg et al. 2004/. The extents of future lakes have been modelled with GIS using the DEM /Brydsten 2006/. The lakes treated in the landscape model and additional lakes only used in the land-use maps are shown in Figure 7-13.

All existing lakes are, and most of the future lakes will be, shallow. Only the inlet canal and two future lakes in the vicinity of the island of Gräsö are deeper than 10 metres. The physical characteristics of the lakes and basins included in the landscape model are shown in Table 7-4 and Table 7-5, respectively.

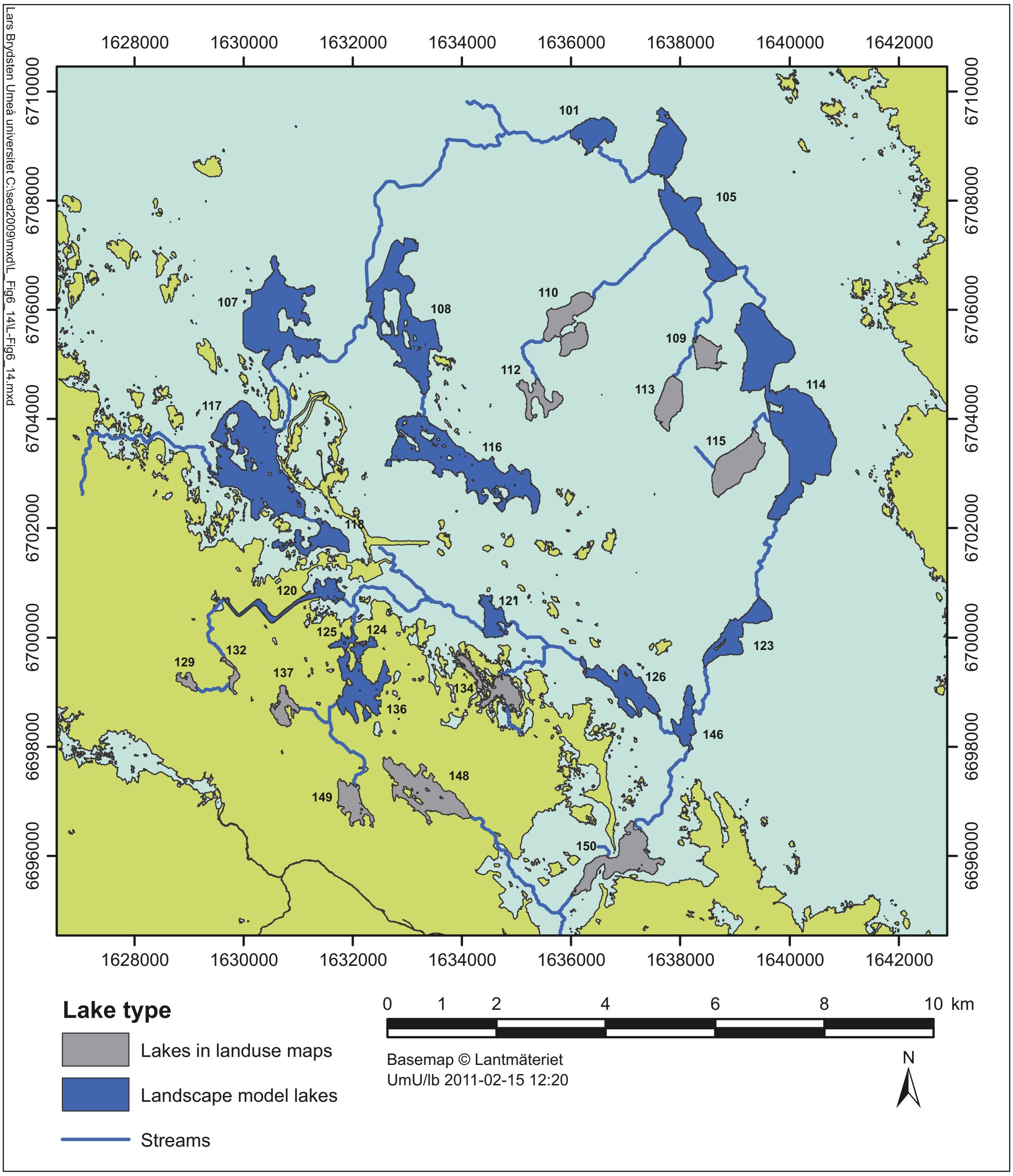


***Figure 7-13.** Lakes used in the landscape model (blue) and additional lakes (gray) that are only used in the land-use models.*

Table 7-4. Physical characteristics of lakes used in the landscape model.

Basin	Lake	Mean depth (m)	Max depth (m)	Area (m²)	Volume (m³)	Altitude (m)
101	Future lake	0.65	1.39	336,800	218,920	–25.80
105	Future lake	6.21	24.50	1,359,700	8,443,737	–34.27
107	Future lake	1.83	5.03	1,431,600	2,619,828	–8.16
108	Future lake	1.70	5.57	1,422,074	2,417,526	–15.00
114	Future lake	6.10	17.78	2,655,500	16,198,550	–27.40
116	Future lake	1.37	4.79	1,601,900	2,194,603	–14.04
117	Future lake	1.84	4.55	1,866,600	3,434,544	–5.64
118	Future lake	1.12	3.12	359,800	402,976	–4.86
120	Inlet channel	2.01	10.19	301,100	605,211	–2.49
121	Future lake	0.66	2.22	238,300	157,278	–10.59
123	Future lake	0.69	2.38	465,500	321,195	–20.69
124	Puttan	0.37	1.29	82,741	30,614	0.48
125	Norra Bassängen	0.31	0.88	76,070	23,582	0.40
126	Future lake	1.51	4.13	560,200	845,902	–12.28
136	Bolundsfjärden	0.61	1.81	611,311	372,900	0.42
146	Future lake	0.83	2.30	241,400	200,362	–13.89

Table 7-5. Characteristic for the basins used in the landscape model. The *Lake %*-parameter is calculated as the lake area divided by the basin area. The *First land* parameter is the first time for the basin to include land and the *Last Sea* parameter is the latest time for an sea area to exist within the basin.

Basin	Area (m²)	Lake %	Min Alt. (m)	Average Alt. (m)	Max Alt. (m)	First Land (AD)	Last Sea (AD)
101	21,808,500	1.54	–27.21	–16.14	–0.16	1997	8015
105	35,580,100	3.82	–58.79	–13.27	19.00	798	11,156
107	4,838,200	29.59	–13.24	–6.68	8.17	669	3497
108	7,582,800	18.75	–20.61	–10.09	7.51	767	5011
114	26,318,500	10.09	–45.24	–13.26	22.18	–1185	8545
116	14,103,000	11.36	–18.92	–9.11	7.57	757	4783
117	16,124,000	11.58	–10.01	4.24	23.55	–1347	2997
118	2,004,700	17.95	–8.00	–1.71	10.81	287	2848
120	10,334,708	2.91	–12.26	7.18	26.85	–1725	2409
121_1	3,560,331	6.69	–12.77	–4.23	9.42	486	4007
121_2	892,256	0.00	–4.95	–0.83	6.78	876	2865
121_3	637,500	0.00	–8.76	–2.98	7.52	765	3620
123	7,713,300	6.04	–23.13	–12.75	11.00	261	6482
124	243,809	33.94	–0.80	2.27	8.82	574	1888
125	421,424	18.05	–0.42	2.41	8.01	693	1902
126	6,250,610	8.96	–16.42	–6.34	9.48	477	4379
136	3,594,878	17.01	–1.34	2.98	12.49	53	1898
146	3,821,804	6.32	–16.18	–6.59	11.04	255	4748

7.5 Temporal development of biosphere objects

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

Since each biosphere object is associated with the local topography of a sea or lake basin, the physical boundaries of the object reflect the geometry of the bedrock and the overlying till and glacial sediments, which change marginally during an interglacial. In contrast, the properties of the biosphere objects change continuously, e.g. due to shoreline displacement, wave erosion and sedimentation, lake infilling and ecosystem succession. When the glacial ice sheet has disappeared, all biosphere objects will typically go through a similar succession, from being part of the open sea, over a sea bay phase, to a lake, which eventually will transform into a wetland. The associated work flow for describing the development of a biosphere object is illustrated in Figure 7-14.

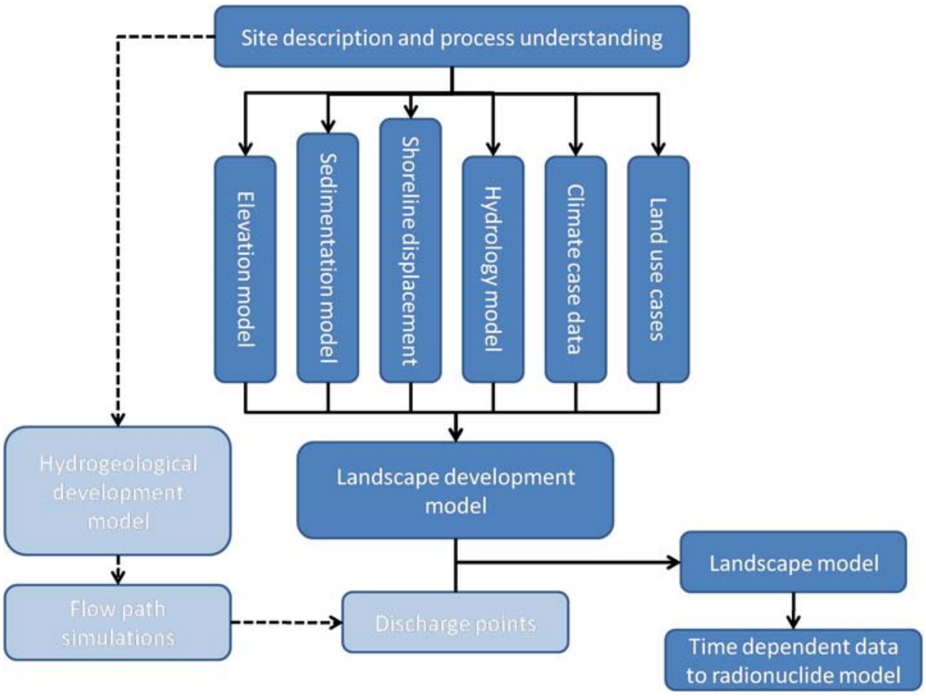


Figure 7-14. *Flow chart of activities and inputs to obtain the biosphere object characteristics. The starting point is the description of present-day and historical conditions from the site description. Data from the site description together with process understanding provide the starting point for producing models describing the site development for a number of disciplines. All the combined models are then merged together into a landscape development model. By using the discharge information from the hydrogeological modelling, the biosphere objects are identified. The landscape model is constructed by extracting information from the areas identified as biosphere objects from the landscape development model. Light blue colours indicate activities not performed within the biosphere modelling in SR-Site.*

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

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

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

At the start of an interglacial, all objects are submerged by approximately 180 metres of water. This landscape is described as a submerged landscape, and all objects interact with their neighbouring objects. As the shoreline displacement proceeds, the objects gradually emerge above the sea and become lakes and wetlands. At this stage, the dominating interactions start to go one way, slowly turning into a terrestrial surface flow system where the chain of objects is linked in a one way direction from the most upstream object and down to the final outlet to the Baltic Sea. Figure 7-15 shows the landscape model displayed on the landscape development model at three different times during the modelled time period.

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

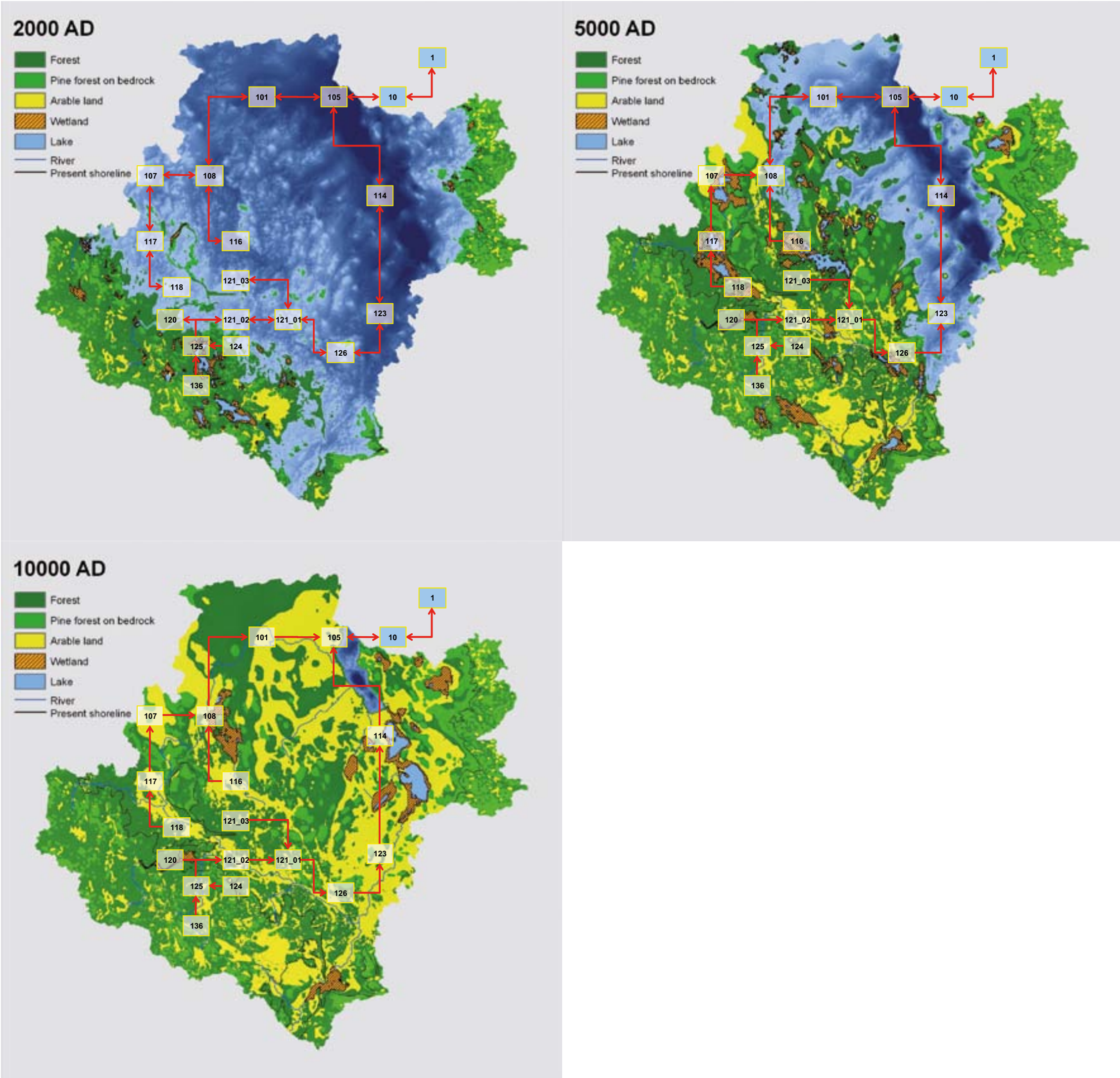


Figure 7-15. *The landscape model displayed on the landscape development model at three different time steps (2000, 5000 and 10,000 AD). The boxes show biosphere objects (with id numbers) at their approximate locations in the landscape and red arrows indicate the surface water flow paths connecting the objects. The blue boxes represent the combined objects of Öregrundsgrepen (object 10), see text, and the model area outlet, the Baltic Sea (object 1).*

7.6 The landscape model during the reference glacial cycle

As described in Chapter 4 and Chapter 5 the landscape will change dramatically during the time period of a glacial cycle. This does not necessary mean that the configuration of biosphere objects will alter. The landscape modelling describes how the biosphere objects undergo a succession from sea stage, via lake/wetland to a terrestrial stage during non-glacial conditions. This is a development that may take between 8,000 and 20,000 years depending on where in the landscape the object is located. The landscape model comprises mainly terrestrial ecosystems when the first period of periglacial domain starts at Forsmark (Figure 7-16).

At that time, only one or two objects are still in the lake phase and no objects represent the sea. The submerged landscape is used to describe the glacial climate domain (Figure 7-16). This is due to the possibility of having a situation where a human population is using the marine landscape for food gathering when the ice edge is close to the site. This situation will only be possible in submerged conditions during ice cap retreat. There is no other relevant landscape configuration under glacial conditions due to the absence of inhabitants.

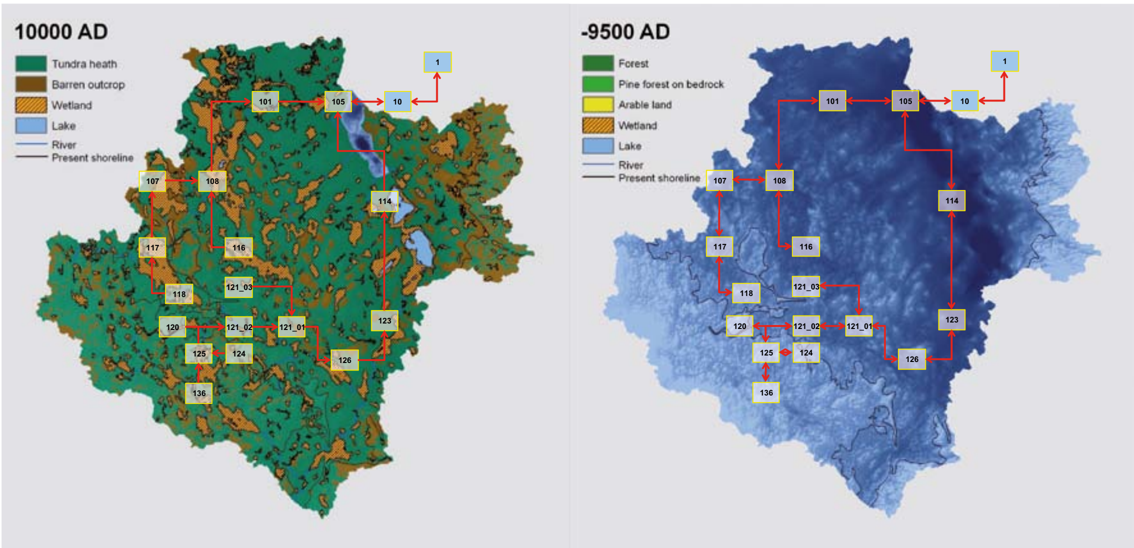


Figure 7-16. Figure illustrating the landscape model under periglacial (left) and submerged (right) conditions. The boxes show biosphere objects (with id numbers) at their approximate locations in the landscape, and red arrows indicate the surface water flow paths connecting the objects. The blue boxes represent Öregrundsgrepen (object 10) and the model area outlet, the Baltic Sea (object 1).

7.7 Parameterisation of biosphere objects

The landscape development model is used to describe properties of the biosphere objects over time during the interglacial period. By following the succession for each biosphere object on the landscape development model, a large amount of data is extracted, which is described in Section 7.7.1. This data has been used to set values to the parameters in Table 7-6 that are used in the biosphere radionuclide model /Avila et al. 2010/. These parameters are described in more detail in Sections 7.7.2–7.7.4.

Table 7-6. Parameters in the biosphere radionuclide model for which parameterisation is made with data from the landscape development model (dw stands for dry weight).

Parameter name	Description	Unit	Source file
Aqu_area_obj	Water area in the lake basin.	m^2	Parameters_TS_all_basins.xls
area_subcatch	Area of the subcatchment.	m^2	ParametersSS.xls
area_wshed	Watershed area.	m^2	Parameters_TS_all_basins.xls
depth_aver	Average water depth.	m	Parameters_TS_all_basins.xls
depth_max	Maximum water depth.	m	Parameters_TS_all_basins.xls
growth_rego	Average accumulation rate of sediment calculated for lake and marine bottoms.	m/year	Parameters_TS_all_basins.xls
res_rate	Resuspension rate.	kg dw/(m^2year)	ParametersTS.xls
sed_rate	Sedimentation rate.	kg dw/(m^2year)	ParametersTS.xls
Ter_area_obj	Area with peat in the lake basin.	m^2	Parameters_TS_all_basins.xls
threshold_agriculture	Point in time when wetland is 2 m above sea level.	year	ParametersSS.xls
threshold_end	Point in time when ingrowth of wetland stops.	year	ParametersSS.xls
threshold_start	Point in time when lake isolation starts.	year	ParametersSS.xls
threshold_stop	Point in time when lake isolation is completed.	year	ParametersSS.xls
Aqu_z_rego_pg	Depth of aquatic postglacial sediments under sea, lake or stream	m	Parameters_TS_all_basins.xls
Aqu_z_regoMid_gl_lake	Average depth of glacial deposits in lake.	m	ParametersSS.xls
Lake_z_regoLow	Depth of the lower regolith (till) in the lake/terrestrial stage.	m	ParametersSS.xls
Sea_z_regoLow	Average depth of glacial till in sea basin	m	ParametersSS.xls
Ter_growth_rego	Growth of wetland relative to water area.	m^2/(m^2year)	Parameters_TS_all_basins.xls
Ter_z_regoMid_pg	Depth of the post glacial clay in terrestrial middle regolith layer (covered by peat).	m	Parameters_TS_all_basins.xls
Ter_z_regoUp	Depth of the terrestrial upper regolith layer (peat).	m	Parameters_TS_all_basins.xls
z_regoMid_gl_basin	Depth of the glacial clay of the aquatic middle layer in the sea basin.	m	ParametersSS.xls

7.7.1 Data extracted from the landscape development model

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

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

For each time step (500 years) the marine module generates the following maps in raster format (20 m):

(i) thickness of postglacial fine-graded sediments (clay or silt),

(ii) a DEM,

(iii) a Quaternary surface geology map.

The lake module generates for each lake a text-file with the following parameters in 100 year steps (the parameter names used in the biosphere radionuclide model are within brackets):

(iv) time step (Time)

(v) area of photic zone (area_photic) (m^2)

(vi) area of accumulation bottom (area_accBot) (m^2)

(vii) area of transport bottom (area_tranBot) (m^2)

(viii) area of erosion bottom (area_eroBot) (m^2)

(ix) water area (Aqu_area_obj) (m^2)

(x) water volume (Aqu_vol_obj) (m^3)

(xi) peat covered area (Ter_area_obj) (m^2)

(xii) peat volume (Ter_vol_obj) (m^3)

(xiii) sediment volume (vol_sed) (m^3)

(xiv) average water depth (depth_aver) (m)

(xv) maximum water depth (depth_max) (m)

(xvi) average sediment thickness (z_rego_aver_obj) (m)

(xvii) maximum sediment thickness (z_rego_max_obj) (m)

(xviii) average mineral soil thickness beneath peat layer (Ter_z_regoMid) (m)

(xix) mineral soil volume beneath peat layer (Ter_vol_regoMid) (m)

In addition, the lake module generates raster maps for each 500 year time step with the following contents:

(xx) a DEM,

(xxi) thickness of peat,

(xxii) thickness of postglacial mineral soils,

(xxiii) peat area and open water surface.

For some variables the results from the marine and lake modules are merged to build continuous raster maps:

(1) the DEM:s (ii and xx) gives a continuous temporal DEM:s representing land, lake bottoms and sea bottoms,

(2) mineral soil thickness results (i and xxii) gives temporal Z4a-layers to the regolith depth model,

(3) the marine QD map (iii) and the lake land use map (xxiii) give a complete QD map (this is later refined with wetland not emanated from infilled lakes).

Values in the continuous raster maps generated by the marine module must be discretisised to single parameters (min-, max-, average values etc.) for each basin. This is performed in GIS using a polygon layer with basins and different raster layers as input and the function “Zonal statistics”. The parameters are calculated for each time step and are listed in Table 7-7.

Table 7-7. Parameters calculated with GIS "Zonal statistics" using a polygon layer with basins and raster layers for digital elevation model (DEM), post-glacial sediment thickness (PGS) and sea bottom type (erosion, transport or accumulation, ETA) from /Brydsten 2009/.

Parameter	GIS-layer	Unit	Comment
Area_photic	DEM	m^2	Area shallower than 20 m in the sea and shallower than 4.3 m in lakes
Area_accBot	ETA	m^2	Area accumulation bottom
Area_tranBot	ETA	m^2	Area transport bottom
Area_eroBot	ETA	m^2	Area erosion bottom
Aqu_area_obj	DEM	m^2	Sea/lake water area
Aqu_vol_obj	DEM	m^3	Sea/lake water volume
Vol_sed	PGS	m^3	Volume of post-glacial sediments
Depth_aver	DEM	m	Average sea/lake water depth
Depth_max	DEM	m	Maximum sea/lake water depth
Z_regoav_obj	PGS	m	Average post-glacial sediment thickness calculated for the wet basin area
Z_regomax_obj	PGS	m	Maximum post-glacial sediment thickness
Z_accBot	PGS	m	Average post-glacial sediment thickness on accumulation bottoms

Parameters generated by both the marine module and the lake module are merged and build one single column in a common database. Unique parameters for either the marine module or the lake module are filled up with zero-values for the phase of no interest. The records in the database are the time steps.

7.7.2 Parameters describing regolith thickness

Sea_z_regoLow (m)

This parameter represents the total depth of the glacial till in the marine basin. The depth and distribution of this layer is constant over time, covering the bedrock surface from the deglaciation onwards. The depth of this layer is based on the RDM /Hedenström et al. 2008/. The parameter (z_regolow) values presented are mean for each marine basin, prior to isolation (Table 7-8). Minimum and maximum values represent the minimum and maximum of the mean thickness in the identified marine basins and a uniform distribution is assumed.

Table 7-8. Mean, minimum and maximum depth (m) of the lower regolith (z_regolow) below the identified biosphere objects when they are in the sea stage. Minimum and maximum values represent the minimum and maximum of the mean thickness in the identified basins.

Biosphere object	mean	minimum	maximum
10	3.62	2.39	6.50
101	3.62	2.39	6.50
105	4.59	2.39	6.50
107	3.62	2.39	6.50
108	4.27	2.39	6.50
114	4.68	2.39	6.50
116	3.91	2.39	6.50
117	2.89	2.39	6.50
118	3.26	2.39	6.50
120	2.39	2.39	6.50
121_01	4.53	2.39	6.50
121_02	3.21	2.39	6.50
121_03	5.78	2.39	6.50
123	6.50	2.39	6.50
124	2.67	2.39	6.50
125	3.12	2.39	6.50
126	5.32	2.39	6.50
136	2.39	2.39	6.50

Lake_z_regoLow (m)

This parameter represents the total depth of the glacial till in the lake basin. The depth and distribution of this layer are constant over time, covering the bedrock surface from the deglaciation onwards. The depth of this layer is based on the RDM /Hedenström et al. 2008/. Mean values for the lake basin after isolation are used in the model. Mean, minimum and maximum values of the depth of the glacial till are presented in Table 7-9. Minimum and maximum values represent the minimum and maximum of the mean thickness in identified lake basins and a uniform distribution is assumed.

Table 7-9. Mean, minimum and maximum depth (m) of the till layer (z_regolow) below the identified biosphere objects when they are in the lake/terrestrial stage. Minimum and maximum values represent the minimum and maximum of the mean thickness in identified lake basins. * The biosphere objects 121_02 and 121_03 do not have a lake stage and the till layers are assumed to be similar to the till layers of the sea basins.

Biosphere object	mean	minimum	maximum
10	Does not reach a lake stage		
101	4.78	2.57	9.45
105	5.09	2.57	9.45
107	4.78	2.57	9.45
108	5.09	2.57	9.45
114	5.12	2.57	9.45
116	4.00	2.57	9.45
117	3.53	2.57	9.45
118	3.29	2.57	9.45
120	2.57	2.57	9.45
121_01	7.73	2.57	9.45
121_02*	4.53	2.39	6.50
121_03*	3.21	2.39	6.50
123	7.06	2.57	9.45
124	2.99	2.57	9.45
125	3.16	2.57	9.45
126	9.45	2.57	9.45
136	3.01	2.57	9.45

z_regoMid_gl_basin (m)

The parameter value represents the depth of glacial clay in the marine basin. The depth and distribution of this layer is regarded as constant over time, covering the till and bedrock surface from the deglaciation onwards. The depth of this layer is specific for each object, based on the RDM /Hedenström et al. 2008/. The values presented in Table 7-10 are means for each marine basin prior to isolation. Minimum and maximum values represent the minimum and maximum of he mean thickness in the identified marine basins and a uniform distribution is assumed.

Table 7-10. Mean, minimum and maximum depth (m) of the glacial clay (z_regoMid_gl_basin) below the identified biosphere objects when they are in the sea stage. Minimum and maximum values represent the minimum and maximum of the mean thickness in the identified marine basins.

Biosphere object	mean	minimum	maximum
10	0.58	0.00	2.29
101	0.58	0.00	2.29
105	1.34	0.00	2.29
107	0.58	0.00	2.29
108	0.83	0.00	2.29
114	2.00	0.00	2.29
116	0.68	0.00	2.29
117	0.06	0.00	2.29
118	0.36	0.00	2.29
120	0.03	0.00	2.29
121_01	0.79	0.00	2.29
121_02	0.44	0.00	2.29
121_03	1.17	0.00	2.29
123	2.29	0.00	2.29
124	0.00	0.00	2.29
125	0.01	0.00	2.29
126	0.87	0.00	2.29
136	0.02	0.00	2.29

Aqu_z_regoMid_gl_lake (m)

This parameter represents the depth of glacial clay in the lake basin. The depth and distribution of this layer is regarded as constant over time, covering the till and bedrock surface from deglaciation onwards. The depth of this layer is specific for each object, based on the RDM /Hedenström et al. 2008/. Mean, minimum and maximum values of the depth of the glacial clay layer are presented in Table 7-11. Minimum and maximum values represent the minimum and maximum of the mean thickness in the identified lake basins and a uniform distribution is assumed.

Table 7-11. Mean, minimum and maximum depth (m) of glacial clay (Aqu_z_regoMid_gl_lake) below the identified biosphere objects when they are in the lake/terrestrial stage. Minimum and maximum values represent the minimum and maximum of the mean thickness in the identified lake basins. * The biosphere objects 121_02 and 121_03 do not have a lake stage and the glacial clay layers are assumed to be similar to the glacial clay layers of the sea basins.

Biosphere object	mean	minimum	maximum
10	Does not reach a lake stage		
101	1,87	0,00	5,30
105	3,28	0,00	5,30
107	1,87	0,00	5,30
108	2,22	0,00	5,30
114	3,75	0,00	5,30
116	1,62	0,00	5,30
117	0,39	0,00	5,30
118	0,85	0,00	5,30
120	0,00	0,00	5,30
121_01	3,22	0,00	5,30
121_02*	0,44	0,00	2,29
121_03*	1,17	0,00	2,29
123	5,30	0,00	5,30
124	0,00	0,00	5,30
125	0,03	0,00	5,30
126	3,66	0,00	5,30
136	0,00	0,00	5,30

Aqu_z_rego_pg

This parameter describes the thickness of post glacial gyttja clay that is increasing during the lake stage.

Ter_z_regoMid_pg

This parameter describes the thickness of post glacial gyttja clay found below the peat in the wetland. This thickness represents the accumulated gyttja-clay during the lake stage.

Ter_z_regoUp

This parameter describes the thickness of the peat layer in the wetland and increases with time until the lake basin has been filled.

7.7.3 Parameters describing biosphere object geometries and developmental stages

Aqu_area_obj (m²)

This parameter represents the surface area of an aquatic object and is calculated for each time-step used in the radionuclide model. In the radionuclide model the marine basins have the same area for most of the time. However, when the marine basins gets shallower and closer to being lakes the aquatic area of each object decreases due to that parts of the basins become land. Maximum and minimum areas of the marine biosphere objects are 35,580,100 m^2 and 243,809 m^2, respectively (see also Table 7-4 and 7-5).

Ter_area_obj (m²)

This parameter represents the surface area covered with peat in a biosphere object and is calculated for each time-step used in the radionuclide model. This area is zero until the bay starts to be isolated.

Area_wshed (m²)

This parameter represents the surface area of the watershed. Watershed is an extent of land where water from rain or snow melt drains downhill into a body of water, such as a river, lake, reservoir, estuary, wetland, sea or ocean. The drainage basin includes both the streams and rivers that convey the water as well as the land surfaces from which water drains into those channels, and is separated from adjacent basins by a drainage divide (also called water divide). When marine basins are located adjacent to the coast or land they exhibit watersheds areas larger than zero, whereas when they are located in open sea the contribution from the watershed goes via the coastal basins and the parameter is zero (see also Section 7.1).

Area_subcatch (m²)

The sub-catchment is defined as the catchment of the outlet of a lake minus the catchment of the inlet of the same lake. The sub-catchment is used in the biosphere radionuclide model for calculation of diffuse discharge of water into the lake, i.e. inflow of water not included in the major stream discharge. The sub-catchment area is a constant (only used during the lake phase) and always smaller than the basin area, see Table 7-12. The sub-catchment of a hypothetical lake is shown in Figure 7-3.

Table 7-12. The table shows the sub-catchment areas for the identified biosphere objects.

Biosphere object	Sub-catchment area (m^2)
101	3,556,200
105	23,138,500
107	4,287,000
108	4,196,400
114	25,254,400
116	14,103,000
117	16,074,300
118	2,004,700
120	3,334,421
121_1	888,100
121_2	892,256
121_3	637,500
123	6,009,000
124	243,809
125	421,424
126	2,415,549
136	4,200,176

depth_aver (m)

This parameter represents the average depth in a biosphere object, the marine basin, and is calculated for each time-step used in the radionuclide model.

depth_max (m)

This parameter represents the maximum depth in a biosphere object, the marine basin, and is calculated for each time-step used in the radionuclide model.

threshold_start (y AD)

This parameter represents the year a threshold starts isolating a bay that will become a lake. Lakes are formed due to land-rise, which isolates marine basins from the adjacent marine areas. In order to illustrate the gradual process when a sea bay becomes a lake, with occasional salt water intrusion, three occasions are identified for each biosphere object; in addition to a modelled isolation year start and stop years are presented. Start year represents the year when the marine basins becomes a lake basin isolated for at least parts of the year and stop represent when there is no longer any salt water intrusion to the basin. The threshold start for each basin is presented in Table 7-13. Basin 117 is the first object that starts the isolation from sea to lake. Basin 105 is the last basin that starts isolation from sea to lake. Min and max were estimated by subtracting and adding 200 years to the estimated value, where 200 years approximates 1 m change in shoreline displacement rate (present situation). A uniform distribution was assumed.

threshold_stop (y AD)

This parameter represents the year when the isolation of a lake from a marine object is complete. Lakes are formed due to land-rise, which isolates marine basins from the adjacent marine areas. Sea level changes during a year makes the transformation from marine to limnic conditions less clear. Therefore, in addition to a modelled isolation year start and stop years are presented. Start year represents the year when the marine object becomes a lake basin isolated for at least parts of the year and stop represents when there is no longer any salt water intrusion to the basin. The threshold stop for each basin is presented in Table 7-13. Basin 124, is the first object that completes the isolation from sea to lake. Basin 105 is the last basin that completes isolation from sea to lake. Min and max were estimated by subtracting and adding 200 years to the estimated value, where 200 years approximates 1 m change in shoreline displacement rate (present situation). A uniform distribution was assumed.

Table 7-13. Treshold_start and threshold stop represent the start and stop of the isolation period for each basin in Forsmark. Treshold_agri is the time piont when agricultual use of parts of the mire is possible and Threshold_end is the time piont when the lake basin is filled with peat (see also Table 7-4).

Biosphere object	threshold _start (y AD)	threshold_stop (y AD)	threshold_agri (y AD)	threshold_end (y AD)
101	7479	8376	8496	8300
105	10,453	11,634	11,768	21,800
107	3157	3725	3867	9000
108	4610	5278	5412	11,600
114	7983	8924	9044	23,100
116	4393	5044	5178	8400
117	2675	3212	3358	8300
118	2531	3059	3205	5200
120	2106	2610	2759	11,800
121_1	3648	4248	4380	5600
121_2	2700	3175	3361	3100
121_3	3000	3500	3870	3000
123	6019	6793	3361	8500
124	1603	2077	3870	2600
125	1616	2091	6919	2500
126	4005	4629	2229	4800
136	1613	2088	2243	6800

threshold_agri (y AD)

This parameter describes the time point when the wetland or part of the wetland is situated 2 m above the sea level. At this time it would be possible to drain the wetland and use it for agricultural purposes (see description and discussion in Chapter 5 and Table 7-13). Min and max were estimated by subtracting and adding 200 years to the estimated value, where 200 years approximates 1 m change in shoreline displacement rate (present situation). A uniform distribution was assumed.

threshold_end (y AD)

This parameter describes the time point when the lake basin has been filled with peat and the whole biosphere object is a wetland (Table 7-13). Min and max were estimated by subtracting and adding 200 years to the estimated value, where 200 years approximates 1 m change in shoreline displacement rate (present situation). A uniform distribution was assumed.

7.7.4 Parameters related to sedimentation, resuspension and lake infilling

sed_rate_gross (m y^{-1})

The sed_rate_gross parameter (m y^{-1}) is for the marine phase the gross sedimentation rate used in the marine module and for the limnic phase calculated as change in sediment volume ($vol\_sed_t - vol\_sed_{t-1}$) divided by the mean water area for the two time steps (($Aqu\_area\_obj_t + Aqu\_area\_obj_{t-1}$)/2) and this quotient is divided by the time step length to get the unit m y^{-1}.

vol_resusp (m^3)

The vol_resusp parameter (m^3) is the gross resuspension and is calculated as the gross sedimentation (m^3) (gross sedimentation rate multiplied by water area and time step length) minus the change in sediment volume ($vol\_sed_t - vol\_sed_{t-1}$).

res_rate_basin (mm y^{-1})

The res_rate_basin parameter (mm y^{-1}) is the resuspension rate and for the marine phase calculated for the whole basin (calculated for all tree bottom types although resuspension only occurs on transport or erosion bottoms). It is calculated as resuspension volume (vol_resusp) divided by the mean water area for the two time steps (($Aqu\_area\_obj_t + Aqu\_area\_obj_{t-1}$)/2) and this quotient is divided by the time step length to get the unit m y^{-1}. For the limnic phase the parameter is calculated as the gross sedimentation rate (sed_rate_gross) multiplied by 0.654 /Weyhenmeyer 1997/. The multiplier is the mean value for small lakes in /Weyhenmeyer 1997/.

res_rate (kg dw m^{-2} y^{-1})

This parameter represents an estimate of resuspension and is calculated for each time-steps used in the radionuclide model. Resuspension is the process by which abiotic and biotic material that has been deposited on the bottom sediment is reconveyed into the overlaying water column. A resuspended particle may be resuspended c. 60 times y^{-1} in lakes /Valeur et al. 1995/ and more than 100 times y^{-1} in sea basins before it is permanently buried or transported out of the system. Here, resuspension is defined as the amount of material that is subjected to resuspension in a year and is expressed as kg dw m^{-2} y^{-1}. In the model a radionuclide is connected to a particle as soon as the particle reaches the sediment and therefore it is not of importance to measure the rate of resuspension as the same particle may be counted many times.

Instead it is of importance to estimate the amount of particles that is resuspended in a year. Resuspension is calculated for each time-step in the radionuclide model. It is set to zero for time steps where the area for transport and erosion bottoms are zero and for remaining time steps calculated as resuspension volume (vol_resusp) divided by the mean area for transport and erosion bottoms for the two time steps (($area\_tranBot_t + area\_tranBot_{t-1} + area\_eroBot_t + area\_eroBot_{t-1}$)/2) and this quotient is divided by the time step length to get the unit m y^{-1}.

sed_rate (kg dw m^{-2} y^{-1})

This parameter represents the net amount of particles that is deposited on lake and sea bottoms during a year and is expressed in kg dw m^{-2} y^{-1}. Some of this material will permanently accumulate and some will be resuspended and return to the water column. This is calculated for each time-step in the radionuclide model. It is calculated as change in sediment volume ($vol\_sed_{t} - vol\_sed_{t-1}$) divided by the mean water area for the two time steps (($Aqu\_area\_obj_{t} + Aqu\_area\_obj_{t-1}$)/2) and this quotient is divided by the time step length to get the unit m y^{-1}. For the limnic phase the gross and net sedimentation rates are equal.

growth_rego (my^{-1})

This parameter represents the growth (in height) of the regolith layer, and is calculated for each time-step used the in radionuclide model. Growth_rego is a mean value for sediment growth in the entire basin area. In marine basins growth_rego occurs only in the areas with accumulation bottoms whereas in erosion and transport bottoms the growth of the regolith layer may be negative. As a result, growth_rego can be negative due to large export of material from erosion and transport bottoms, i.e. there is a net export of material out of the basin.

ter_growth_rego (m^2(m^{-2} y^{-1}))

This parameter describes the rate of terrestrialisation in the biosphere object, where the infilling of peat turns the lake into a wetland.

7.7.5 Conclusions on site specific parameters

Compared to other safety assessments performed to date, SR-Site is in a unique position to include site data in the biosphere modelling. The available site data describe both important ecological and hydrological processes as well as provide concentrations of elements in site specific organisms, regolith and waters, together with a high resolution DEM and a detailed stratigraphy of the regolith /SKB 2010b/. This dataset is probably the most detailed collection of synchronised surface data ever produced in Sweden. Moreover, site investigations of the two candidate sites Forsmark and Laxemar-Simpevarp were coordinated, which gives valuable possibilities to validate data and build confidence. The radionuclide modelling of the biosphere has, as far as possible, utilised the site specific data, both for describing processes and parameters and for populating the model with parameter values.

8 Discussion and conclusions

This chapter discusses the work to produce and the resulting final Forsmark landscape description. First, the overall landscape development is summarised and discussed in the context of the questions at issue and then a discussion is provided on the confidence in the approach and the main assumptions that were made. Finally, the synthesised development model and the output from the identified present and future biosphere objects are treated together with the understanding of transport processes in space and time.

8.1 Concluding landscape development

This section synthesises the landscape development at Forsmark. First a discussion on the relevant long-term processes is provided, and then a summary of the first 1,000-year period is presented. The remaining part of the reference glacial cycle and beyond is discussed, using the SR-Site climate domains to frame the biosphere issues related to landscape development.

8.1.1 Long-term processes of importance for site development

Long-term landscape development in the Forsmark area is dependent on two main, and partly interdependent factors: climate variations and shoreline displacement. These two factors in combination strongly affect a number of processes, which in turn determine the development of ecosystems. Some examples of such processes are erosion and sedimentation, groundwater recharge and discharge, soil formation, primary production and decomposition of organic matter.

Climate variations will directly change the conditions for ecosystem formation, e.g. the formation of wetland complexes, and cause north- and southward migration of species and ecological communities. Changes of species distributions have the potential of affecting whole ecosystems through the emergence or disappearance of species that may have a key function in the ecosystem. Examples of such species are the megaherbivores that are thought to have kept the forests fairly open during long periods after the latest deglaciation, or a predator that directly may alter the food web and thereby the whole ecosystem. Climate variations during the SR-Site reference glacial cycle are described in Chapter 3.

The second important factor for long-term landscape development, shoreline displacement, is a secondary effect of climate variations. It is caused by the interaction between glacially induced isostatic depression/recovery on the one hand, and eustatic sea-level variations on the other. Periodically, shoreline displacement has strongly affected the Forsmark area, both before and after the latest deglaciation. Accordingly, the area has repeatedly been situated below sea level for long periods (cf. Chapter 3 in /Söderbäck 2008/).

At the time of the latest deglaciation of the Forsmark area around 8800 BC, the nearest shoreline was situated c. 100 km west of Forsmark and the area was covered by approximately 150 m of glacio-lacustrine water. Thereafter, the isostatic rebound in the Forsmark area and in areas further north has been continuous and slowly declining. The rate of rebound in Forsmark has decreased from c. 3.5 m/100 years directly after the deglaciation to a present rate of c. 0.6 m/100 years, and it is predicted to decrease further to become insignificant around 30,000 AD (Figure 8-1).

This means that the shoreline displacement causes a continuing and predictable change in the abiotic environment, e.g. in water and nutrient availability. It is therefore appropriate to describe the origin and succession of some major ecosystem types in relation to shoreline displacement. One example of this is the isolation of a sea bay into a lake, the following ontogeny of the lake and its further development into a wetland.

The development of the Baltic Basin since the latest deglaciation is characterised by changes in salinity, caused by the interplay between variations in the relative sea level and the isostatic uplift, which has resulted in relocation of thresholds connecting the Baltic Basin to the Atlantic. The development of the Baltic Basin during the post-glacial period has been divided into four main stages /Munthe 1892, Björck 1995, Fredén 2002/, summarised in Table 8-1. Three of these stages; Yoldia, Ancylus and Littorina, are named after molluscs, which reflect the salinity of the stages.

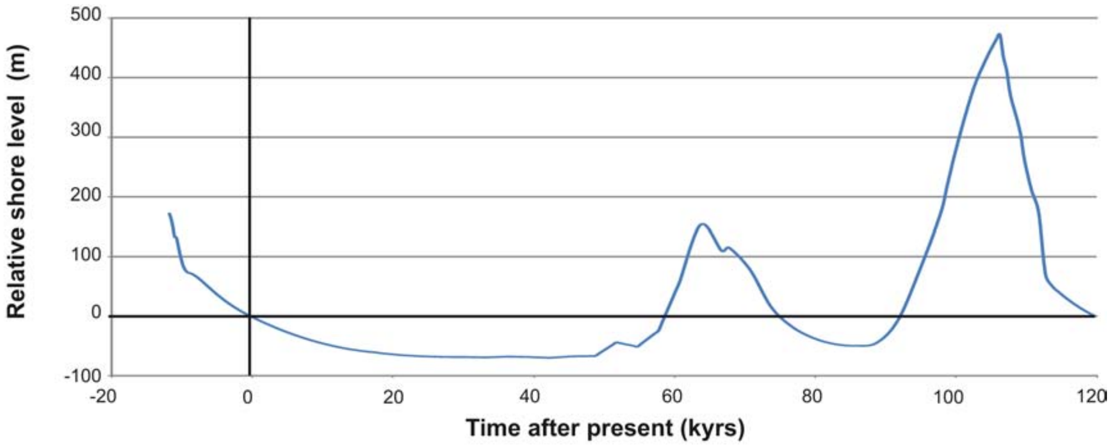


Figure 8-1. *Shoreline displacement at Forsmark in the reference glacial cycle. The levels during the first c. 8,000 years of the future period constitute extrapolated values based on observed relative sea-level data /Påsse 2001/, whereas the following part of the curve is constructed from Glacial Isostatic Adjustment modelling /SKB 2010a/. Positive numbers on the relative shore level elevation indicate that the site is submerged. Note that for most of the time that the figure shows submerged conditions, the site is covered by an ice sheet.*

Freshwater conditions prevailed during most of the deglaciation of Sweden. The first Baltic stage, the Baltic Ice Lake, was characterised by freshwater conditions and large input of glacial meltwater. Weak brackish conditions prevailed c. 9300–9100 BC, during the middle part of the Yoldia Sea stage, e.g. /Andrén et al. 2000, Wastegård et al. 1995/, when saline water entered the Baltic basin through the narrow straits in Västergötland and Närke. The maximum salinity was between 10‰ and 15‰ in the western part of the Yoldia Sea /Schoning et al. 2001/. However, when the Forsmark area was deglaciatied around 8800 BC, i.e. during the shift between the Yoldia and Ancylus stages, freshwater conditions prevailed in the Baltic.

The postglacial isostatic rebound in southernmost Sweden today is negligible and it will therefore not affect the future salinity in the southern Baltic Sea during the temperate period. In contrast, the isostatic recovery in central and northern Sweden is significant /Påsse 2001/. Due to the rising of the Southern Kvark sill, i.e. the narrowest part of the Baltic Sea between Åland and Sweden where the maximum depth today is c. 40 m, we can anticipate large changes in the exchange of water between the Bothnian Sea and the Baltic Proper in the future.

Accordingly, isostatic recovery will relatively soon dominate salinity variations north of Åland, regardless of prevailing climate conditions, and the uncertainty in the prediction of future salinity is therefore considerably lower for the Bothnian Sea than for the Baltic Proper. Extrapolation of the shoreline displacement models /Påsse 2001/for sites situated both east and west of Åland indicates that the present Bothnian Sea will become a freshwater lake around 25,000 AD (cf. Figure 8-2).

Table 8-1. The four main stages of the Baltic Sea. The Littorina Sea here includes the entire period from the first influences of brackish water at about 7500 BC to the present Baltic Sea.

Baltic stage	Calendar year BC	Salinity
Baltic Ice Lake	13,000–9500	Glacio-lacustrine
Yoldia Sea	9500–8800	Lacustrine/Brackish/Lacustrine
Ancylus Lake	8800–7500	Lacustrine
Littorina Sea *sensu lato*	7500–present	Brackish

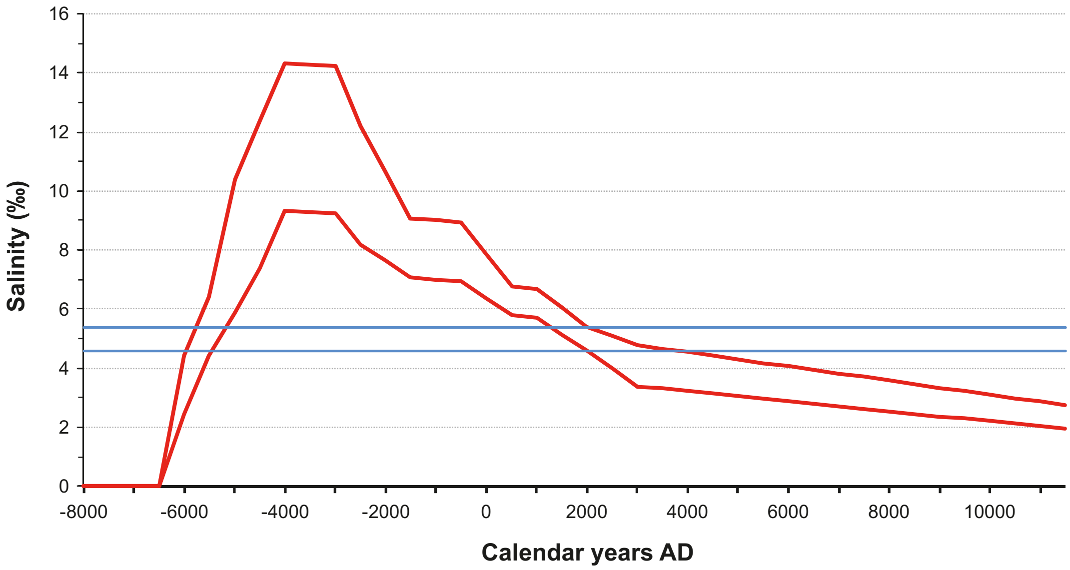


***Figure 8-2.** Estimated range of salinity in the open Bothnian Sea from the freshwater Ancylus Lake stage until the sea has disappeared from the modelled area in Forsmark. Present maximum and mean salinity at Forsmark is indicated by horizontal lines. Estimates of historical salinity are based on /Westman et al. 1999/, whereas the prediction of the future assumes that present salinity will decrease linearly until the Bothnian Sea is isolated from the Baltic Sea around 25,000 AD. It should be noted that any prediction of the future salinity is highly uncertain; the upper limit of the future salinity assumes constant climate conditions, whereas the lower limit assumes 30% higher precipitation as an effect of greenhouse warming.*

8.1.2 The initial 1,000 years after repository closure

The shoreline displacement, measured as relative sea-water level, is projected to be nearly 6 m during the next 1,000 years, based on an almost constant isostatic rebound rate of 6 mm/year /Ekman 1996, Hedenström and Risberg 2003/. Recent monitoring of the sea level in the Baltic /SMHI 2009/ shows a new trend during the last 30 years, indicating that the sea level presently is rising at a rate of about 3 mm/year. This is likely a combined result of melting glaciers and expansion of sea water due to higher global temperatures /Meehl et al. 2007/. With such a trend, the shoreline regression will slow down and possibly even turn into a slight transgression.

Most probably, however, the shoreline displacement will continue to be regressive during the next 1,000 years. With the predicted rate of 6 mm/year, the coastline will move around 1 km from the repository to 3000 AD. Thus, parts of the former seafloor will become land (see Figure 8-3). The ongoing shoreline regression causes an ecosystem succession, in which the present shore in sheltered places, dominated by herbs and grasses, is transformed into forest, whereas for exposed areas usually dominated by rock outcrops and boulders, the rate of succession is expected to be less pronounced. Some bays with shallow thresholds towards the Bothnian Sea will be isolated and transformed to lakes (Figure 8-3).

The newly isolated lakes will occasionally be affected by flooding of brackish water from the Bothnian Sea during periods of high sea water levels (see Figure 8-4 for an example of this in the present-day lakes in the area). Due to natural infilling (sedimentation and vegetation growth) of the coastal basins and lakes, sediment and organic matter is expected to accumulate, and eventually all lakes will be transformed to land. The rate of sedimentation in the lakes is dependent on lake volume /Brydsten 2004/, whereas the colonization of littoral plants requires shallow water (<2 metres) and a shore with a low slope and without a wave-breaking zone. Accordingly, the rate of infilling is strongly dependent on lake depth, area and volume /Brydsten and Strömgren 2010/.

All the present-day lakes in the Forsmark area are small and shallow. This means that large parts of the lakes will be transformed to wetland during the coming 1,000 years. For example, Lake Puttan and Norra Bassängen, situated close to the planned repository, will be almost completely transformed to wetland, whereas a minor part of Lake Bolundsfjärden will be maintained as open water in the year 3000 AD. The catchment of Bolundsfjärden will be drained by an open stream through the basins of Bolundsfjärden and Norra Bassängen, whereas Puttan, due to its small catchment, probably will lack an open stream /Vikström and Gustafsson 2006/.

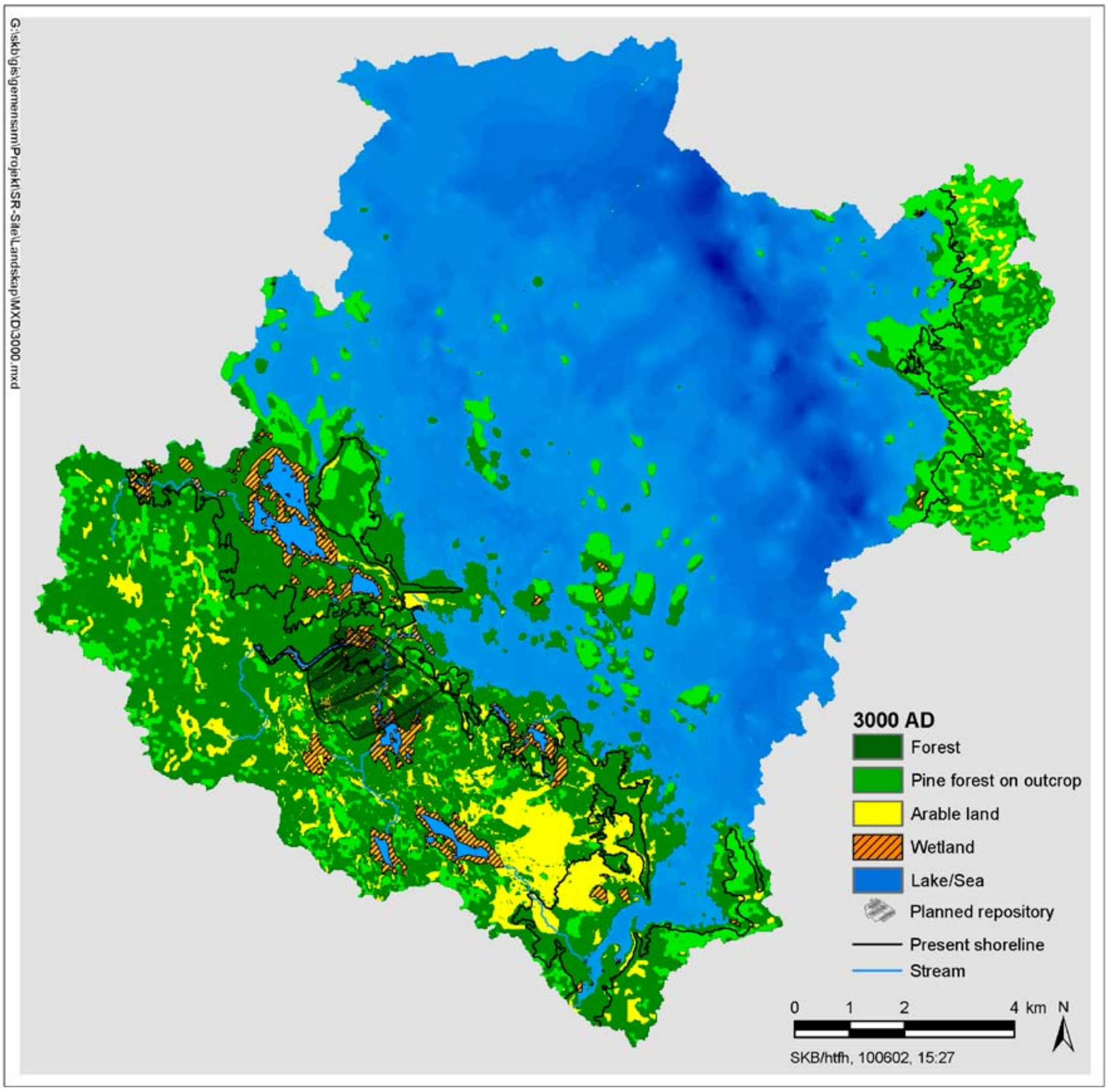


Figure 8-3. *The expected landscape of the Forsmark area at 3000 AD. All areas that potentially can be cultivated are represented on the map as arable land. The present day shoreline is marked as a black line and darker shades of blue represent deeper sea.*

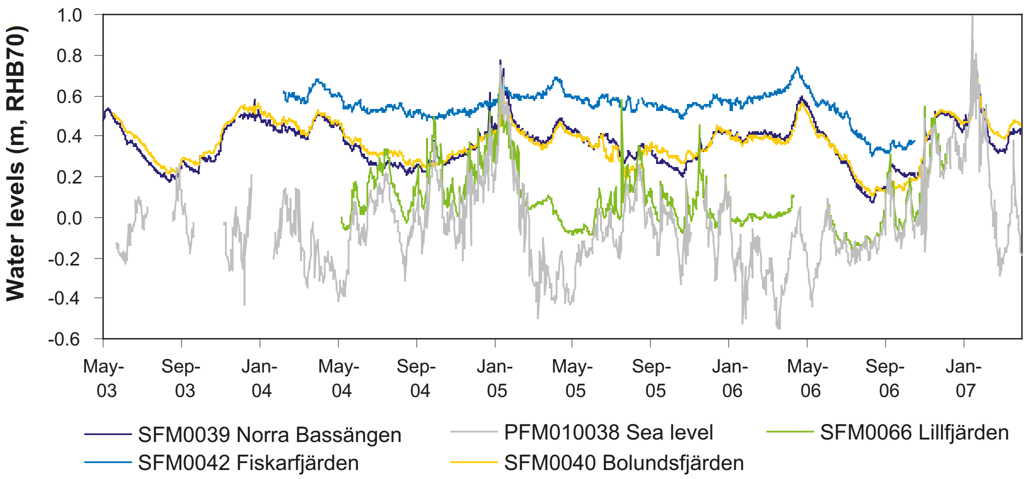


Figure 8-4. *Daily average surface water levels in the Bothnian Sea and in four of the larger Forsmark present-day lakes situated at low elevation. Note the events in January 2005 and January 2007, in which sea water intruded into the lowest-elevation lakes. Figure from /Johansson 2008/.*

The human-made, deep inlet canal for cooling water to the nuclear power plant, situated immediately north of the planned repository, will be isolated from the sea around 2100 AD. If it is left unaltered after decommissioning of the power plants, it will remain as a lake for a long time. Moreover, two new, relatively large lakes situated north of the repository and west of the present “Biotest basin”, will be isolated from the sea in the later part of the period (see Figure 8-3).

As the seafloor close to the coast gets shallower, erosion will occur on wave-exposed bottoms. Some sheltered areas inside a developing, denser archipelago will show accumulation for a short period before the bottom becomes land /Brydsten 2007/. The circulation in Öregrundsgrepen is expected to remain essentially the same as today /Karlsson et al. 2010/. The salinity of the Bothnian Sea is expected to decrease slightly to around 4.8 ppt during the initial 1,000 years, assuming unaltered runoff to the Bothnian Sea /Gustafsson 2004/.

The potential for sustainable human exploitation of food resources in the area over the coming 1,000 years is not expected to differ much from the situation today, assuming that known methods are used. Only minor parts of the newly formed land will be suitable for cultivation, mainly due to the boulder-rich sediments in the former sea and lake areas, but also due to problems with draining the low-elevation new areas. New areas will, however, be available for grazing of domesticated animals.

The potential water supply for humans is expected to be fairly unaltered during this period. Lakes existing in the area today, e.g. Bolundsfjärden and Puttan, contain water not suitable for human use due to fringing mires and occasional high salinity. In the future, the deep canal north of the repository has potential as a freshwater reservoir when the salinity decreases, and also the stream through Bolundsfjärden may potentially be used for freshwater supply. However, water from lakes and streams in the area will probably also in the future be less suitable as drinking water, and the main potential use of surface water is for irrigation. New wells may be drilled in the bedrock or dug in the regolith in the area which is land today, whereas the new land will be too young for wells if current practises are maintained /Kautsky 2001/. However, the water quality of drilled wells in this area is poor and few wells are today useful for drinking water production /Ludvigson 2002/.

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

8.1.3 Biosphere development after 1,000 years until the end of the initial temperate period

According to the SR-Site base case, temperate conditions will persist in Forsmark until 10,000 AD. During this period, the regressive shoreline displacement is assumed to continue, but at a gradually declining rate, see Chapter 4 of this report. Initially, the coastline will move at a rate of approximately 1 km per 1,000 years. This will strongly influence the landscape, especially during the first part of the period, and eventually it will result in a situation where the planned repository is located inland rather than at the coast (see Figure 8-5).

The strait at Öregrund, south of the modelled area, is expected to be cut off about 3000 AD and Öregrundsgrepen will turn into a bay. This will affect the water circulation, and due to the continued narrowing of the bay the water turnover will be further restricted. However, in the beginning of the period turnover times are not expected to be longer than a couple of days, except for minor sub-basins which are near isolation /Engqvist and Andrejev 2000/. During the period from 3000 to 5000 AD, a semi-enclosed archipelago is expected to develop northeast of the repository. Around 5000 AD, many straits in this archipelago will become closed and a number of lakes will become isolated from the sea.

At 5000 AD, the Öregrundsgrepen bay has withdrawn ca 5 km from the repository. A small stream drains the area above the repository, and some small and shallow lakes are situated along the stream. This small stream will around 5000 AD flow into a large stream to the south-east. This large stream consists of the region downstream of the confluence of the Forsmarksån and Olandsån, draining a large part of Northern Uppland (drainage area $1.3 \cdot 10^3$ km^2). In the period up to 10,000 AD, the Öregrundsgrepen bay gradually shrinks to finally form a short and narrow bay along the island of Gräsö (Figure 8-5).

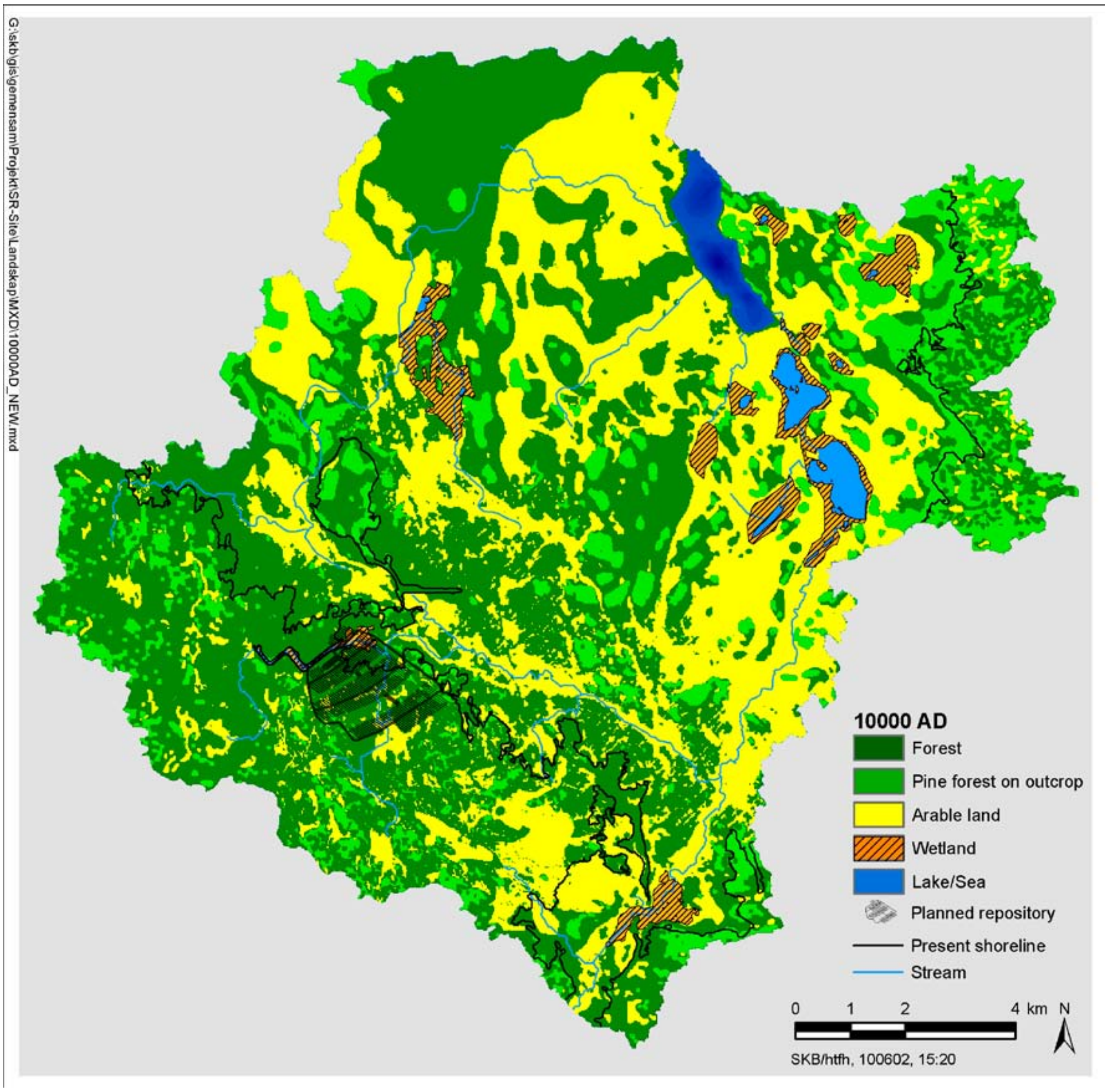


Figure 8-5. *The expected landscape of the modelled Forsmark area at 10,000 AD. All areas that potentially can be cultivated are represented on the map as arable land. The present day shoreline is marked as a black line and darker shades of blue represent deeper sea.*

In the modelled area, a large number of lakes will be isolated from the sea during the period from 3000 AD to 10,000 AD. Most of the new lakes are small and shallow, and are expected to quite quickly be transformed into mires. A few deeper lakes are projected to exist for more than some millennia. Around 10,000 AD, almost all lakes in the area have been infilled and only some initially relatively large and deep lakes near the island of Gräsö are expected to remain (Figure 8-5).

The salinity of the sea will continuously decrease due to the isostatic rebound of the shallow sills between Ålands hav and the Baltic Proper (see Figure 8-2). Around 6000 AD, the salinity is expected to have decreased to 3–4 ppt, which means that an ecosystem similar to that in the Northern Quark, with low abundance of marine species, has developed.

According to /Brydsten 2009/, accumulation of sediments occurs both on bottoms at large water depths and on shallow bottoms inside the belt of the skerries which are sheltered from wave power, whereas erosion occurs mainly on shallow bottoms exposed to waves. Transport bottoms can be found in all places between these two extremes, i.e. at intermediate depth with moderate wave exposure.

Accordingly, the seafloor in the model area shows a characteristic evolution over time, beginning with a period of accumulation due to large water depth early after deglaciation. Then comes a period with transport, after which erosion dominates when the water depth decreases even more.

Finally, transport and accumulation may occur in sheltered locations during a short period before the sea bottom becomes land. This means that there are very limited parts of the model area that show continuous accumulation of sediments throughout the whole marine period. The small areas with continuous accumulation are situated in the deepest parts of Öregrundsgrepen /Brydsten and Strömgren 2010/.

The number of people that potentially can be sustained by food produced within the Forsmark area is strongly dependent on the distribution of different land-use types. The arable land needed to support one person is several hundred times smaller than the corresponding areas of other land-use types.

The shoreline withdrawal means that the area for fishery is continuously reduced. Much of the newly formed land will be unsuitable for farming due to boulder- and stone-rich deposits, but there are significant parts in central Öregrundsgrepen with fine-grained sediments that can be cultivated. If not cultivated, most of the new land is expected to be suitable for pasture and also for forestry, wild game and collection of mushrooms and berries. The food productivity is much higher in agricultural areas than in aquatic or non-cultivated terrestrial areas. Accordingly, the potential food productivity in the total modelled area is expected to increase due to an increasing proportion of arable land as new land areas are formed.

The availability of freshwater for human supply is expected to gradually increase with the decreasing marine influence in the area. New lakes and streams will form in the new areas, but both the present and most of the future lakes will be relatively short-lived due to their shallowness. It seems likely that the water from lakes and streams also in the future will be less suitable as drinking water, and the main potential use of surface water is for irrigation.

The climate during the rest of the temperate period may vary considerably, with both warmer and colder periods. The main effect of temperature changes will be on the vegetation period, which today varies regionally between 170 and 210 days dependent on elevation, local topography, aspect direction and distance to the seashore. Changed temperatures may give rise to drier or wetter climate and to changed snow cover and frost characteristics, and this can in turn affect the dominant vegetation and mire build-up. It is however assumed that the climate variations during the rest of the temperate period will not exceed the regional spatial variation and the between-year variations observed at the site today.

8.1.4 Development during the remaining part of the reference glacial cycle

According to the reference glacial cycle (Chapter 3), Forsmark will go through a number of climate changes from temperate, periglacial (with or without permafrost) and glacial conditions. After next glaciation, a new period of submerged conditions is also predicted.

Temperate climate domains

After the initial temperate period (after 10,000 AD), a relatively short period of periglacial conditions will follow. The periglacial conditions will once again change back to temperate conditions that more or less will continue until 25,000 AD. Another temperate period is expected around 40,000 AD that will last for about 5,000 years. During far-future temperate conditions, Forsmark will have characteristics that mimic the late parts of the initial temperate period. This means that there will be a landscape that comprises terrestrial ecosystems with few or no lakes and no sea. The terrestrial system will consist of forests, mires and areas possible for agriculture. Higher altitude areas with outcrops of bedrock will be forested with pine.

Periglacial climate domains

Periglacial periods are characterised by tundra vegetation and permafrost features. The precipitation is low, due to the limited evaporation transporting water to the atmosphere. The low evaporation means that wet ground is prevalent and the surplus water is unable to seep into the ground because of the permafrost /French 2007/. This results in extensive wetlands, but the amount of peat formed is negligible because plant productivity is low. Even though there may be a snow cover of up to 50 cm during winter, raised parts are frequently blown free of snow and there intensive erosion occurs by the blowing ice crystals. The tundra is devoid of forests. The vegetation consists of herbs and shrubs, at raised dryer places lichens dominate and on wet ground mosses. The vegetation period is short.

The major part of the vertebrate fauna of the tundra migrates south during winter. The birds that are abundant during summer migrate over long distances to sub-tropical areas. Small mammals e.g. lemmings, do not migrate and spend most of their life under the isolating snow-cover grazing.

Even on gentle slopes, the soil slips downhill with the peat cover on top, i.e. solifluction occurs. Other processes are upward migration of stones induced by freeze-thaw processes, causing tundra-polygons and thermokarst phenomena. Thus, there are many processes disturbing the soil and also exposing it to erosion.

Taliks, i.e. unfrozen areas in the permafrost region under lakes or rivers, are potentially places which animals and humans can settle. However, even if the taliks can be potential locations for human settlement, the low productivity in the permafrost region requires utilisation of a large area to supply the resources needed by even a small community. The talik feature is also of interest when constructing conceptualisations of transport of matter from the bedrock to the surface system.

Glacial climate domains

During glacial periods Forsmark will be covered by an ice sheet. During restricted periods, the ice sheet is thin over the site and elevated areas of the surface can protrude above the ice surface. There, lichens, grasses or herbs may be present. On the ice-surface, microbes, algae and some insects can exist. At the ice-margin, a productive aquatic community may exist. This can sustain a fish population which can be exploited by the animals living on the ice (e.g. birds, polar foxes, polar bears) and humans. The populations of vertebrates and humans are likely to migrate over large areas due to low food productivity or severe weather conditions. In most cases, a human population will probably comprise occasional visitors, due to the hostile environment and the variable ice-situation. It is possible that a human population could be present for longer periods close to the ice margin along the coast and live on fish.

Submerged conditions

In the reference glacial cycle, two periods of submerged conditions are identified. During these periods, Forsmark is covered by sea. The submerged conditions follow always directly after the ice sheet has withdrawn and the Forsmark bedrock is depressed by the ice load. After the last glaciation that ended in 8800 BC at Forsmark, the first terrestrial areas appeared around 1000 BC. The last areas in the Forsmark landscape that will turn terrestrial are calculated to do so at around 11,500 AD. This means that the submerged conditions will have two phases, one first phase of ca 8,000 years when the whole area is submerged, and one that continues for 12,000 years when the sea gradually withdraws and the land area accordingly expands. This definition does not entirely correspond to the reference glacial cycle /SKB 2010a/ in that the whole landscape is taken into account and not just a temporal succession for a point above the repository target area.

A submerged condition is not a climate domain. It is a state when the processes and properties related to the marine or limnic system (aquatic ecosystem) dominate at Forsmark. These ecosystem types are not expected to change dramatically due to changes in climate, except for the effects of the long-term change in salinity (see Figure 8-2). Therefore, the submerged future landscape is treated as identical to the historical and present aquatic ecosystems at Forsmark.

8.2 The Forsmark landscape – concluding remarks

This final section gives a short description of our confidence in the work, the main assumptions made, the accuracy of the models and uncertainties involved in the process of building an integrated landscape development model.

8.2.1 Long-term processes and geometric features

In SR-Site, the description of the development of the biosphere uses information from the climate descriptions /SKB 2010a/. The long-term climate-driven processes that affect Forsmark define the types of ecosystems that develop in time. The landscape develops from a state of a submerged marine ecosystem after a glaciation, via a landscape succession containing coastal, lake and wetland ecosystems, to a Forsmark that is dominated by forest and terrestrial ecosystems. The long-term landscape development at Forsmark is thereby driven by the global climate and processes originating from global climate, like the shoreline displacement. For a comprehensive description of the climate models and assumptions made concerning climate, see /SKB 2010a/.

In this report, the Forsmark landscape is described taking the climate into account. This is done by using the climate domains described in /SKB 2010a/. However, a fully integrated landscape development with climate parameters is not presented. Instead we have used the main processes and features associated with the climate domains defined in the reference glacial cycle /SKB 2010a/ to describe the landscape development domain by domain. Supporting calculations of transitions between temperate and periglacial domains have also been undertaken elsewhere /Avila et al. 2010/. The outputs from these descriptions are then used in the overall merged development model, describing the landscape of Forsmark during a glacial cycle.

Many of the analyses of surface systems within SR-Site are focused on the development of today's landscape, influenced by the transgressing shoreline which divides the area into a submerged and a terrestrial part. This domain transition will, during this interglacial, continue for another 9,000 years into the future and therefore constitutes a significant part of the time period considered in SR-Site. The shoreline is a place of special attention, since it is the most dynamic part of landscape due to the ongoing marine transgression. It is along the shoreline that coastal processes determine the development; unconsolidated sediments are eroded and transported to deeper areas, waterborne nutrients create a productive littoral zone where flooding regularly occurs, and much of the marine primary production is concentrated to the shallow waters in the vicinity of the shoreline.

This coastal zone migrates continuously as a consequence of isostatic rebound, which means that traces of coastal processes ascend with the land and can be found higher up than the current shoreline. Furthermore, as soon as land emerges from the sea, other types of processes start to dominate landscape development; terrestrial processes create a zonation as a consequence of exposure. Areas at higher altitudes have been exposed to these transforming processes during a longer period than have areas at lower altitudes. For example, land higher up is more weathered, soil-forming processes have created soils with a higher degree of maturity, and wetlands have accumulated more gyttja and peat.

Studies of these terrestrial environments in different successive stages constituted a fundamental part of the SR-Site surface systems programme. Lower-lying land, i.e. of a younger terrestrial age, is assumed to develop in the same way as the older parts of the terrestrial landscape, and the development of older land higher up in the terrain is assumed to continue along the same successional path until shifts in climate regimes are projected to alter the dominant processes of transformation. Such a concept of "space-for-time substitution" is used in all disciplines within landscape modelling in SR-Site. It is applied to knowledge from the site investigations, but also in numerical models and studies of analogue areas currently experiencing climate regimes different from today's Forsmark.

The landscape geometry can be seen as a common platform for models used in landscape modelling in SR-Site. All other models and descriptions rely on a good geometric knowledge. In this work, we have used a number of data sources to build a digital elevation model (DEM) valid for the present situation. This model is then used together with data from the regolith depth to construct a bedrock surface model and a model describing the stratigraphy of soils and sediments. To understand the uncertainty in the DEM, a validation was undertaken /Strömgren and Brydsten 2009/. The mean error in the SKB 10-metre DEM is 0.32 m with a standard deviation of 1.10 m, and the uncertainty in the 50-metre DEM is only slightly larger with a mean error of 0.35 m and a standard deviation of 1.45 m. However, larger errors are likely to be found in both the areas of the 10- and 50-metre DEMs, since the maximum errors for these areas are more than 10 m.

The above analysis can be used for assessing the size of errors in the catchments in the Forsmark area. Catchments can be produced from the existing DEM and from a DEM where the error distribution calculated is randomly assigned. Comparing the catchments produced from different DEMs would give a measure of the size of the errors caused by errors in input data to the existing Forsmark DEM.

To make a realistic description of landscape development at Forsmark during a glacial cycle, the sedimentation and erosion processes in aquatic (marine and limnic) ecosystems have to be taken into account. In SR-Site, a coupled regolith-lake development model (RLDM) was developed and applied to the Forsmark area. The model consists of two modules: a marine module that simulates sediment dynamics (erosion, transport and accumulation) in the sea (including the periods with fresh water in the Baltic) and a lake module that simulates lake ontogeny. In addition, two sub-models have been constructed: a sub-model that predicts generation of small wetlands that do not originate from infilled lakes and a sub-model that calculates export of fine-grained particles out of the model area.

An increase in postglacial clay volume between 9500 BC and 7000 BC is caused by the development of large areas of accumulation bottoms during that period. The decrease in volume during the period 7000 BC–3000 BC is caused by successively more sea bottoms being situated above the wave base and thus a shift from accumulation bottoms to transport bottoms. At least 40 million m^3 postglacial clay is exported out of the model area during this period. From 2000 BC, the volume increases constantly except during a short period around 7000 AD. This is caused partly by more lakes accumulating postglacial clay and partly by increasing areas of near-shore accumulation bottoms in the sea /Brydsten and Strömgren 2010/.

At the end of the modelled period (35,000 AD), when all lakes are totally infilled and the development of the landscape is stabilised, the volume of the marine part of the postglacial clay is about 73% of the total volume. This agrees well with measured values of postglacial clay volumes in existing totally infilled lakes in the Forsmark area. The organic sediments (which end up as peat) are associated with infilled lakes or hanging wetlands and are in the RLDM treated as permanent accumulations, always increasing over time. The total peat volume is dominated by organic material generated by the lake infill processes; therefore, the peat volume increase rate is closely associated with the number of lakes with ongoing infill processes. At the end of the RLDM period (35,000 AD), the total fen peat volume is about 34 million m^3, i.e. about half of the volume of postglacial clay at the same time.

The DEM, and then also the RLDM, are sensitive to relative sea-level change, sediment dynamics, and lake-infilling processes. In this work, the 1970 AD DEM was used and adjusted for the relative sea-level change. In future work it would be more correct to use the Z4a-layer of the regolith depth model (upper surface of the glacial clay). This should lead to increased water depths, larger areas with accumulation bottoms, and thicker postglacial clay strata. The accuracy of the calculations of future lake extents, as shown above, depends on the accuracy of the DEM as well as on possible erosion of the thresholds. If the thresholds consist of postglacial clay or glacial clay, fluvial erosion at the lake outlets may lower the threshold down to the altitude of the upper surface of the till or bedrock. Because the RLDM includes data on the stratigraphy at the lake thresholds, RLDM could be used to adjust the lake thresholds, which may lead to changes in lake sizes. The possible effects of adjusted lake thresholds are not evaluated within SR-Site.

8.2.2 Ecosystem succession and land-use

The description of the Forsmark ecosystem succession during a glacial cycle is one of the main features of the SR-Site biosphere. The future areas potentially affected by deep groundwater discharge are defined as biosphere objects containing specific ecosystems. In this work we have divided the landscape into three types of ecosystems, terrestrial, limnic and marine. During the site investigation and site description phase, during 2002–2008, the Forsmark ecosystems were investigated in terms of abiotic and biotic properties. Processes and features of relevance for describing the systems, and for calculating transport of radionuclides within and between them, were identified. Also, a lot of effort was put into understanding the genesis of the different entities in each ecosystem. A historical and present site description was the output from this exercise and is reported in /Söderbäck 2008, Lindborg 2008/.

Having the historical and present description of Forsmark at hand, the future development of the landscape with its ecosystems was put together. This work, involving all scientific disciplines in the biosphere project, is a difficult task that relies heavily on the processes identified as the main drivers for ecosystem succession.

Long-term ecosystem development in near-coastal areas of Fennoscandia is driven mainly by two different (but related) factors: shoreline displacement and climate change. In addition, human activities have strongly influenced both terrestrial and aquatic ecosystems, especially during the last centuries. Today, the spatial distribution of different ecosystems in the Forsmark area is related to a number of different factors, such as the nature of the Quaternary deposits, altitude, topography and land-use

/Andersson 2010, Aquilonius 2010, Löfgren 2010/. These factors have, to a varying degree, shaped the landscape we see today and will also be of importance for the future distribution of ecosystems. The climate will also set boundaries to this distribution, but on a more regional scale.

The final ecosystem succession output is a conceptual model describing how the ecosystems change in time due to geometrical factors, initial regolith properties, the shoreline displacement, sedimentation, ingrowth of vegetation and climate. This model is then used in the landscape development model (see next section) to distribute the information at a landscape level over time.

The confidence in the ecosystem succession is high. By using the present differences in elevation at Forsmark as an analogue for time (due to shoreline displacement), we can argue that the ecosystem succession seen today will be a good representation of the future development of areas today submerged. However, this is only valid for a temperate climate such as we have today during this interglacial. The reference glacial cycle as presented in /SKB 2010a/ is telling us that Forsmark will experience also a periglacial climate with permafrost conditions. To mimic periglacial conditions we used information from other places, presently having colder climates. This information was applied at Forsmark to model the effects on the landscape.

The inhabitants – the users of the landscape – must be seen in combination with the landscape, topography, soils, vegetation, and climate. It is also important to view the landscape and its inhabitants in a broader temporal perspective, to put the landscape in an historical context /Berg et al. 2006/. In SR-Site we used present data and the historical information together with models describing future possibilities of land-use, to understand how a future population can utilise the Forsmark landscape.

The physical landscape constitutes the foundation for the cultural landscape. The physical setting, at least to some extent, always governs land-use and sets the limits, both historically and today, for human activity. It is therefore of the utmost importance to gain an understanding of aspects including the topography, soils and potential for different types of vegetation to understand the future. In a society under pressure, marginal resources that are not sustainable over long periods of time are sometimes used. One example is swidden cultivation (Sw. svedjebruk), which is only viable in areas where very large amounts of land are available. Accordingly, if something is to be sustainable it cannot be exploited close to the border of the impossible. On the other hand, new technologies such as land drainage and fertilisers can extend the border of the possible /Berg et al. 2006/.

The settlement situation in Forsmark in the early-modern period was heavily dependent on the establishment of Forsmarks bruk ironworks. In the 17th century, a large number of ironworks were established around Dannemora. Most of these are known as Vallonbruk due to the fact that people from southern and south-eastern Belgium, i.e. Walloons, established them or ran them during the 17th and the 18th centuries. They were essentially self-contained communities that were separate from the surrounding agricultural society.

The shore displacement and the subsequent drainage of the lands also made it possible for the villages to be dispersed, i.e. farms were established outside the village toft. The majority of the arable fields today are made up of these old wetlands, which later became meadows. The old arable fields with a continuity of several hundred years have today become pastures or have been forested. A model describing the land-use succession during the last 1,000 years is presented in Figure 8-6. In SR-Site we focused on land-uses linked to agriculture and natural ecosystems to describe future possible human activities.

In the beginning of an interglacial, only marine land-use is possible. Marine animals and sea weed may be used by a population living far away, by the shoreline outside of Forsmark. As the shoreline displacement continues, eventually land will appear and lakes take form. The emerging land gives the possibility to use limnic and terrestrial parts of the landscape, and agricultural land-use becomes possible. When salt-water intrusion is no longer likely, it is assumed that the wetland can be converted to agricultural land at any time.

Future agriculture in Forsmark was evaluated by classifying the availability of arable land from maps of Quaternary deposits /Hedenström and Sohlenius 2008/ and from the output of the RLDM /Brydsten and Strömgren 2010/, thus giving altogether 33 time steps between 1500 BC and 35,000 AD. The classification of land as arable was done by using current regional agriculture practices as a reference. The results showed that for most areas, the underlying sediments are primarily composed of stone- and boulder-rich till, which is not suitable for cultivation.

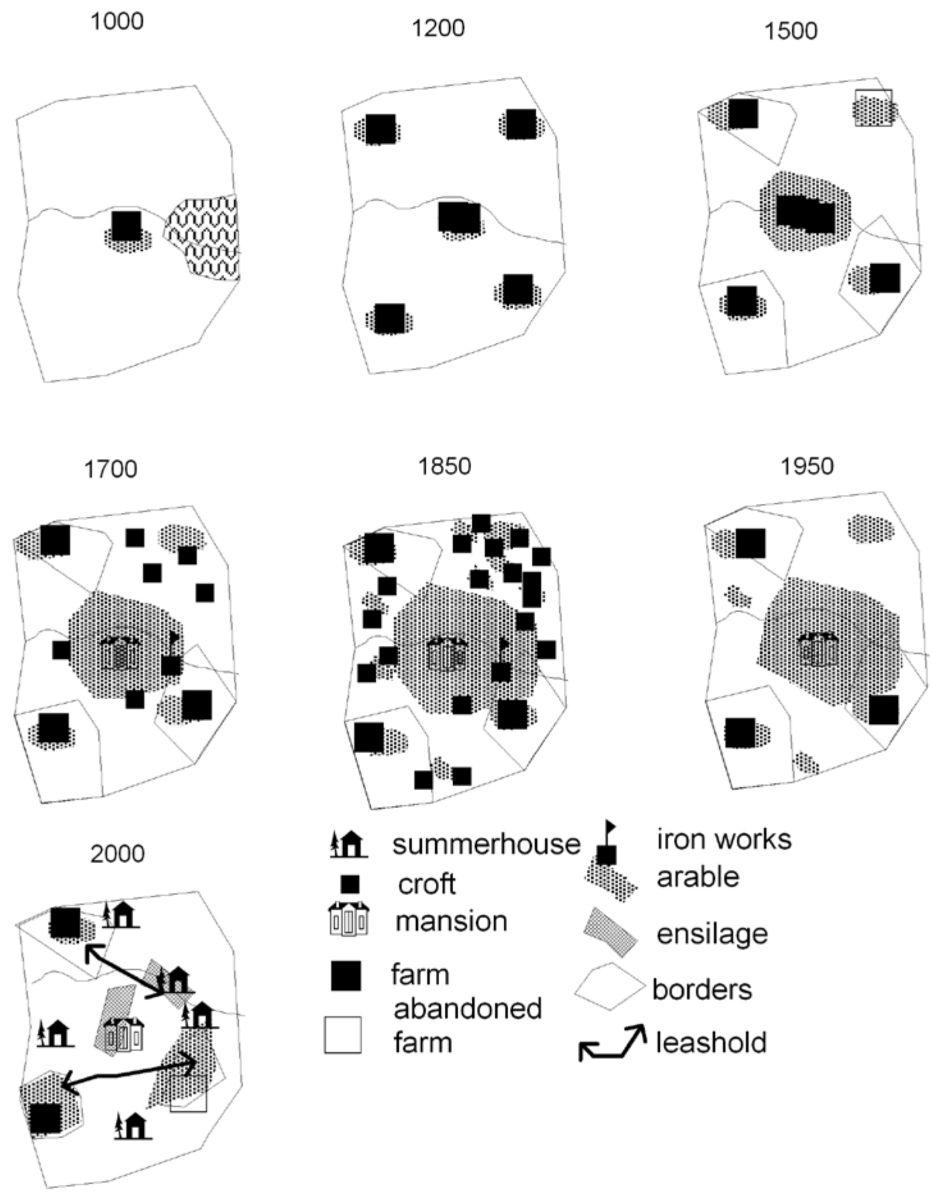


Figure 8-6. *A model illustrating the settlement changes in the region of Forsmark during the period 1000–2000 AD /Berg et al. 2006/*

The majority of areas of interest (biosphere objects) will in the future be covered by peat. Agricultural use is possible, but only for a limited time. This because peat decomposes and subsides quickly when drained and cultivated, thus making agriculture possible only for a few tens of years. Drainage of fen-peat can result in fertile agricultural soils but the low nutrient content and the low pH of bog peat makes it unsuitable for cultivation.

When discussing the near future, the potential for sustainable human exploitation of food resources in the area over the coming 1,000 years is not expected to differ much from the situation today. Only minor parts of the newly formed land will have the potential for cultivation due to the boulder-rich sediments in the former sea and lake areas, but also due to problems with draining the low-elevation new areas.

8.2.3 Discharge areas and biosphere objects

Biosphere objects are defined as areas in the landscape that potentially could receive radionuclides released from a repository. This means that we have to use hydrogeological information that, in time and space, gives us information about flow paths up to the biosphere from the repository volume.

It also means that we need to define the landscape description in units suitable to delimit such discharge areas. This is done by using the discharge pattern that emerges from the flow path simulations and linking the discharge points identified to specific ecosystems at the surface. So, the strategy of mapping the simulated discharge areas onto the distributed landscape development model gives us a good understanding of where in the landscape we can expect to find biosphere objects.

Geometries of the landscape will change with glacial cycles; as bedrock is eroded the regolith is reworked by glacial and post-glacial processes. However the general geometrical patterns are expected to be similar and the identified biosphere objects span a wide range of sizes and positions in the landscape. Thus, it is argued that the geometric properties of future objects will be captured in the variation of identified biosphere objects.

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

The basin of one of the original biosphere objects (121) was partitioned into three separate biosphere objects in order to represent discharge directly into a stream or a wetland without going through a lake stage. One of these objects, 121_03, is small with respect to both area of the sub catchment and watershed. Thus, to examine the effect of this subdivision of a biosphere object, we decided to incorporate the sub objects into the landscape model to be used in the overall assessment. Note that these sub objects (121_2 and 121_3) were not delimited according to the standard methodology and should be seen as extremes.

8.2.4 Landscape development model

The landscape development model is defined by putting all available surface system information together in time and space. In this work, a description of the Forsmark landscape is produced, with all the features, processes and properties needed to describe plausible futures that can be used in the modelling of potential future radionuclide releases.

The model has distributed information in grid cells with a scale of a few tens of metres for both abiotic and biotic properties, and for the time scales needed to describe the far future. However, the landscape development model is not a prediction of what is to come, but realistic descriptions of relevant futures. This description of a potential future relies on the site-specific understanding gained from several years of investigations and modelling exercises.

The landscape model describing developments at Forsmark is constructed with the elevation model as a backbone. This model includes the upper surface of sediment in the sea and in lakes, as well as soils on land. A good present-day elevation reference for the area is essential for many other models such as hydrological models and regolith models. With the soil and sediment information from the site description, a soil-depth model was produced. Step by step a model of the present landscape of Forsmark was constructed and new information was added.

The final landscape development model is, as described above, a synthesis of all available information on abiotic and biotic properties, processes and long-term succession. This means that the uncertainties in each of the underlying models are to be taken into account when discussing potential uncertainties in the landscape development model. However, the future development of the Forsmark landscape is not to be seen as a distinct prediction, but more as a relevant example on how Forsmark may develop during the present interglacial period. We argue that this example, built on extensive site data and process understanding, also is relevant for all future interglacials to come.

We also believe that this dynamic approach, with its final simulated succession model, gives us a useful tool to explain the results, not only to the initiated reader but to the public and non professionals searching for information on how site-specific data used in risk calculations are extracted and how the site understanding is implemented in the dose calculations. We argue that this landscape description and the data extracted from modelling done within the framework of this report is the state of the art supporting tool for predicting future risk for humans and environment, in case of future releases from a repository for spent nuclear fuel.

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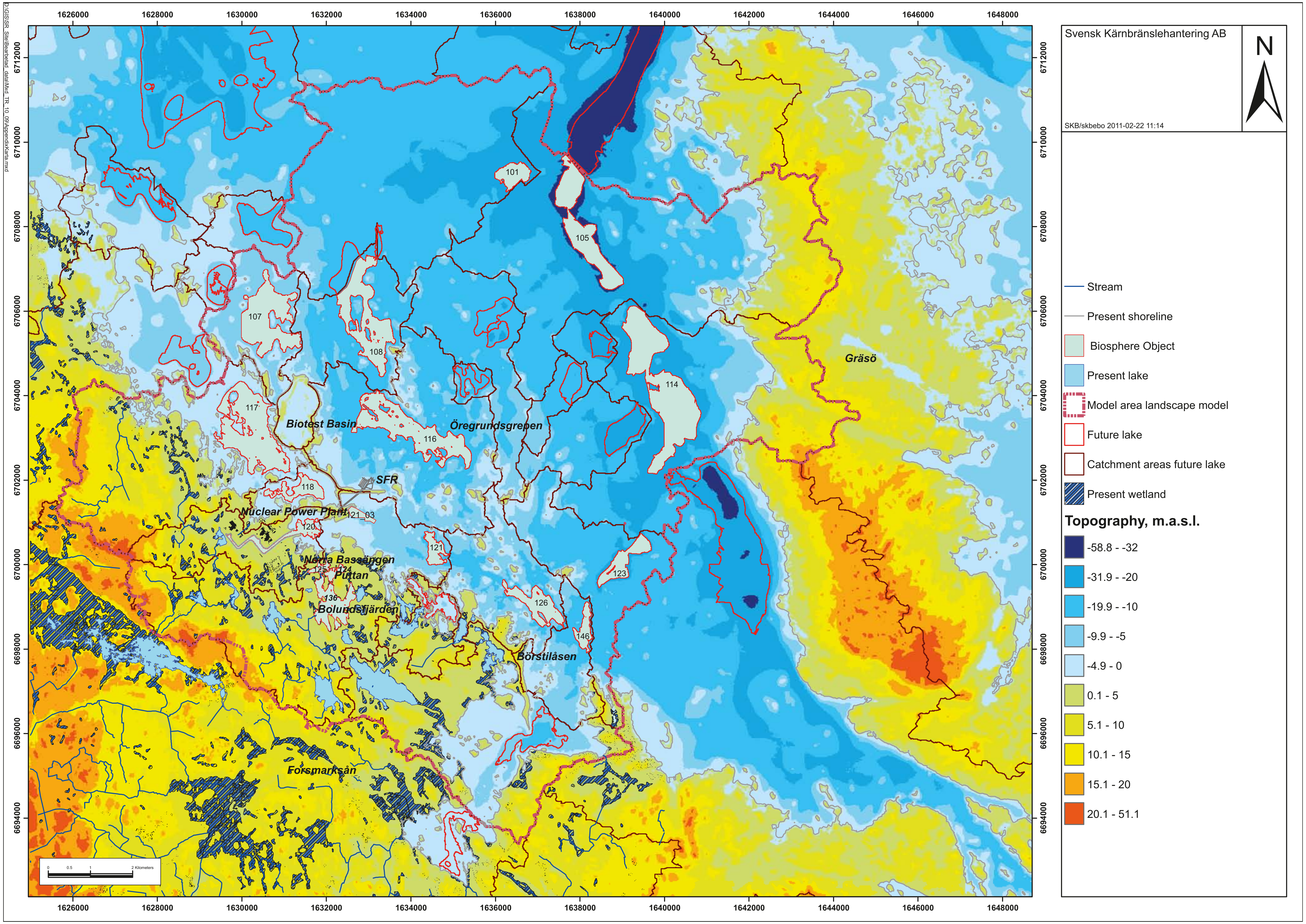
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