R-08-11

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Site descriptive modelling

SDM-Site Forsmark

Tobias Lindborg (editor), Svensk Kärnbränslehantering AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Tel +46 8 459 84 00

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Preface

This document is the main report of the SurfaceNet project, a compilation and integration of site descriptions and numerical models for the surface system at the Forsmark site. The project is a preparatory step for an overall site description of Forsmark (SDM-Site Forsmark), intended to support the safety assessment, environmental impact assessment and the design of a potential repository of nuclear waste.

The undersigned has edited the report and has been responsible for the methodology development in consultation with the below listed persons responsible for specific subjects or science topics.

The following persons have had the main responsibilities for specific subject areas in the project:

Hydrology and geohydrology: Sten Berglund, *SKB*, Emma Bosson, *SKB* and Per-Olof Johansson, *Artesia grundvattenkonsult*.

Quaternary deposits, sediments and soils: Anna Hedenström, *Sveriges Geologiska Undersökning* and Gustav Sohlenius, *Sveriges Geologiska Undersökning*.

Chemistry: Björn Söderbäck, *SKB*, Birgitta Kalinowski, *SKB* and Mats Tröjbom, *Mopelikan*.

Geometrical modelling: Lars Brydsten, *Umeå University* and Mårten Strömgren, *Umeå University*.

Terrestrial ecosystem: Anders Löfgren, *EcoAnalytica*.

Limnic ecosystem: Sara Norden, *SKB* and Eva Andersson, *Sweco*.

Marine ecosystem: Erik Wijnbladh, *SKB*, Karin Aquilonius *Studsvik Nuclear AB*, Anders Engqvist, *Kungliga Tekniska Högskolan* and Sören Floderus, *Wider IP*.

Human population and land use: Sofia Miliander, *Vattenfall AB*.

Geographical Information System: Helena Nyman, *Sweco* and Malin Andrée, *Sweco*.

Anders Ström, *SKB*, Johan Andersson, *JA Streamflow*, Kristina Skagius, *Kemakta Konsult AB* and Anders Winberg, *Conterra AB* acted as a technical coordinating group (KATJA) during the project.

This report has been reviewed by internal and external experts. Specifically, a review has been conducted by members of the SKB international Site Investigation Expert Review Group (SIERG): Mike Thorne, *Mike Thorne and associated Ltd*, UK and Jordi Bruno, *Amphos XXI Consulting S.L.,* Spain. It has also been reviewed in parts by Ulrik Kautsky, *SKB* and some of the members of the project group listed above.

Stockholm, December 2008

Tobias Lindborg

Project leader SurfaceNet

Summary

The Swedish Nuclear Fuel and Waste Management Co. SKB, has undertaken site characterization of two different areas, Forsmark and Laxemar-Simpevarp, in order to find a suitable location for a geological repository for spent nuclear fuel. The site characterization comprises both the bedrock and the surface systems. This report focuses on the site descriptive modelling of the surface system at Forsmark. The overall objective of this work has been to develop and document an integrated description of the surface system, based on available data from the complete site investigations. This description will serve as a basis for a site-adapted layout of the final repository, for assessment of the repository's long-term radiological safety and to support the environmental impact assessment of the repository.

The characterization of the surface system at the site was primarily made by identifying and describing important properties in different parts of the surface system, properties concerning e.g. hydrology and climate, Quaternary deposits and soils, hydrochemistry, vegetation, ecosystem functions, but also current and historical land use. The report presents available input data, methodology for data evaluation and modelling, and resulting models for each of the different disciplines. Results from the modelling of the surface system are also integrated with results from modelling of the deep bedrock system.

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 120 km north of Stockholm. The investigated area is located along the shoreline of Öregrundsgrepen, a funnel-shaped bay of the Baltic Sea. The area is characterized by small-scale topographic variations and is almost entirely located at altitudes lower than 20 metres above sea level. The Quaternary deposits in the area are dominated by till, characterized by a rich content of calcite which was transported by the glacier ice to the area from the sedimentary bedrock of Gävlebukten about 100 km north of Forsmark. As a result, the surface waters and shallow groundwater at Forsmark are characterized by high pH values and high concentrations of certain major constituents, especially calcium and bicarbonate.

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 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 giving rise to 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, the values of which are based on measurements, are typical or slightly higher than in the surrounding region. Groundwater levels in Quaternary deposits 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.

Post-glacial land uplift, in combination with the flat topography, implies fast shoreline displacement. This has resulted in a young terrestrial system that contains a number of newborn lakes and wetlands. The recently isolated and shallow oligotrophic hardwater lakes that are typical for the area are unique in Sweden.The marine ecosystem at Forsmark is situated in a relatively productive coastal area in a region of otherwise fairly low primary production. 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.

Based on an overall conceptual model, it was possible to identify pools and fluxes of elements in the landscape that are of potential relevance for a safety assessment. The quantification of these elements, using both field- and model-based estimates, makes it possible to determine the relative importance of the different ecosystems with regard to elemental transport and accumulation. A special emphasis has been put on the description of transport and accumulation of organic matter, since detailed knowledge on the carbon dynamics provides a way of analysing how different ecosystem components are linked to each other through fluxes of energy, i.e. carbon. This provides a baseline for making predictions of dispersal and accumulation of matter, including radionuclides, within and between ecosystems. By this approach, the safety assessment is provided with a tool to predict how and where radionuclides are transported and accumulated in the landscape, making it possible to calculate potential doses to humans and other biota for the specific site.

In the terrestrial landscape at Forsmark, many of the vegetation types are sinks for organic matter. The largest sink is the vegetation itself, but also the soil accumulates organic material, although in smaller quantities. The exception is the wetlands that are of significant importance for accumulation of organic matter and other elements, such as phosphorus, in the soil organic pool. In particular, the reed-dominated wetlands surrounding many of the lakes accumulate large amounts of organic matter and associated elements.

The most important inflow of elements to lakes is via water from the terrestrial areas. The larger lakes at Forsmark are, similar to the wetlands, important sites for accumulation of organic matter and many other elements, whereas some of the smaller lakes probably function more as flow-through systems. Transport from land, lakes and streams gives only a minor contribution of organic matter to the marine ecosystem. The major fluxes of organic matter in the marine ecosystem are instead governed by advective water fluxes.

The resulting description of dominating pools and fluxes in the different ecosystems makes it possible to assess the relative importance of different processes for the transport and accumulation of various elements and substances, including radionuclides, within and between ecosystems. This description constitutes, together with the site-specific quantifications of important properties and processes in different parts of the surface system presented in this report and in a number of discipline-specific background reports, a comprehensive basis for the modelling of radioactive dose to humans and to other biota in the safety assessment. Moreover, the description will contribute to a site adaptation of the repository, and be an important basis for the environmental impact assessment.

Sammanfattning

Svensk Kärnbränslehantering AB, SKB, har utfört platsbeskrivningar på två olika platser, Forsmark och Laxemar-Simpevarp, för att hitta en lämplig plats för ett slutförvar för använt kärnbränsle. Platsbeskrivningarna görs för både berg- och ytsystemet. Denna rapport fokuserar på den platsbeskrivande modellen av ytsystemet i Forsmark. Det övergripande syftet med detta arbete har varit att utveckla och dokumentera en integrerad beskrivning av ytsystemet, baserad på tillgängliga data från platsundersökningarna. Beskrivningen utgör en grund för platsanpassad utformning av slutförvarsanläggningen, liksom för en värdering av denna anläggnings långsiktiga säkerhet. Dessutom utgör beskrivningen underlag för en miljökonsekvensbeskrivning av slutförvaret.

Karakteriseringen av ytsystemet har tagits fram genom identifiering och beskrivning av viktiga egenskaper i olika delar av ytsystemet. Dessa delar omfattar t.ex. hydrologi och klimat, kvartärgeologi och jordmån, hydrokemi, vegetation, ekosystem, samt nuvarande och historisk markanvändning. I rapporten presenteras tillgängliga data från platsundersökningarna, liksom utvärderingar och sammanställningar av dessa data. Vidare redovisas modelleringsmetodik och resulterande modeller för de enskilda disciplinerna. Dessutom görs en jämförelse och integrering av beskrivningar och modellresultat mellan det ytliga systemet och det djupa berget.

Forsmark är beläget vid kusten i Östhammars kommun i norduppland, ungefär 120 km norr om Stockholm. Den undersökta platsen ligger i anslutning till Öresundsgrepen, en trattformad vik av Östersjön som är öppen mot norr och som i öster avgränsas av Gräsö. Området karaktäriseras av småskalig topografisk variation och är till största delen beläget lägre än 20 meter över nuvarande havsnivå. De kvartära avlagringarna i området domineras av en kalkrik morän som härrör från den sedimentära berggrund som finns i Gävlebukten, ca. 100 km norr om Forsmark. Den kalkrika moränen medför att ytvattnet och det ytliga grundvattnet i Forsmark har högt pH och höga koncentrationer av kalcium och bikarbonat.

Den genomsnittliga årliga nederbörden och avrinningen är 560 mm respektive 150 mm. De största sjöarna i området är Fiskarfjärden, Bolundsfjärden och Eckarfjärden. Sjöarna är relativt små och grunda, med ett genomsnittligt djup på 0,1 till 1 meter och ett genomsnittligt maxdjup på 0,4 till 2 meter. Havsvatten tränger in i de lägst belägna sjöarna under tillfällen med höga havsvattenstånd. Våtmarker är frekventa och täcker 25–35 % av de beskrivna avrinningsområdena.

Stora vattendrag förekommer inte inom platsundersökningsområdet. Vattendragen nedströms Gunnarsboträsket, Eckarfjärden och Gällsboträsket är aktiva under större delen av året, men kan torka ut periodvis under torra år som t ex 2003 och 2006. Många vattendrag har fördjupats och breddats längs avsevärda sträckor i syfte att avvattna området.

Moränens horisontella hydrauliska konduktivitet och vattenavgivningstal, som är baserade på mätningar inom området, uppvisar värden som är typiska eller något högre än i regionen i stort. Grundvattenytan i avlagringarna ligger vanligen mycket nära markytan, i genomsnitt närmare markytan än 0,7 m under 50 % av tiden. Ytnära grundvattennivåer medför en stark koppling mellan evapotranspirationen, det omättade marklagrets vatteninnehåll och grundvattnet.

Landhöjningen i kombination med den flacka topografin har medfört en snabb och kontinuerlig strandlinjeförskjutning efter den senaste isavsmältningen. Detta har resulterat i ett ungt landskap ovan strandlinjen, med många nyskapade sjöar och våtmarker. Sjöarna i området är mycket grunda och klassificeras som kalkoligotrofa. Denna sjötyp som är vanlig längs Upplandskusten är unik när det gäller övriga Sverige. Det marina ekosystemet i Forsmark tillhör ett relativt produktivt kustområde i en region som annars präglas av låg primärproduktion. Havsbotten i området domineras av erosions- och transportbottnar, och bottenmaterialet utgörs framför allt av sand och grus med varierande inslag av glaciala leror.

Med utgångspunkt från en övergripande konceptuell modell identifierades vilka pooler och flöden av grundämnen i landskapet som kan ha betydelse för en säkerhetsanalys av ett framtida förvar. Dessa pooler och flöden kvantifierades sedan för olika ekosystem med hjälp av data från både fältmätningar och modelleringar. Särskild vikt har lagts vid beskrivningen av transport och ackumulation av organiskt kol, eftersom kunskap om kolets omsättning gör det möjligt att visa hur olika delar av ett ekosystem är kopplade till varandra genom flödet av energi i form av organiskt bundet kol. Flöde och ackumulation av kol inom och mellan ekosystem anger också i viss mån ramarna för flöde och ackumulation av andra ämnen, inklusive radionuklider. Beskrivningarna ger därigenom underlag för att förutsäga hur och var radionuklider kommer att transporteras och ackumuleras i landskapet, ett underlag som sedan kan användas vid säkerhetsanalysen för att beräkna potentiell radioaktiv dos till människa och annan biota baserat på platsspecifika data.

I det terrestra landskapet i Forsmark utgör många av de dominerande vegetationstyperna sänkor för organiskt material. Den största sänkan är vegetationen själv, men även jorden ackumulerar organiskt material, fast då i mindre omfattning. Undantaget är våtmarkerna där det sker en betydande ackumulation av organiskt kol och även av andra grundämnen, t.ex. fosfor, i sedimentpoolen. Speciellt i vassbältena som omger många av sjöarna och våtmarkerna i området, ackumuleras stora mängder organiskt material och därmed många andra ämnen som är associerade till organiskt material.

Det viktigaste inflödet av olika grundämnen till sjöar är det som kommer via vatten från det omgivande terrestra systemet. I de större sjöarna i Forsmark sker, liksom i våtmarkerna, en betydande ackumulation i sedimenten av organiskt kol och många andra grundämnen, medan de mindre sjöarna troligen fungerar mer som genomströmningsområden. Transport av ämnen från land, sjöar och vattendrag till havet ger bara en liten del av det totala bidraget till det marina systemet i Forsmark. De största flödena av organiskt material liksom av andra ämnen i det marina systemet sker istället genom vattentransport mellan havsbassänger.

Den resulterande beskrivningen av dominerande pooler och flöden i de olika ekosystemen gör det möjligt att bedöma den relativa betydelsen av olika processer för transport och ackumulation av olika ämnen, inklusive radionuklider, inom och mellan ekosystem. Denna beskrivning utgör, tillsammans med de platsspecifika kvantifieringar av viktiga egenskaper och processer i olika delar av ytsystemet som presenteras i denna rapport och i ett antal ämnesspecifika underlagsrapporter, ett omfattande underlag för modellering av radioaktiv dos till människor och övrig biota i samband den kommande säkerhetsanalysen av ett framtida slutförvar. Kunskapen om viktiga egenskaper och processer i ytsystemet utgör också underlag för en platsanpassad utformning av förvaret, liksom för den kommande miljökonsekvensbeskrivningen av förvaret.

Contents

1 Introduction

1.1 Background

Radioactive waste from the Swedish nuclear power plants is managed by the Swedish Nuclear Fuel and Waste Management Co. (SKB). The Swedish programme for geological disposal of spent nuclear fuel is approaching a major milestone in the form of permit applications for an encapsulation plant and a deep geological repository. For siting of the geological repository, SKB has undertaken site characterization at two different locations, Forsmark and Laxemar-Simpevarp. The site investigations have been conducted in campaigns, punctuated by data freezes. After each data freeze, the site data have been analysed and modelling has been carried out with the overall purpose of developing a site descriptive model (SDM). A SDM is an integrated model of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, bedrock transport properties and the surface system. In this report, the surface system is defined as the upper part of the bedrock, the Quaternary deposits and the biotic and abiotic parts of the ecosystems at the surface.

The surface system part of the SDM, e.g. hydrology, Quaternary deposits, chemistry, vegetation, animals, human population and land use, is compiled in this report. The ecosystem description is an integration of information on the site and its regional setting, covering the current state of the biosphere as well as the ongoing natural processes affecting its long-term development. Prior to this report, earlier versions of surface system descriptions have been produced for the Forsmark area. Version 0 /SKB 2002/ established the state of knowledge prior to the start of the site investigation programme. Version 1.1 /SKB 2004/, which was essentially a training exercise, was completed during 2004 and version 1.2 in June 2005 /Lindborg 2005/. Version 1.2, a preliminary site description, concluded the initial site investigation work /SKB 2005b/. It formed the basis for a preliminary safety evaluation, a preliminary repository layout, and the first evaluation of the long-term safety of KBS-3 repositories in the context of the SR-Can project /SKB 2006a/.

This report presents the surface system description part of the final Forsmark SDM produced in the site investigation stage. This SDM version is refered to as SDM-Site Forsmark. The main report describing all modelling disciplines in SDM-Site Forsmark is "Site description of Forsmark at completion of the site investigation phase" /SKB 2008/. The present site description of the surface system includes two main components:

- a written synthesis of information related to the site, summarising the state of knowledge as well as describing ongoing natural processes which affect its long-term evolution, and
- a site descriptive model, in which the collected information is interpreted and presented in a form that can be used, or further synthesised, in numerical models for engineering, and in environmental impact and long-term safety assessments.

1.2 Objectives

The overall objective of this part of the site descriptive modelling work at Forsmark was to develop and document an integrated description of the surface system, based on available data from the complete site investigation. This description will serve as a basis for a site-adapted layout of the final repository, for assessment of the repository's long-term radiological safety (SR-Site) and to support the environmental impact assessment of the repository with site understanding and descriptions. The description was required to be based on a fundamental understanding of the surface system, which is achieved by analysing the reliability and assessing the reasonableness of the assumptions made with respect to the current state of the Forsmark site and naturally ongoing processes. Furthermore, the work was required to make use of all knowledge and understanding built into previous model versions and the feedback obtained from the safety assessment SR-Can.

The specific objectives of the work were to:

- analyse the primary, site-specific, data available in data freeze Forsmark 2.2 and 2.3, together with other representative data from the Forsmark area,
- develop and document ecological (including human demography and land use), geological, hydrological and near-surface hydrogeological models,
- develop an integrated site description covering all disciplines represented in the surface system,
- describe site-specific processes and properties important for the understanding of transport of matter within and between the bedrock- and surface systems,
- perform an overall confidence assessment.

The strategy applied for achieving the stated objectives was to base the SDM on the quality-assured field data from Forsmark that were available in the SKB databases Sicada and Geographical Information System (GIS) at the date defined for data freeze 2.2. This data freeze contained all data planned to be collected during the site investigation from the target area. All new data that were available at the date defined for data freeze 2.3, i.e. on March 30th 2007, have been used for complementary analyses and verification of the models. Since the site investigation has carried on beyond the date of data freeze 2.3, although at a much lower intensity, additional data have become available post data freeze 2.3. These "late" data have, as far as possible, been assessed and commented upon in relation to the models derived.

1.3 The site

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 120 km north of Stockholm. The candidate area for site investigation is located along the shoreline of Öregrundsgrepen. It extends from the Forsmark nuclear power plant in the northwest, to Kallrigafjärden in the southeast (Figure 1-1) and is approximately 6 km long and 2 km wide. The north-western part of the candidate area was selected as the target area for the complete site investigation work /SKB 2005a/. Although the investigations were concentrated to the candidate area for a repository, a number of investigations have been conducted over a larger area, covering the whole landscape on land and in the sea in the regional surroundings (Figure 1-2).

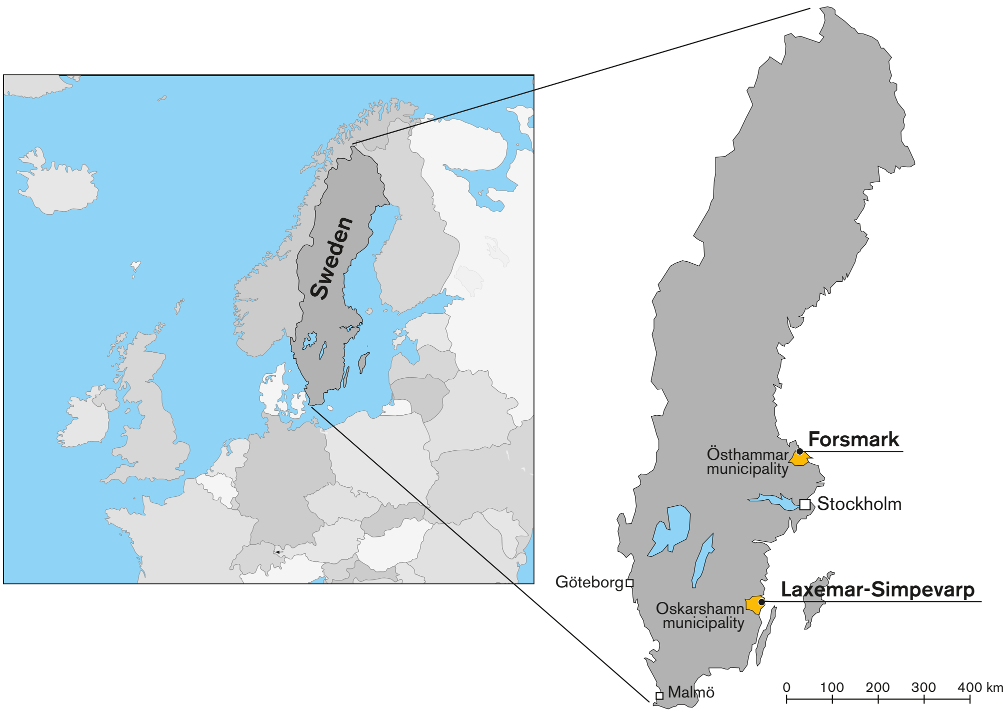

Figure 1-1. Map of Sweden with the two sites Forsmark and Laxemar-Simpevarp.

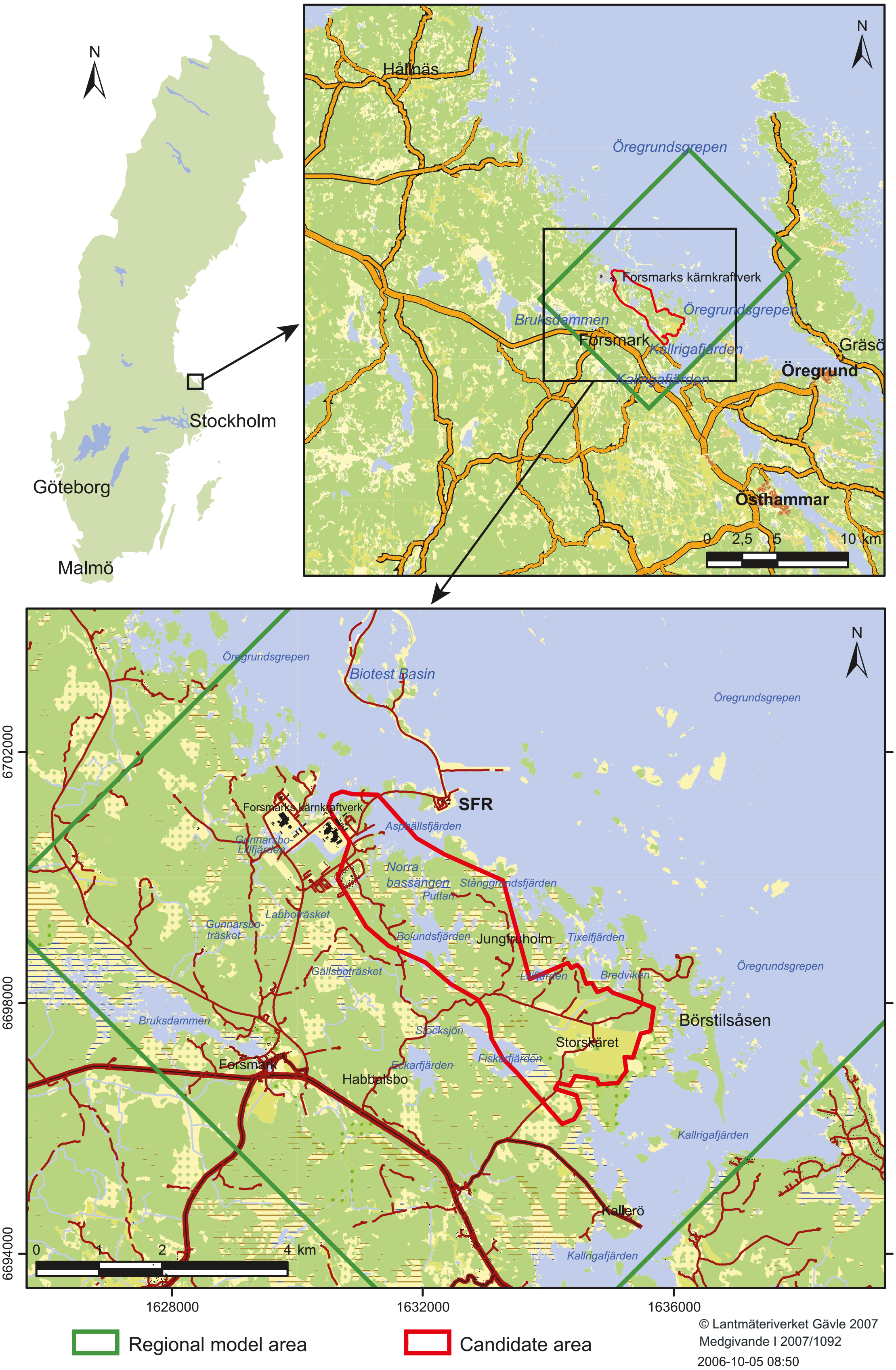

Figure 1-2. *Overview of the Forsmark area and identification of model areas.*

The Forsmark area consists of a crystalline bedrock formed between 1,890 and 1,850 million years ago during the Swecokarelian orogeny /Söderbäck (ed) 2008/ and it has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale ductile high-strain zones and the brittle deformation has given rise to large-scale fracture zones. Tectonic lenses, in which the bedrock is much less affected by ductile deformation, are enclosed between the ductile high strain zones. The candidate area is located in the north-westernmost part of one of these tectonic lenses.

The study area is characterized by small-scale topographic variations and is almost entirely located below 20 m.a.s.l. (metres above sea level), see Figure 1-3. Till is the dominant Quaternary deposit. The surface water and shallow groundwater at Forsmark is characterized by high pH values and high concentrations of certain major constituents, especially calcium and bicarbonate.

1.4 This report

This report presents the integrated description of the surface system at the Forsmark site after the completion of the surface-based investigations. The report gives a summary of the models and the underlying data supporting the current understanding of the surface system. It is intended to describe the properties and conditions at the site and to give the information essential for demonstrating understanding, and relies heavily on a number of discipline-specific background reports concerning details of the data analyses and modelling. The present report and the hierarchy of background reports in the overall SDM reporting is illustrated in Figure 1-4 and is further described below.

Figure 1-3. *Photograph from Forsmark showing the low gradient shoreline with recently isolated bays due to the rapid land uplift.*

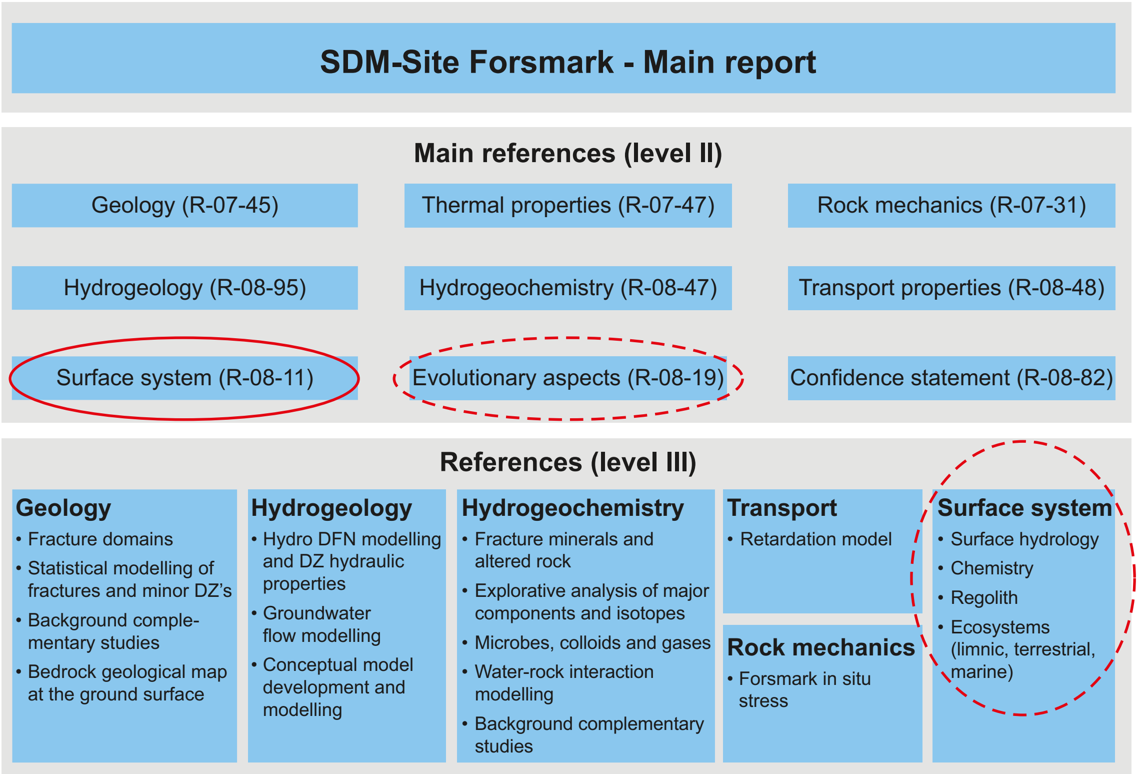

***Figure 1-4.** SDM-Site main report and background reports at different levels produced during modelling stages 2.2 and 2.3. DZ = Deformation Zones and DFN = Descrete Fracture Network. This report is encircled by a red line and supporting sub reports are encircled by dotted red.*

The main subreports produced within the SurfaceNet site description project and integrated in this report are:

- Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas. Site descriptive modelling, SDM-Site (R-08-19).
- The terrestrial ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (R-08-01).
- The limnic ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (R-08-02).
- The marine ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (R-08-03).
- Description of the regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark (R-08-04).
- Description of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark (R-08-08).
- Hydrochemistry of surface water and shallow groundwater. Site descriptive modelling, SDM-Site Forsmark (R-07-55).

The reader should use this report as a summarizing guide to the discipline-specific descriptions covering the surface system at Forsmark. The report also provides the integration between the scientific fields and the overall linking between the bedrock and the surface system, using transport of matter in and between different domains, from the upper bedrock to the surface, as a main theme.

The first chapter (this introduction) informs the reader as to the aims of the work by setting out the major questions at issue. The chapter also illustrates how the project has been managed in general and how and where the final surface system description is reported.

Chapter 2 lists all input data used, both from the site investigations and from elsewhere. The list also refers to the publications associated with the data and summarizes how data were used.

In Chapter 3, a description of methodology and data handling gives the reader an overview of how the descriptions and models were developed. In the first section, the overall strategy of the SurfaceNet project is described, and the following sections give information on discipline-specific methodologies.

Chapter 4 describes the results. Section-by-section the final discipline-specific results are presented, together with references used.

Chapter 5, gives an overview of both the surface system and the upper part of the bedrock system in an integrated way. By using the transport of matter from the bedrock to the surface as the overall theme, the integration between different domains is described and an overall conceptualisation, in terms of transport, is developed.

In Chapter 6, a summarizing integrated synthesis of the different descriptions and models is presented. Further, site-specific data are discussed, supporting the site conceptualisation and overall synthesis. Finally, our confidence in the description is discussed.

Appendix 1 is a map of the Forsmark region.

1.5 Definitions

In this report, a number of scientific terms are used. To guide the reader in the usage of these terms, a table (Table 1-1) is presented below, listing the definitions of terms used in this report.

Table 1-1. Definitions on terms used in this report.

Concept/term	Definition
Abiotic	Not directly caused or induced by living organisms.
Autotroph	Organism that produces organic matter from CO_2 and environmental energy rather than by consuming organic matter produced by other organisms. Here synonymous with primary producers.
Biotic	Caused or induced by living organisms.
Conceptual model	A qualitative description of the components in a system.
Descriptive model	A quantitative description of the components in an ecosystem. Can be static or dynamic (see below).
Dynamic model	A dynamic model describes the behaviour of a spatially distributed parameter system in terms of how one qualitative state can turn into another.
Ecosystem model	Conceptual or mathematical representation of an ecosystem. Simplifying complex food webs down to their major components or trophic levels, and quantify these as either numbers of organisms, biomass or the inventory/concentration of some pertinent chemical element.
Flux	Flow of energy or material from one pool to another.
Food web	Group of organisms that are linked together by the transfer of energy and nutrients that originates from the same source .
Functional group	Collection of organisms based on morphological, physiological, behavioural, biochemical, environmental response or trophic criteria.
Gross primary production (GPP)	Net carbon input to an ecosystem – that is, net photo-synthesis expressed at an ecosystem scale ($gCm^{-2}yr^{-1}$) /Chapin et al. 2002/.
Heterotroph	Organism that consumes organic matter produced by other organisms rather than producing organic matter from CO_2 and environmental energy; includes decom-posers, consumers and parasites /Chapin et al. 2002/.
Mass balance	A model describing the import and export of elements or matter in a system, which thereby makes it possible to identify unknown mass flows or estimate mass flows that are difficult to measure.
Net ecosystem production (NEP)	The difference between gross primary production and ecosystem respiration /Chapin et al. 2002/.
Net primary production (NPP)	The difference between gross primary production and plant respiration.
Pool	Quantity of energy or material in an ecosystem compartment such as plants or soil /Chapin et al. 2002/.
Respiration	Biochemical process that converts carbohydrates into CO_2 and water, releasing energy that can be used for growth and maintenance. Heterotropic respiration is animal respiration plus microbial respiration, ecosystem respiration is heterotrophic plus autotrophic respiration /Chapin et al. 2002/.

2 Input data

A large amount of data are available from the Forsmark site to use for building a SDM of the surface system. Both data from the site investigations performed by SKB since 2002, and from elsewhere are available. This chapter first lists the different types of investigations used by SKB to give the reader an overview of the input sources available. Then, two tables are presented (Table 2-1 and 2-2) which provide the information needed to understand and evaluate the actual input data used in the description of the surface system of Forsmark, as it is presented in this report. Input data is also discussed in Chapter 3 where the methodology to produce the discipline specific descriptions is described. For a thorough description on discipline-specific input data, and how these data have been treated, we refer to the background reports listed in section 1.4.

2.1 Quaternary geology and ground geophysics

The mapping of Quaternary deposits was initiated in 2002 and the field work has continued through 2002–2007. Data are both surface-based and of stratigraphical character. The major components of data from the initial stage of the site investigations are listed below.

- Stratigraphical and analytical data from auger drillings and pits.
- Stratigraphical investigations of till in machine-cut trenches.
- Ground penetrating radar (GPR) and Continuous Vertical Electrical Sounding (CVES) measurements for regolith investigations (test of methods, ground penetrating radar survey 2003, two interpretation reports, one utilizing GPR- and CVES-surveys, the other only GPR measurements).
- Updated information on bedrock topography, and hence the thickness of the regolith, using seismic tomography from the reflection seismic survey, Stage 1.
- Estimation of bedrock topography (and regolith thickness) along refraction seismic profiles.
- Investigations of marine and lacustrine sediments – stratigraphical and analytical data.
- A map and associated description based on the mapping of Quaternary deposits performed in 2002–2003.
- Elemental distribution in till at Forsmark – a geochemical study.
- Microfossil analyses of till and sediment samples from Forsmark.
- Results from peatland investigations.

The following data were added to the previously existing data set and are valid as new input for this version of the site description.

- Updated soil type map.
- Quaternary geology map for the shallow areas along the coastline.
- Interpreted map of Quaternary deposits for the lakes and shallow areas off shore.
- Additional stratigraphical and analytical data from auger drillings, corings and excavations.
- Chemical analyses and radiometric datings of sediments and peat.
- Stratigraphical investigation of a marine sediment core.
- Petrographical analyses of boulders and gravel in till.
- Additional estimations of bedrock topography and regolith thickness along refraction seismic profiles.

2.2 Meteorology, hydrology and hydrogeology

The meteorological, hydrological and near-surface hydrogeological investigations comprise the following major components.

- Establishment of two meteorological stations and collection of meteorological data.
- Monitoring of snow depth, snow water content, ground frost and ice cover.
- Identification of surface-water catchments.
- Survey of lake thresholds, lake bathymetry, and brook gradients and cross-sections.
- Establishment of four surface discharge gauging stations for collection of water level, electrical conductivity, temperature and discharge data.
- Installation of surface-water level gauges and collection of water-level data.
- Installation of groundwater monitoring wells and pumping wells in Quaternary deposits (QD) and collection of groundwater-level data.
- Slug tests and pumping tests in wells in QD.
- Laboratory measurements of hydraulic properties on QD samples (hydraulic conductivity and water retention curve).
- Installation of BAT-type filter tips and permeability tests and pore pressure data collection in the tips.

In addition to the investigations listed above, the modelling summarised in the present report is based on data from the SKB databases Sicada and SKB-GIS on:

- topographic and other geometrical conditions,
- surface-based geological investigations of QD and soil type mapping,
- composition and stratigraphy from boreholes, pits and trenches in QD,
- the hydrogeological properties of the bedrock and groundwater levels from the percussion-drilled boreholes,
- soil and water chemistry.

2.3 Chemistry

Chemical data from the surface system are available from a number of different media and object types, as described below.

- Surface-water samples – precipitation, lake, stream and sea water. Precipitation data are available from two sampling stations (cf. Table 3-6 in /Tröjbom and Söderbäck 2006/), whereas surface-water samples from 6 lakes, 4 shallow sea bays and 8 streams were collected monthly, and periodically even more often, from the start of the site investigations in 2002. From summer 2004, the sampling programme was reduced to 5 lakes, 1 sea bay and 4 streams /Nilsson and Borgiel 2005/.
- Shallow groundwater samples. Sampling and analysis of shallow groundwater from soil tubes (samples from more than 50 soil tubes have been analysed, and about 30 of these soil tubes were sampled repeatedly (cf. Table 3-3 in /Tröjbom and Söderbäck 2006/)) and from 7 private wells were included in the programme.
- Regolith samples. Samples of QD have been taken during drilling of boreholes and soil tubes, and from machine-excavated trenches. There are also a number of sediment samples from the bottom of lakes and the sea, as well as a few peat samples from bogs (cf. Tables 3-8 in /Tröjbom and Söderbäck 2006/).
- Biota samples. Organisms from different functional groups have been sampled from the lake, sea and terrestrial ecosystems /Hannu and Karlsson 2006/.

2.4 Ecology

This discipline uses to a large extent data from other disciplines, such as Quaternary geology, hydrology and hydrochemistry. Investigations made exclusively for ecological purposes within the site investigation, and reported before data freeze 2.3, are listed below. The volume and variety of surface ecological data have increased considerably since data freeze 1.2.

- Surface water sampling at the same sampling points as defined above for hydrochemistry, as well as at two additional sampling points in shallow sea bays and two additional points in running waters. In addition to the parameters analysed within the hydrochemical programme, some other parameters are analysed within the ecological programme, e.g. nutrient salts, chlorophyll, carbon species and silica. Also, a number of physical parameters are measured in the field, e.g. turbidity, depth visibility and colour.
- Identification of catchments, lake-related drainage parameters and lake habitats.
- Water-depth soundings in shallow bays.
- Investigations of soils and solum types.
- Sampling and analyses of surface sediments in lakes and shallow bays.
- Vegetation inventory in part of the municipality of Östhammar and vegetation mapping with satellite data of the Forsmark and Tierp regions.
- Terrestrial vegetation biomass and primary production.
- Investigation of the amount of dead wood.
- Surveys of mammal populations in Forsmark over the period 2003–2007.
- Age composition and reproduction of the local population of moose. Data since 2002.
- Inventory of fish.
- Inventory of amphibians and reptiles.
- Bird monitoring at Forsmark 2002–2007.
- Distribution, biomass and turnover of tree- and field-layer roots.
- Tree litterfall from three localities.
- Soil respiration measurements from a number of different vegetation types.
- Bioturbation studies at three localities.
- Water velocity, bottom substrate, vegetation, shading and technical encroachments in streams.
- Chemical composition of terrestrial vegetation-deposits and biota.
- Sedimentation rates in a wetland and shallow sea bays.
- Investigation of bat species.
- Benthic vegetation and fauna in lakes and shallow sea bays.
- Measurements of primary production and respiration in shallow sea bays.
- Benthic biomass and primary production in Lake Bolundsfjärden.
- Inventory of vascular plants and classification of wetlands.
- Biomass of benthic bacteria and planktonic bacteria.
- Oceanographic measurements.

Table 2-1. Available abiotic data from the surface system and their handling in SDM-Site Forsmark.

Available site data Data specification	Ref.	Usage in SDM-Site Analysis/Modelling	Comments
Geometrical and topographcal data			
Geometry, topography, bathymetry, Digital Elevation Model (DEM).	P-04-25 P-04-125 R-04-70 R-08-62	Basic input to flow and transport models, 20 m horisontical resolution DEM used as input to regolith depth model.	
Geological data			
Surface data			
Geological maps, Quaternary deposits, verbal descriptions.	SGU Ae 73 SGU Ae 86 P-03-11 R-04-39 P-03-101 P-06-88 R-08-04 SKB GIS	Conceptual model, distribution of Quaternary deposits, 2D model and input to 3D regolith-depth model.	
Petrograpic analysis of gravels and boulders.	P-06-87	Glacial history, petrograpic composition of regolith.	
Soil type map.	R-04-08, updated 2006, SKB GIS	Conceptual and quantitative model, input to historical/evolutionary model.	No reference is available relating to the updated soil-type map, only available in GIS.
Stratigraphical and analytical data			
Stratigraphical and analytical data from boreholes in bedrock and regolith.	P-03-14 P-03-64 P-04-111 P-04-138 P-04-139 P-04-140 P-04-148 P-06-89 P-06-92 P-07-01	Stratigraphical distribution and characterization of Quaternary deposits. Depth to bedrock. Input to 3D regolith-depth model.	
Stratigraphy and spatial distribution of marine and lacustrine sediments and peat.	R-01-12 P-03-24 R-03-26 P-04-86 P-04-127 TR-03-17 P-05-139 P-06-88 P-06-89 P-06-92 P-06-220 P-06-301 P-07-196	Conceptual model. Description of stratigraphical distribution and characteristics of sediment in lakes and mires. Chemical properties and distribution of organic deposits in mires. Input to 3D regolith-depth model.	
Stratigraphic data from machine-cut trenches.	P-04-34 P-04-111 P-05-138 P-05-166 P-06-45 P-07-01	Depth and stratigraphical distribution of Quaternary deposits. Conceptual model of regolith, input to 3D regolith-depth model. Physical properties of QD.	
Investigation of evidence of neotectonic movements.	P-03-76 P-04-123 R-05-51 P-05-199	Conceptual understanding. Depth and stratigraphy of Quaternary deposits.	

Available site data Data specification	Ref.	Usage in SDM-Site Analysis/Modelling	Comments
Physical properties of sediment and peat, textural composition.	P-03-14 P-04-34 P-04-86 P-04-111 P-04-148 R-04-08 P-05-138 P-05-139 P-05-166 P-06-88 P-06-92 P-07-196	Conceptual understanding of regolith, input to quantitative modelling of hydraulic properties. Dominated by data on textural composition but also water content for determination of accumulation rate of sediments and peat.	
Chemical analyses and radiometric datings of glacial and post-glacial sediments.	P-03-14 TR-03-17 P-03-118 P-04-34 P-04-86 P-04-111 P-04-148 R-04-08 P-05-139 R-06-96 P-06-220 P-06-301	Conceptual model, input to quantitative model of chemical properties.	
Chemical analyses of peat.	P-04-127 P-06-301 P-06-220	Conceptual model, input to quantitative model of chemical properties.	
Microfossil composition in glacial sediments.	P-04-110 P-05-199	Conceptual understanding, dating of sediments, glacial/interglacial history.	
Geophysical data			
Ground penetrating radar.	P-04-78 P-04-156	Depth to bedrock. Conceptual model and 3D model of regolith depth.	
Refraction seismics.	P-04-81 P-05-12 P-06-138 P-06-45	Depth to bedrock. Conceptual model and 3D model of regolith depth.	
Reflection seismics.	P-04-99 P-04-158	Depht to bedrock. Conceptual model and 3D model of regolith depth.	
Helicopter-borne survey data.	P-03-41 P-04-157 P-04-282	Depth of regolith.	Only used in Regolith depth model version 2.2.
Meteorological data			
Regional data			
Precipitation, temperature, wind, humidity and global radiation up to March 2007.	R-99-70 TR-02-02 P-05-221 P-06-322 P-07-175 Sicada	Basis for general description and quantitative modelling of surface water and groundwater flow. Comparison with local meteorological data for extention of time series.	
Site Investigation data			
Precipitation, temperature, wind, humidity, global radiation and potential evapotranspiration June 2003 – March 2007 from the meteorological stations at Högmasten and Storskäret.	P-05-152 P-05-221 P-06-322 P-07-175 Sicada	Basis for site-specific description of the meteorological conditions, and conceptual, descriptive and quantitative modelling of surface water and groundwater flow. Comparison with regional meteorological data for extention of time series.	

Available site data Data specification	Ref.	Usage in SDM-Site Analysis/Modelling	Comments
Snow depth, ground frost and ice cover.	P-03-117 P-04-137 P-05-134 P-06-97 P-07-81	Validation of snow routine in quantitative modelling.	
Hydrological data			
Regional data			
Regional discharge data.	R-99-70 TR-02-02 Sicada	Specific discharge in initial conceptual, descriptive and quantitative modelling.	
Site Investigation data			
Geometric data on catchment areas, lakes and water courses.	P-04-25 P-04-141 SKB GIS	Delineation and characteristics of catchment areas and lakes, geometrical input to the MIKE-SHE modelling.	
Installation of automatic discharge gauging stations.	P-05-154	Basis for measurements of discharge, electrical conductivity and temperatures at four locations in brooks.	
Automatic discharge measurements.	P-07-135 Sicada	Data for site-specific description and water balance, conceptual and descriptive modelling, and for calibration of quantitative water flow modelling.	
Manual discharge measurements.	P-03-27 P-04-146 P-05-153 P-05-171 P-07-95 Sicada	General description of temporal variability in surface water discharge.	
Installation of surface-water level gauges.	P-03-64 P-04-139	Basis for surface water level measurements.	
Level measurements in lakes and the sea.	P-04-313 P-05-245 P-06-263 P-07-113 Sicada	Surface water-groundwater level relations, conceptual and descriptive modelling, and calibration of quantitative modelling with MIKE SHE.	
Hydrogeological data			
Inventory of private wells.	R-02-17	Description of available hydrogeological information.	No attempt is made to infer hydraulic parameters from capacity data.
Data on installed groundwater monitoring wells, abstraction wells and BAT filter tips.	P-03-64 P-04-136 P-04-138 P-04-139 P-06-89	Description of QD type and depth to bedrock, basis for groundwater level measurements and hydraulic tests.	
Hydraulic conductivity of Quaternary deposits.	P-03-65 P-04-136 P-04-138 P-04-140 P-04-142 P-06-224	Basis for assigning hydraulic conductivity of Quaternary deposits in conceptual and quantitative models.	
Groundwater levels in Quaternary deposits.	P-04-313 P-05-245 P-06-263 P-07-113 Sicada	Conceptual and descriptive modelling, and calibration of quantitative models.	

Available site data Data specification	Ref.	Usage in SDM-Site Analysis/Modelling	Comments
Oceanographic data			
Regional oceanographic data.	TR-02-02 TR-99-11 TR-08-01	Quantitative modelling (see /Lindborg 2005, Wijnbladh et al. 2008/).	
Chemical data			
Precipitation.	P-05-143	Description.	
Surface water.	P-05-274 P-07-95	Description.	
Groundwater.	R-06-19	Description.	
Regolith.	R-06-19	Description.	
Biota.	P-06-220	Description, modelling.	
Biota and regolith.	P-07-32	Description.	

Table 2-2. Available biotic data for the surface system and their handling in SDM-Site Forsmark.

Available site data Data specification	Ref.	Usage in SDM-Site Analysis/Modelling
Terrestrial data		
Compilation of existing information 2002.	R-02-08	Description.
Mammal population survey.	P-04-04	Density estimates underpin calculations of biomass and consumption.
Mammal ecological data and carbon budget.	R-05-36	Definitions of habitat and food sources.
Amphibians and reptiles.	P-04-07	Definitions of habitat and food sources and esitmates of densities.
Bird monitoring.	P-03-10 P-04-30 P-05-73 P-06-46 P-07-02	Density estimates underpin calculations of biomass and consumption.
Vegetation inventory.	P-03-81 P-06-115	Description of some vegetation types.
Vegetation mapping.	R-02-06	Description of the spatial distribution of different vegetation types, which is used in both descriptions and element modelling.
Validation of vegetation map.	P-04-314	Description of the vegetation.
Data from soil mapping.	P-04-08	Carbon content in soils underpin ecosystem and element modelling.
Soil respiration measurements.	R-06-125 P-07-23 TR-07-13	Description of vegetation types and ecosystem modelling.
Litter layer.	P-03-90 P-05-80	Description of vegetation types and ecosystem modelling.
Dead wood.	P-04-124	Description of vegetation types and ecosystem modelling.
Litter fall and litter decomposition.	R-07-23	Description of vegetation types and ecosystem modelling.
Bioturbation.	R-06-123	Description of vegetation types.

Available site data Data specification	Ref.	Usage in SDM-Site Analysis/Modelling
Fine roots.	P-05-166 R-07-01 TR-07-11	Description of vegetation types and ecosystem modelling.
Fungi.	TR-04-26	Description of vegetation types.
Field-layer biomass and production.	P-05-80	Description of vegetation types and underpin ecosystem and elemental modelling.
Tree parameters.	TR-06-29	Description of vegetation types and ecosystem modelling.
Birch on clear-cuts.	P-04-315	Description of vegetation types.
Leaf Area Index (LAI) and tree stand data.	TR-06-29	Underpin both hydrological modelling (MIKE-SHE) and spatial modelling of NPP.
Properties and function of wetlands.	TR-04-08	Description of vegetation types.
Limnic data		
Habitat borders.	P-04-25	Definition and delineation of habitats, used in description and modelling.
Limnic producers.	R-02-41 R-03-27 P-04-05 P-05-136 P-05-150 P-06-220 P-06-221	Biomass and production of proucers used in description and ecosystem modelling.
Limnic consumers.	R-02-41 R-03-27 P-04-06 P-05-136 P-06-220	Biomass of consumers used in description and ecosystem modelling.
Marine data		
Fish biomass and species composition.	SICADA P-05-148 P-04-06	Description, modelling.
Vegetation survey, species composition and biomass.	SICADA R-07-50 P-05-135 P-03-69 R-99-69	Description, modelling.
Bottom fauna, species composition and biomass.	SICADA P-05-135 P-03-67 R-99-69	Description, modelling.
Marine life from video.	SICADA P-03-68	Description, modelling.
Production and respiration.	SICADA P-06-252	Description, modelling.
Phyto- and zoo-plankton.	SICADA P-05-72	Description, modelling.
Benthic and pelagic bacteria.	SICADA P-06-232	Description, modelling.
Bird population.	See Ref. under Terrestrial	Description, modelling.

3 Data evaluation and modelling methodology

The site description is multi-disciplinary in that it covers all potential properties of importance for the overall understanding of the site, for design of the deep repository, for safety assessment and for the environmental impact assessment. The overall strategy applied in the 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 SKB Geographic Information System (GIS), and then to integrate these discipline-specific models into a unified site description. The quantitative, discipline-specific models are stored in the SKB model database Simon, from where quality assured versions of the models can be accessed by the downstream users of the site description.

The interface between the surface and bedrock systems has been considered in the evaluation of deep and shallow groundwater movement, as well as in the chemical description of the groundwater. The present conceptualisation of the hydraulic properties of the Quaternary deposits is implemented in the hydrogeological modelling, and also into modelling and evaluation of the impact of infiltration on the present groundwater chemical composition. The shallow groundwater system, including the upper part of the bedrock, is modelled with flow conditions consistent with the bedrock hydrogeological model /Johansson 2008, Follin et al. 2008/.

The work has been conducted within the project group SurfaceNet. The members of the project group represent the disciplines of geology, 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.

In order to ensure that the SDM is based on quality assured data and that the model and submodels derived based on these qualified data are correct and are the models that are delivered to, and used by, the end users, 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 QA procedures and routines and applied in the site modelling, is summarised below.

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. The execution of this process is specified in the SKB QA document SDK-508.

Primary data collected at the site are brought into the site descriptive modelling from the databases Sicada and GIS only. Information regarding the procedures for data collection and factors of importance for the interpretation of data can be taken from the documentation (P-reports) 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. The execution of the process of order and delivery of data from the databases is specified in the SKB QA documents SD-112 (Sicada) and SD-113 (GIS).

3.1 Overall strategy for the surface-system description

To achieve a site-specific description of the biosphere at a proposed location for a deep 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 characterization 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 (ed) 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 is visualized, reducing the potential range of future states of the ecosystem, and uncertainties in estimating radionuclide flow and in turn radiological consequences to humans and 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.

Building a descriptive model for the surface system can be described in the following four steps, see Figure 3-1.

- Building 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.

3.1.1 Conceptual models

A conceptual model is a necessary starting point to identify different properties that may affect the stocks and flows of matter in the ecosystems at the site. 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 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 which 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. However, the resolution of the terrestrial landscape has in our case been a function of the resolution of satellite classification techniques and the diversity of major vegetation types. Similarly, the spatial resolution of lakes has been set by the possibilities to monitor each lake separately. The categorization of lake habitats is done using a classification system of habitats developed specifically for this

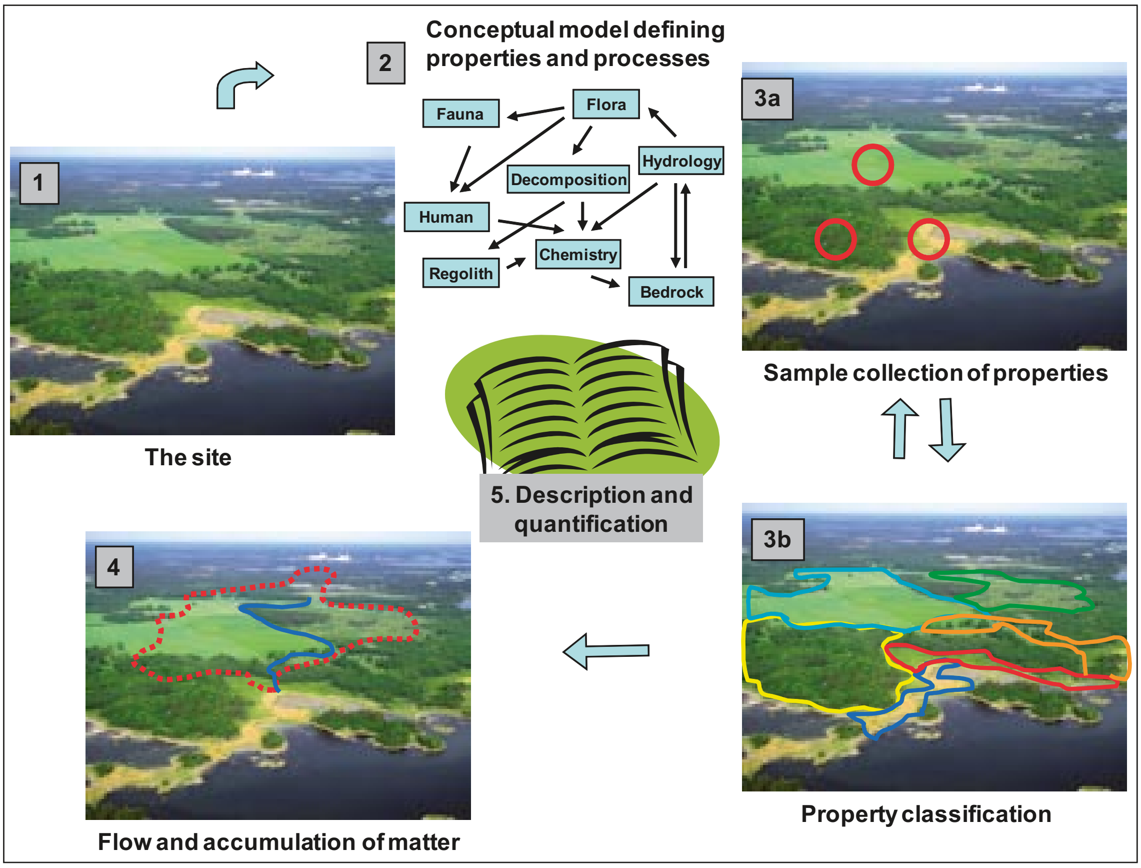

Figure 3-1. *The process of building a site descriptive ecosystem model. The site (1) is defined. A conceptual model (2) is produced describing functional units, their properties and the fluxes of matter/energy between them. Samples are collected at the site (3a) using quantitative statistics to describe the biotic and abiotic properties in the conceptual model. The landscape is divided into a number of distributed model domains using site data and GIS (3b). Flows and accumulation of matter are described using hydrological tools, drainage areas and site data (4). All information is compiled into the site descriptive ecosystem model (5).*

context, but is also general applicable /Brunberg et al. 2004/. The budgets of organic matter in terrestrial systems are described in terms of biomass, primary production, secondary production, decomposition, mineralization and soil chemistry. The budgets of organic matter in lake and sea ecosystems are described in terms of biomass, primary production, secondary production, decomposition and water chemistry /Kumblad et al. 2003/. The conceptual model also includes abiotic factors of importance for vertical or horizontal transport of matter, such as precipitation and groundwater movement, see Figure 3-2.

3.1.2 Collection of site-specific data

The two Swedish sites considered as potential locations for a future repository for spent nuclear fuel are both situated at the coast and both include a large number of different ecosystems such as forests, agriculture land, wetlands, lakes and sea. By using the conceptual model and site-specific data we established local budgets of standing stocks and flows of matter for the different units into which the landscape was spatially partitioned. The site-specific data are present in GIS, covering the specific area in a large database. This makes it possible to use over-layering techniques when merging data, e.g. making spatially explicit estimates of standing organic matter from different functional groups such as tree layer, shrub layer, field layer and ground layer.

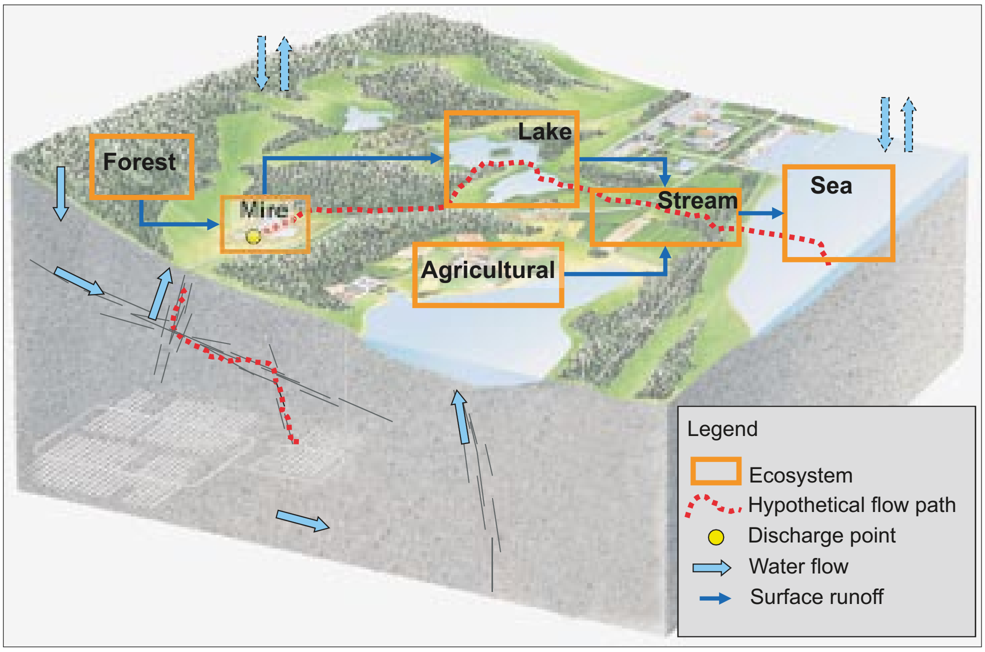

Figure 3-2. *An overall conceptual model describing the different domains and the transport of matter at a landscape level.*

3.1.3 Description and quantification of transfer and accumulation processes

Carbon and energy (e.g. kJ or kcal) can be used as interchangeable currencies in the description of ecosystem dynamics /Chapin et al. 2002/. Accordingly, organic carbon constrains the metabolism of heterotrophic organisms at different levels in the food chain. This affects both the growth and abundance of organisms, and thus the ecosystem composition. The availability and metabolism of organic carbon thereby also affects the fate and recycling of other elements, e.g. nutrients or radionuclides, in ecosystems. The proportions between carbon, nitrogen and phosphorous are often close to constant within an ecosystem, but may differ between systems, e.g. terrestrial and limnic systems /Elser et al. 2000/. Matter is recycled between organisms in the food web and the physical environment within the ecosystem, and may also accumulate within the terrestrial system as peat or within aquatic systems as organic sediments. Accumulation often means that the matter leaves the short-term recycling, and some kind of disturbance in the long-term cycle has to occur to release it to circulation again, e.g. humans start to plough old lake beds or harvest peat. In the long-term cycling, matter is leaching from the terrestrial ecosystem into watercoursers, following watercourses into lakes and in the end discharging into the sea. Some matter is accumulated along this pathway, for example in lake beds. The intention of this work was mainly to construct a spatially explicit ecosystem model that is able to describe these processes in the landscape.

The first step is to connect the different units by quantifying flows of matter between units within the ecosystem. Surface hydrology is considered the most important component determining transport of matter /Blomqvist et al. 2002/, and is thus subjected to quantitative modelling using site-specific data in order to understand vertical and horizontal movements of surface water. The functional water units of the landscape are defined by catchment areas that are constructed from water divides in the landscape (Figure 3-3). This provides a tool to separate or link different subareas and ecosystems within the landscape. Moreover, by the use of hydrological and ecological models, it is possible to calculate turnover times for any chosen unit in the landscape.

The aquatic systems are important for the transport of matter, but also for accumulation in lake or sea bed. Mass-balance calculations describing the flows of matter at the level of a catchment area are made based on hydrology and water chemistry, providing information concerning

Figure 3-3. *The catchment area of Norra Bassängen in Forsmark provides an example of a catchment area used for modelling transport and accumulation of elements and matter (mass-balance).*

transport of matter into running water and lakes. By quantifying recharge and discharge, it is possible to calculate input and loss of matter in the lake. Matter transport in streams represents loss from terrestrial systems, making it possible to compare estimated and actual loss from terrestrial systems.

The final recipient of the transported water and matter is the sea, where the water discharges. Transported solid matter is often accumulated in shallow bays, which consequently show large primary production due to high nutrient availability. The bay also serves as the interface to the open sea, where important exchanges of matter may occur depending on water currents and hypsography.

In the last step, the model is transformed into a mass-balance model to describe how and where matter is transported and accumulated in the landscape. During this phase the uncertainty of the model is evaluated.

One great challenge is to integrate all the collected data into a common model. During the integration, a number of simplifying assumptions had to be made. However, it will always be possible to back-track the information to greater detail, by reference to the extensive site-specific database. This approach ensures that many of the simplifying assumptions made going from step 2 to 4 in Figure 3-1 may be modelled and their validity tested. A mass-balanced ecosystem model including food webs provides a way of analysing how matter is linked between different ecosystem components through fluxes of e.g. carbon.

The balance of nutrients required to support maximum growth of terrestrial plants is not site-specific and the nutrient that limits growth determines the cycling rates of all other nutrients. This stoichiometry defines patterns of cycling of most nutrients in ecosystems /Elser and Urabe 1999/. It is thereby possible to establish quotients between important elements in, for example, vegetation, to facilitate mass flow and accumulation calculations for other nutrients or radionuclides from established carbon fluxes and masses. Moreover, by estimating inflow and outflow of matter in the ecosystem units, it is possible to reduce the potential variation in flows and accumulation by setting the physical and biological limits for estimations of e.g. carbon accumulation in a lake bed. Therefore, we strongly believe that the ecosystem modelling approach, as a fundamental support, combined with the use of site-specific data, will result in more accurate and precise estimations of flows and accumulation of elements and radionuclides, than to use only transfer factors, because of the introduced site-specific limitations.

If we describe standing stocks and flows of matter accurately, we will have a baseline for making predictions of dispersal and accumulation of chemical elements or substances, such as radionuclides, released in the area. By this approach, the safety assessment is provided with a tool to predict how and where radionuclides are transported and accumulated in the landscape, making it possible to calculate potential doses to humans appropriate to the specific site /Kumblad et al. 2003/. By adding a historical perspective on the development of the landscape, we will also be able to predict future transport and accumulation of matter during natural succession and under different management regimes.

3.2 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 (ed) 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 two sites, and this information is utilized in the descriptions given in /Söderbäck (ed) 2008/ and also herein.

3.3 Geometric models

3.3.1 Digital elevation model

A Digital Elevation Model (DEM) is a digital representation of a continuous variable over a two-dimensional surface. Typically, digital elevation models describe terrain relief. Many types of surface models – such as hydrological models and geomorphometrical models – use a DEM as input data. DEM resolution is the size of DEM cells.

To construct a DEM, a number of input data are used from different sources. The sources are existing DEM from the Swedish national land survey (LMV) with a resolution of 50 metres, the SKB DEM with a resolution of 10 metres /Wiklund 2002/, elevation lines from digital topographical maps, digital nautical charts and paper nautical charts (from the Swedish Maritime Administration), depth soundings in both lakes /Brunberg et al. 2004/ and the sea /Elhammer and Sandkvist 2005, Brydsten 2004/ interpreted depth data in the sea, measurements of brooks /Brydsten and Strömgren 2005/, fixed points, and some “dummy depths” in areas where no other data are available. In cases where the different sources of data were not in point form, such as existing elevation models of land or depth lines from nautical charts, they were converted to point values using ArcGis 9.

Two alternatives of DEMs were produced for the Forsmark area; one version describes land surface, sediment level at lake bottoms, and the sea bottom, the other version describes land surface, lake water surface, and sea bottom. Ordinary Kriging in ArcGis 9 Geostatistical Analysis extension was chosen as interpolation method /Davis 1986, Isaaks and Srivastava 1989/ for the interpolation of the DEMs. In the version that displays lake bed levels, the cells representing lake beds, inside 25 lakes in the Forsmark area, were replaced by cells representing lake water surface elevation using the Spatial Analyst extension in ArcGis 9.

Normally, a DEM has a constant value for sea surface and a constant value for lake surfaces. However, for Forsmark, the DEM has negative values in the sea to represent water depth, but constant positive values for lake surfaces represent the lake elevations or varying values represent lake bed elevations. Because data from different sources often overlap, several tests were conducted to determine which source of data should be included in the dataset used for the interpolation procedure. After the deletion of some points from overlapping datasets, all data in Forsmark were merged into a database of 1,920,000 points.

The database for the Forsmark area was used as input data for the Kriging interpolation. Kriging is a geostatistical interpolation method based on statistical models that include autocorrelation (the statistical relationship among the measured points). Kriging weights the measured values local to the point of interest to predict an unmeasured location. Weights are based on the distance between the measured points, the prediction locations, and the overall spatial relationship among the measured points. The Kriging interpolation method allows both a cross validation (one data point is removed and the rest of the data are used to predict the removed data point) and a validation (part of the data is removed and the rest of the data is used to predict the removed data) before the interpolation is conducted. Cross validation with different Kriging parameters were performed and the models with the most reasonable statistics were chosen for the Forsmark DEM model area. Finally, validations with the most appropriate Kriging parameters were performed in order to verify that the models would be able to adequately fit unmeasured localities.

The RT 90 2.5 Gon W map projection and the height system RH 70 are used in the elevation models for the Oskarshamn and Forsmark areas. The DEM describing the land surface, sediment levels at lake bottoms, and sea bottom for Forsmark is illustrated in Figure 4-4.

3.3.2 Regolith depth model (RDM)

A geometrical model of the regolith in Forsmark has been constructed /Hedenström et al. 2008/. The model is based on evaluation of drillings and corings, excavations and geophysical investigations. The model describes the total regolith depth, subdivided into seven layers and three generalised lake sediment lenses (Figure 3-4). The layers and lenses in the model are purely geometrical, but constructed according to the conceptual understanding of the site. Properties of the layers and lake sediment lenses are subsequently assigned by the user. For example, the upper layer Z1 can be given different properties in different areas through connection to e.g. maps of Quaternary deposits or soil types.

The model presents the geometry of the lower boundary of each layer, presented as elevation above sea level (RH 70) with a spatial resolution of 20 × 20 m. The resulting interpolated surfaces are presented in a GIS-environment. The model area is a modified Forsmark regional model area in order to include present and future catchment areas (Figure 3-5). The total area modelled is 155 km^2 and includes all surfaces (land, sea and lakes).

The lower level of Z5 is interpolated from the data set of information on depth of the regolith as well as the elevation of bedrock outcrops. Thus, Z5 represents the bedrock surface regardless of whether it is covered by any deposits or not. The layers in the model are summarised and explained below (Table 3-1).

Since there are large parts of the modelled area with a low density of input data, the model is built up mostly from average values for the thickness of different deposits, calculated from input data. The average values were then assigned to different areas in the model in relation to the map of QD according to the conceptual model and overall stratigraphic understanding of the Forsmark area (Table 3-2).

The thickness of the regolith varies within the model domain. In areas where depth information is lacking, average depth values are used. The Regolith Depth Model (RDM) is subdivided into nine sub-domains. For details regarding the modelling methodology, see /Hedenström et al. 2008/.

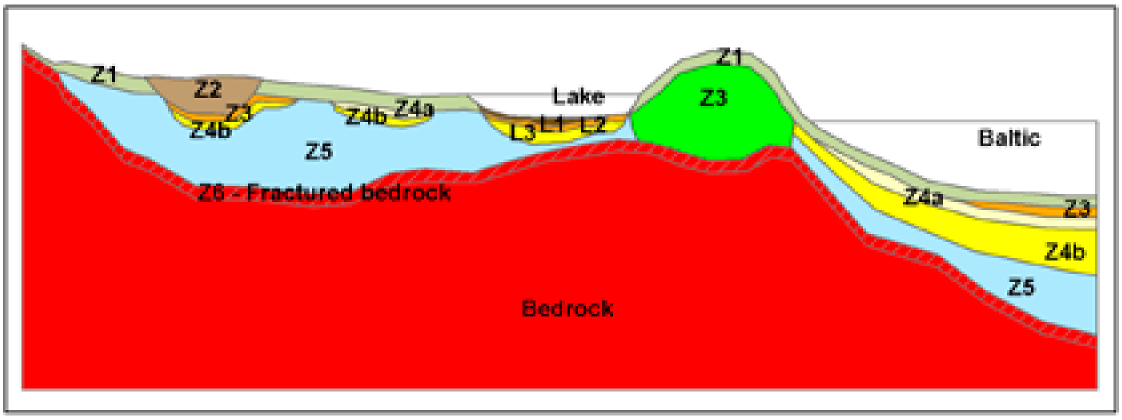

Figure 3-4. *Conceptual model used for the regolith depth model, which gives the spatial distribution of the seven QD layers and three lake sediment lenses modelled in the area. For description of the layers, see Table 3-1.*

Figure 3-5. *Area for modelling of regolith depth in the Forsmark area (from /Hedenström et al. 2008/).*

Table 3-1. Description of the layers used in the regolith depth model for Forsmark (from /Hedenström et al. 2008/).

Description of layer/lens	Simplified Code	Description/Occurrence
Gyttja (algal gyttja, calcareous gyttja, clay gyttja-gyttja clay), Peat	L1	Present inside the boundaries of the lakes. When peat is present as a surface layer within the lake area, this is included in the L1 lens. The sediment in L1 and Z4a partly consists of the same geological units.
Postglacial sand and/or gravel	L2	Present inside the boundaries of the lakes. The sediments in L2 and Z3 partly consist of the same geological unit.
Clay (glacial and postglacial)	L3	Present inside the boundaries of the lakes. The sediments in L3 and Z4a and Z4b consist of the same geological unit.
Surface layer	Z1	The layer is affected by surface processes, e.g. soil-forming processes in the terrestrial parts or sedimentation/transport/erosion in the limnic/marine parts. This layer is present within the entire modelled area, except where the surface is covered by peat or where the model has a lens (under lakes). On bedrock outcrops, the layer is 0.1 m and 0.6 m in other areas. If the total modelled regolith depth is less than 0.6 m, Z1 will be the only layer. The layer can be connected to a GIS application such as the map of Quaternary deposits or soil-type map and assigned properties in accordance with the properties of the deposits.
Peat	Z2	This layer is only present where peat is present in the QD map. Calculated average depths are used for the layer since too few observations are available for interpolation. The average depth used for peat above and below the 5 m.a.s.l. contour line is 1.4 m and 0.4 m respectively. Postglacial sand (Z3) always underlies Z2. If peat intersects glacial clay or sand on the QD map, Z4b underlies Z3.
Postglacial sand/gravel, glaciofluvial sediment and artificial fill	Z3	The layer is only present where the surface layer consists of postglacial sand/gravel, glaciofluvial sediment or artificial fill. The layer geometry is interpolated from input data and average values. This may result in a discrepancy between the modelled Z3 and the marine geological map. In the terrestrial parts, Z3 is assigned average depth values for postglacial sand and artificial fill and glaciofluvial sediment. The glaciofluvial sediment and artificial fill are modelled to always be situated directly on bedrock. Z3 as sand is always present under peat (Z2).
Postglacial clay including gyttja clay	Z4a	Z4a is present in the marine area where postglacial clay is the surface layer. In the marine area, the layer geometry is interpolated from input data and average values. This may result in a discrepancy between the modelled Z4a and the marine geological map. When average values are used, Z4a is always underlain by Z4b.
Glacial clay	Z4b	Z4b is present where glacial clay is the surface layer. Additionally, Z4b is present under Z3 when peat is located next to sand or glacial clay and when sand is located next to glacial clay. In the marine area, the layer geometry is based on interpolation from input data and average values. In the terrestrial area, the layers are assigned calculated average depth values. In the marine area, interpolated Z4b values > 0.5 m are rejected in areas where the geological map shows till or glaciofluvial sediment. This may result in a discrepancy between the modelled Z4b and the marine geological map.
Till	Z5	This layer is present in a major part of the model area. The thickness of the layer is based on interpolation from input data and average values. Z5 is of zero thickness at bedrock outcrops, if the total QD depth is < 0.6 m or if the layers/lenses are located directly on the bedrock surface. The lower limit of Z5 represents the bedrock surface, i.e. Z5 represents a Digital Elevation Model for the bedrock surface.
Fractured bedrock	Z6	This layer has a constant depth of 0.6 m and represents the bedrock upper part, calculated from the interpolated Z5.The layer represents a highly conductive zone that has been observed in many of the hydraulic tests within Forsmark.

Table 3-2. The different sub-domains used for ascribing average QD depth values in areas without primary observation points (from /Hedenström et al. 2008/).

Sub-domain		Quaternary deposit	Layers included in the domain	Depth of sub sums	Total depth (m)
1	Marine area	Till Clayey till or boulder clay Till with a thin surface layer of sand or clay	Z5	6.2	6.2
2	Marine area	1) Clay 2) Glacial clay with a thin surface layer of postglacial sand	Z5+Z4b	6.2+3.2	9.4
3	Marine area	1) Postglacial fine sand 2) Postglacial sand 3) Postglacial sand-gravel	Z5+Z4b+Z3	6.2+3.2+0.9	10.3
4	Marine area	1) Clay gyttja with a thin surface layer of postglacial fine sand 2) Clay gyttja with a thin surface layer of postglacial silt Clay gyttja Gyttja	Z5+Z4b+Z4a	6.2+3.2+0.9	10.3
5	Terrestrial	All QD in terrestrial area, except those included in domains 6–9 or areas where lenses are modelled	Z5	3.56	3.6
6	Terrestrial	Clayey till with low boulder frequency	Z5	5.76	5.8
7	Terrestrial	Peat > 5 m.a.s.l. intersecting sand, gravel or glacial clay in the QD map	Z5+Z4b+ Z3+Z2	3.56+0.5+0.2+1.4	5.7
8	Terrestrial	Peat > 5 m.a.s.l., not intersecting sand, gravel or glacial clay in the QD map	Z5+Z3+Z2	3.56+0.2+1.4	5.2
9	Marine/ Terrestrial	Glaciofluvial esker	Z3	5.76	5.8

3.4 Hydrology and hydrogeology

3.4.1 Modelling methodology

The overall methodology of the modelling of surface hydrology and near-surface hydrogeology within the site descriptive modelling of the surface system is presented in Figure 3-6. A preliminary conceptual model, mainly based on the data gathered and analysed in the Östhammar pre-study /Follin et al. 1996, SKB 2000/, was the starting point of the design of the investigation programme /SKB 2001/. The successive data evaluations and modelling coupled to the data freezes applied in the site-investigation methodology, and input from internal and external reviews, have resulted in revisions and additions to the originally proposed programme.

The data evaluation presented in this report includes meteorological data, surface water levels and discharge rates, groundwater levels, and geometry and water storage and conductivity properties of the hydraulic domains. These data sets were first evaluated separately then subject to an integrated analysis. This integrated analysis, supported by data from related site investigation disciplines and generic data, formed the basis for the elaboration of a site-specific conceptual and descriptive model followed by quantitative flow modelling. The procedure has been iterative and repeated for the different model versions.

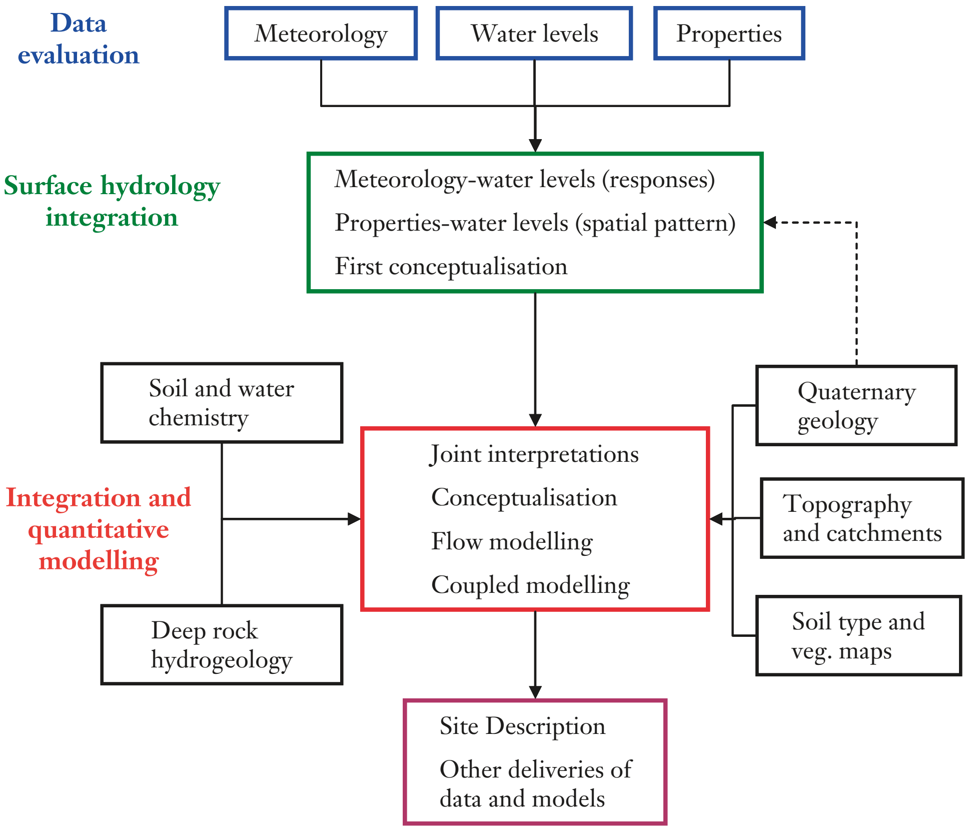

Figure 3-6. *Overall description of the methodology of the hydrological and near-surface hydrogeological modelling performed within the site descriptive modelling of Forsmark.*

3.4.2 Terminology

/Rhén et al. 2003/ established the terminology to be used within the site descriptive hydrogeological modelling. The *conceptual model* should define the framework in which the problem is to be studied, the size of the modelled volume, the boundary conditions, and the equations describing the processes. The (hydrogeological) *descriptive model* defines, based on a specified conceptual model, geometries of domains and parameter values assigned to these domains.

Since the term "hydrology" often refers to all aspects of the hydrological cycle, i.e. atmospheric, surface and subsurface processes and parameters, it should be noted that the following distinction is made between "hydrology" and "hydrogeology" in the data handling within SKB's site investigation programme:

- *Hydrology* refers to the surface water system only; hydrological data include water levels and flow rates in water courses and lakes, and the locations of surface-water divides and the associated catchments and sub-catchments.
- *Hydrogeology* refers to the subsurface system, i.e. the water below the ground surface, including the unsaturated and saturated parts of the subsurface; hydrogeological data include groundwater levels and hydraulic parameters for unsaturated and saturated groundwater flow.

Thus, the terminology is clear as far as the input data are concerned; hydrological data are obtained on the ground surface and in surface waters, and hydrogeological data from the subsurface, primarily from drillings and observation wells (sampling for analysis of hydraulic properties has also been made in pits and trenches).

In the site descriptive modelling it was found useful to make a distinction between *near-surface* and *deep bedrock hydrogeology*. The main reasons for this were the high resolution in time and space required in the description of the surface and near-surface system and the need for describing the interactions between groundwater and specific surface water objects not represented in the deep bedrock models (e.g. lakes). Shallow flowpaths dominate in the water balance of the area and data from this depth interval are important for the ecosystem modelling. Surface water and groundwater interactions are of great importance in characterizing the near-surface hydrogeology.

Obviously, there is an overlap between the "near-surface" and "deep rock" hydrogeological models, since they must incorporate components of each other in order to achieve an appropriate parameterisation and identification of boundary conditions. In the present report, groundwater level data from the percussion-drilled boreholes, i.e. from the upper highly transmissive c. 150 m of the bedrock, is included. For a detailed conceptual and descriptive model of the shallow as well as the deep bedrock, the reader is referred to /Follin et al. 2007, 2008/ (see also Chapter 5).

In the different disciplines of the site investigation several terms are used for the *Quaternary deposits* overlying the bedrock, such as *overburden, soil, regolith,* and *hydraulic soil domains (HSD)*. In the hydrological and hydrogeological parts of this report, the terms *Quaternary deposit(s)*, often abbreviated as *QD,* and *regolith* are used.

In the SKB systems approach to hydrogeological modelling, three hydraulic domains/flow domains are defined, (*i*) hydraulic soil domains (HSD), (*ii*) hydraulic conductor domains (HCD), and (*iii*) hydraulic rock mass domains (HRD). For surface water, the flow domains are (*i*) overland water, (*ii*) water courses, (*iii*) lakes, and (*iv*) the sea. Wetlands are described separately, but are not handled as a separate flow domain in the quantitative flow modelling.

Groundwater recharge is defined as the "Process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation"/ International Glossary of Hydrology (UNESCO/WMO)/. A *groundwater recharge area* may be defined as an area where water flows from the unsaturated zone to the saturated zone or, from a groundwater flow perspective, an area where the shallow groundwater flow has a downward flow component. In the same way, a *groundwater discharge area* may be defined as an area where water leaves the saturated zone or, from a groundwater flow perspective, where the groundwater flow has an upward component /Grip and Rodhe 1985/.

In the present report, a definition of groundwater recharge and discharge areas as areas where the groundwater has a downward or an upward flow component, respectively, is adopted. Groundwater is very shallow in large parts of the Forsmark site investigation area, meaning that vegetation water uptake takes place from the groundwater zone, directly or indirectly by inducing capillary rise, especially during dry conditions. Such areas will, from the definition used, be characterized as groundwater discharge areas.

There are no major watercourses in the central part of the site investigation area. The term *brook* is used for the small, mainly natural watercourses that are present, whereas the term *ditch* is used for man-made features dug for drainage purposes.

The term *groundwater level* is used as a common term for the position of the groundwater table in unconfined aquifers and the potentiometric head in confined aquifers. However, it should be noted that due to differences in salinity with depth, measured groundwater levels in percussion-drilled boreholes should be considered as so called *point water heads*. For some wells, the density differences are so large that these *point water heads* should be transformed to *freshwater heads* and/or *environmental water heads* for interpretation of flow directions. For definitions of point water, freshwater and environmental water heads, and an analysis of the influence of water density differences on groundwater flow direction in the site investigation area, the reader is referred to /Johansson 2008/.

3.5 Regolith and Quaternary geology

The use of the term regolith is based on the need for a concept within which all unconsolidated deposits overlying the bedrock are included, regardless of its origin. This means that Quaternary deposits of all kinds, such as till, clay and peat, together with artificial filling material or granular weathered bedrock are included in the regolith. The term Quaternary deposit (QD) is used to describe the separate geological units. In the terrestrial area, the upper part of the regolith is referred to as *the soil*. Soils are formed by interactions of the parent geological material, climate, hydrology and biota. Different types of soils are characterized by horizons with specific chemical and physical properties.

The methods used to investigate the spatial distribution and properties of the regolith are summarised below, together with a brief data evaluation. The data have been grouped into two main categories: *Spatial distribution* (surface and stratigraphical) and *Properties* (physical and chemical). The spatial distribution of the regolith is presented in geological and soil-type maps as well as in the geometrical Regolith Depth Model (RDM).

3.5.1 Maps

The QD geological map presented in the version 2.3 SDM covers the whole modelled area, i.e. terrestrial, limnic and marine areas. The resulting map is a compilation from six different data sources, initially produced using different methods and adjusted for presentation at different scales (Figure 3-7).

The most detailed map covers the terrestrial area in the central part of the regional model area (Area 1). This map was produced during the initial site investigations /Sohlenius et al. 2004/ and includes bedrock exposures and QD with areas larger than 10 × 10 m. The detailed geological map was initially presented at the scale 1:10,000.

Area 2 is represented by geological maps in the Geological Survey of Sweden ser Ae, adapted for presentation at the scale 1:50,000 /Persson 1985, 1986/. These maps cover the distal parts of the terrestrial area.

In the shallow coastal bays, Area 3, the survey vessel used for the regular marine geological mapping could not enter. Therefore, the distribution of Quaternary deposits was investigated in a large number of point observations from the sea ice or using a small boat /Ising 2006/. The investigations were performed along lines or profiles, approximately 200 metres apart. The point observations were analysed together with information on bottom substrate from diving profiles and the bathymetry. This method makes the precision of the map adapted to presentation at the scale 1:50,000 and no area less than 50 × 50 metres is displayed.

Area 4 is based on detailed marine geological information with a distance of 100 m between the investigation lines /Elhammer and Sandkvist 2005/. Area 5 is based on regional marine geological information with a distance of 1,000 m between the investigation lines /Elhammer and Sandkvist 2005/. Both marine geological maps were initially presented at the scale 1:100,000.

In order to obtain a complete map, the remaining areas located under very shallow water in the marine area and under the lakes and streams required interpretation. The resulting map (Area 6) is based on interpretations from lake and sediment corings /Hedenström 2003/, bathymetry from the DEM and interpolation from the surrounding Quaternary deposits. It should be noted that these areas are the most uncertain in the geological map.

Soil refers to the upper part of the regolith that is affected by soil-forming processes, e.g. bioturbation, frost action and chemical weathering. Soils from eight different land types were studied within the Forsmark regional model area /Lundin et al. 2004/. The land types were defined based on vegetation, land use and wetness. Classifications of soil type and the parent material of the underlying QD were carried out in spade-dug profiles at two sites from each land type.

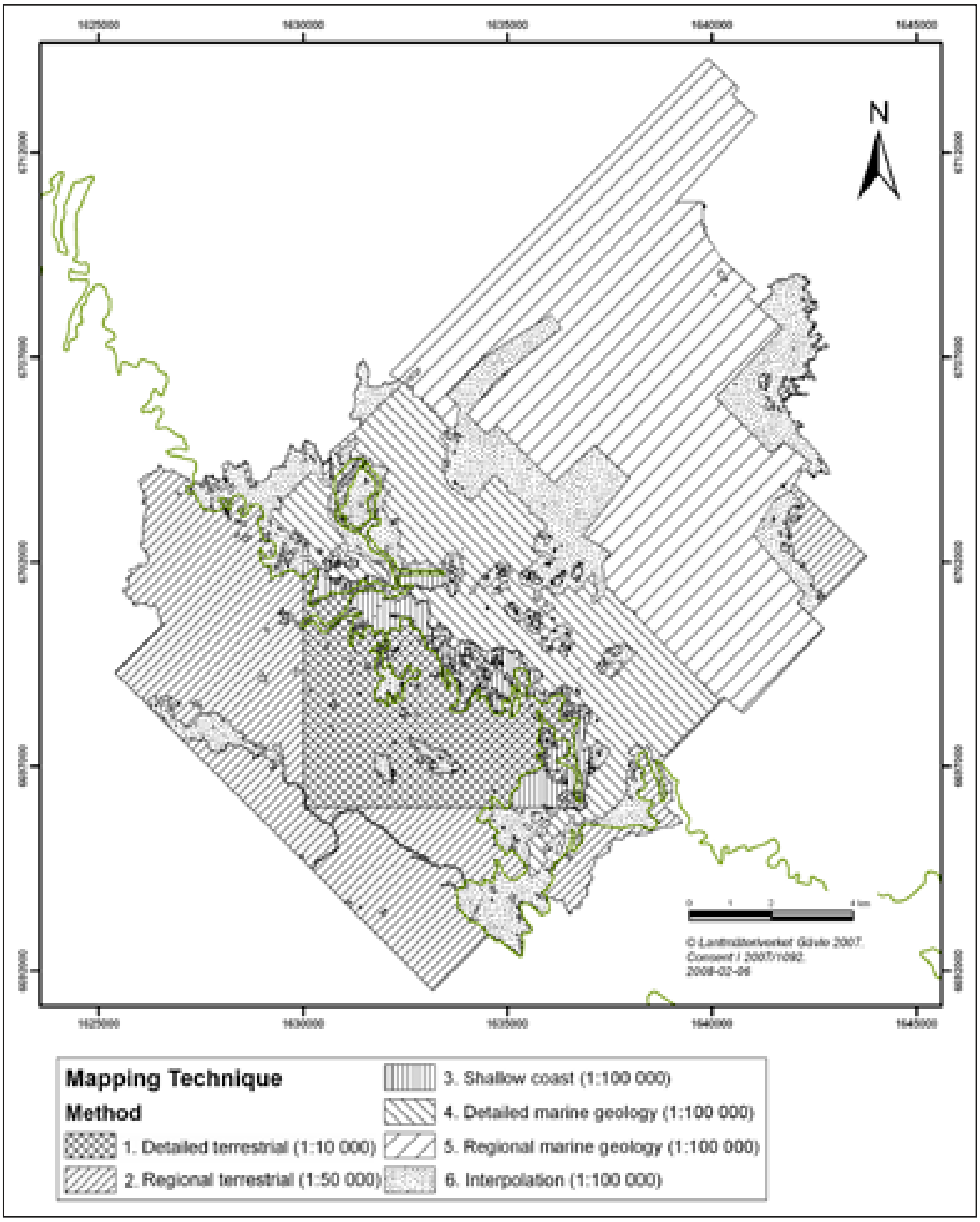

Figure 3-7. The distribution of the different types of input data used to construct the resulting QD geological map used in the 2.3 RDM.

The soil-type investigation did not have total spatial coverage, as was the case for the mapping of QD in Area 1. Instead the spatial distribution of the soil types was determined from a secondary GIS based inventory including information on vegetation types, distribution of QD and a topography-based hydrological index. The map presented by /Lundin et al. 2004/ was later replaced by an updated version based on GIS analyses of the detailed map of Quaternary deposits /Sohlenius et al. 2004/, which provided more detailed information on the distribution of the parent material for the soils.

The soils were classified according to their properties /WRB 1998/, which could then be compared with soils from other areas. For chemical characterization, samples were collected from the 2-3 uppermost soil horizons and analysed for pH, calcium carbonate, organic carbon and nitrogen /Lundin et al. 2004, 2005/. The extrapolations of the chemical analyses into maps were conducted using the initial version of the soil-type map /Lundin et al. 2004/.

3.5.2 Stratigraphic data

Stratigraphic data comprises information on the spatial distribution of the different layers of the individual QD. The information was gained from a large number of drillings, machine-cut trenches, hand-driven corings in sediment and peat, and stratigraphical observations from the geological mapping.

In a majority of the soil-rock drillings, a geologist was present at the drill site to classify the lithology of the Quaternary deposits directly in the field e.g. /Sohlenius and Rudmark 2003, Hedenström 2004b, Hedenström et al. 2004, Lokrantz and Hedenström 2006/. At sites where no geologist was present during the corings, samples collected from 21 corings were inspected later by a geologist and classified into lithological units /Albrecht 2007/.

Generally, the sediments retrieved from percussion coring are more disturbed compared with the samples from auger drillings (Figure 3-8). The samples derived from percussion bore holes (HFM) are disturbed, flushed samples, sometimes holding crushed fragments of bedrock or boulders, thus the stratigraphical descriptions from these sites may sometimes be of poor quality.

Stratigraphic investigations of sediment and peat in lakes, shallow coastal areas and mires were performed using a hand-driven corer, a Russian peat corer /Jowsey 1966/. The corer obtaines undisturbed 1 or 0.5 m long samples (Figure 3-9) which were classified directly in the field.

Figure 3-8. *Left) A majority of the HFM drillings were performed using percussion drilling. The samples retrieved are often crushed and may include some fragments from the bedrock. Right) At the installation of groundwater monitoring wells (SFM-sites), corings were performed using an auger drill. The coring sites are distributed within the investigation area and resulted in samples of higher quality than from the percussion corer. The picture shows clayey till obtained from 4 m depth at Storskäret. Note the detail in the bottom right hand corner.*

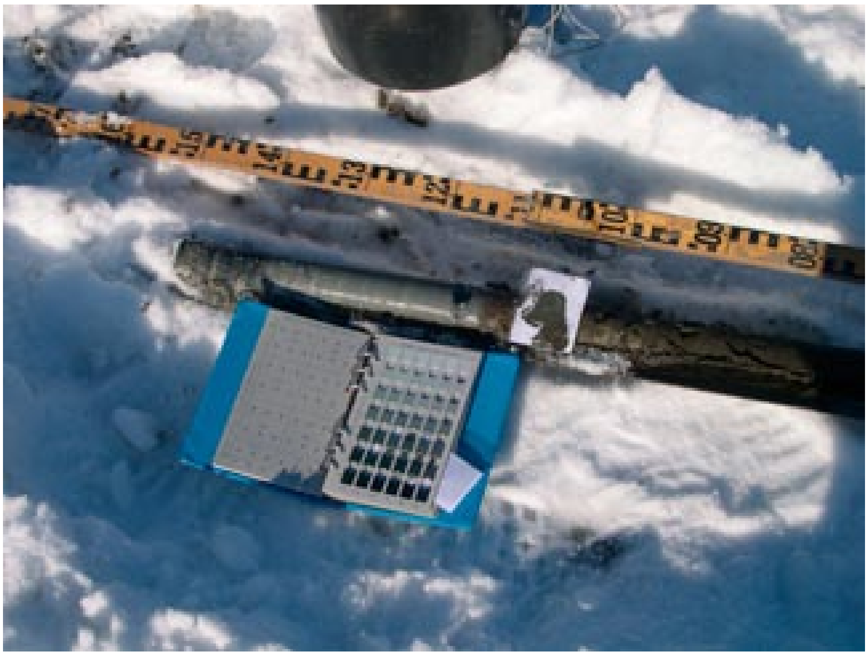

Figure 3-9. *Example of sediment collected from the bed of Lake Eckarfjärden. The corer collects a 1 m long sediment sequence that is inspected and described in the field. The colours of the sediments are classified according to Munsell soil colour charts /Munsell 1975/. The corer is hand driven and is used in soft deposits such as gyttja, clay and peat. The investigated sediments do not include coarse-grained deposits such as till.*

Information on the depth to bedrock was obtained from different geophysical investigations. In the marine area, the geophysical investigations of the Quaternary deposits were interpreted with respect to the different sedimentary layers and used for stratigraphical information as well as total depth to bedrock /Elhammer and Sandkvist 2005/. In the terrestrial areas, the geophysical measurements were mainly used to estimate the total depth to bedrock and the quality of the upper part of the bedrock, e.g. 16 km of high-resolution reflection seismic data, distributed along five profiles within the regional model area, were analysed /Bergman et al. 2004, Bergman 2004/. Refraction seismic measurements are generally more suitable for estimations of regolith depth and the properties of the superficial bedrock, for example fractures in the bedrock surface may be detected. 228 profiles including 10,247 observation points are concentrated to the north western part of the candidate area /Toresson 2005, 2006, Mören and Nyström 2006/ and the area close to Forsmark power plant /Keisu and Isaksson 2004/. A ground penetrating radar (GPR) survey was conducted in Forsmark /Marek 2004a/. Data from 64 km of surveying with GPR was interpreted in order to obtain the depth to bedrock /Marek 2004b/.

3.5.3 Analytical methods and sampling programme

In order to characterize the regolith, samples were collected in a wide range of activities described above; i.e. during the mapping of QD in the terrestrial and marine areas, the soil-type inventories, investigations of marine and lacustrine sediments and various corings and excavations. The majority of the minerogenic (in-organic) samples analysed are glacial deposits, mainly till. The standard analysis to characterize the physical properties of the minerogenic deposits in Forsmark was grain size distribution and $CaCO_3$ content. The grain-size distribution for the coarse material (0.063–20 mm) was analysed by sieving and the fine fraction was analysed using sedimentation in a hydrometer. The analytical methods used are national standard methods /Standardiseringskomissionen i Sverige 1992a and b/.

The water content of peat, and lake and coastal sediment from the Forsmark site has been analysed /Borgiel 2004, Hannu and Karlsson 2006, Sternbeck et al. 2006, Nordén 2007/. The water content was used to determine the porosity and bulk density of the deposits. For these calculations the average mineral grain density of 2.65 g/cm^3 /Talme and Almén 1975/ and a density for the organic matter of 1 g/cm^3 were used. The organic content was calculated as 1.7 times the carbon content, based on the van Bemmelen factor /Jackson 1958/.

In two machine-cut trenches, samples were collected for analyses of physical parameters such as dry bulk density, porosity, water retention and hydraulic conductivity after 1 hour and 24 hour throwflow /Lundin et al. 2005/. From grain size distribution curves, the hydraulic conductivity (K-values) and porosity were calculated for some representative samples.

Additional analyses comprise geochemical analyses such as elemental composition, isotopic and clay mineral analyses, as well as microfossil analyses of till and sediments. In the soil-type inventory, texture, pH, carbon content and nitrogen content were analysed at the different horizons in each soil class. A compilation of the analyses performed on regolith is presented in Table 3-3. Details regarding the analytical techniques can be found in summary in /Hedenström and Sohlenius 2008/ and in detail in each cited reference.

Table 3-3. Analyses performed to characterize the physical and chemical properties of Quaternary deposits during the site investigations in Forsmark.

Parameter analysed	Number of samples or sites/ Description and geological asessment	References
Grain size composition and $CaCO_3$.	433 and 259 samples. Minerogenic deposits mainly from the terrestrial part of the regional model area and sediments in lakes.	/Sohlenius and Rudmark 2003, Lundin et al. 2004, Hedenström 2004a and b, Hedenström et al. 2004, Sundh et al. 2004, Albrecht 2005, Risberg 2005, Lundin et al. 2005, Ising 2006, Lokrantz and Hedenström 2006/
Water retention, porosity and density* from minerogenic deposits in trenches.	26*+5 sites. Mostly till from different horizons from the upper 60 cm of the soil profile.	/Lundin et al. 2004*, 2005/
Theoretical hydraulic parameters.	75 samples. Calculated from grain-size distribution curves of minerogenic deposits.	/Albrecht 2005, Ising 2006, Lokrantz and Hedenström 2006/
Chemical composition.	45 sites. Geochemical analyses of till, sediment and peat.	/Sohlenius and Rudmark 2003, Nilsson 2003, Hannu and Karlsson 2006, Strömgren and Brunberg 2006/
C, N, S, P analyses of sediments.	8 sites, sediment sequences from Kallrigafjärden, Eckarfjärden, Fiskarfjärden, Puttan, Lake #5, Stocksjön, Tixelfjärden, Rönningarna.	/Bergkvist et al. 2003, Hedenström and Risberg 2003, Hedenström 2004a, Hannu and Karlsson 2006, Sternbeck et al. 2006/
Age of sediment and peat.	5 sites. C^{14} and Pb^{210} datings of peat and sediments.	/Hedenström and Risberg 2003, Risberg 2005, Sternbeck et al. 2006/
Clay mineralogy.	12 samples of till and clay.	/Sohlenius and Rudmark 2003, Hedenström 2004a/
Chemical analyses of peat and sediments in mires.	3 sites. Organic carbon, ash content and $CaCO_3$. Elemental analysis.	/Fredriksson 2004, Lokrantz and Hedenström 2006, Hannu and Karlsson 2006, Sternbeck et al. 2006/
Microfossil analyses of sediment.	3 sites. Sediment sequences from Kallrigafjärden, Lake Eckarfjärden and off shore Forsmark.	/Bergkvist et al. 2003, Hedenström and Risberg 2003, Risberg 2005/
Microfossil analyses of till.	13 samples. Redeposited microfossils in minerogenic, glacial deposits.	/Robertsson 2004, Leijon (ed) 2005/
Soil profile chemistry (Organic carbon, Nitrogen, Base cations, Extractable phosphorus, pH).	21 sites. Different horizons of 8 soil-types.	/Lundin et al. 2004, Lundin et al. 2005/

3.6 Chemistry of water, regolith and biota

3.6.1 Hydrochemical data and evaluation methods

The hydrochemical evaluations presented in this report are based on the Forsmark "data freeze 2.2". This data set, which covers the observations from March 2002 to June 2006, comprises observations in precipitation, flowing water, lake water, sea water, shallow groundwater in soil tubes and groundwater in private wells. In addition, groundwater data from the bedrock is included as reference in /Tröjbom et al. 2007/ (cf. /Tröjbom and Söderbäck 2006/ and /Sonesten 2005/ for basic visualisations of data). Different sampling categories are listed below and schematically shown in Figure 3-10, together with an overview of sampling sites (Figure 3-11).

- Surface water samples (PFM) – precipitation, lake, stream and sea water.
- Private wells and springs (PFM) – drilled or dug wells and natural springs either representing shallow groundwater in the overburden or groundwater in the bedrock.
- Soil tubes (SFM) – groundwater monitoring wells drilled into the overburden, usually not extending more than 10 metres deep. The representative sampling depth corresponds to the location of the intake screen, usually the last metre of the soil tube.
- Percussion-drilled boreholes (HFM) – boreholes drilled in the bedrock, usually extending to a depth of approximately 200 metres, sometimes sectioned by packers.
- Cored boreholes (KFM) – core drilled boreholes, usually extending to a depth approaching 1,000 metres, and sectioned at several levels with packers.

A large number of parameters are measured within the different sampling campaigns in the Forsmark area. The parameters may be grouped into a number of categories, based on the sampling interval of each parameter (Table 3-4). These large sets of data require statistical methods in order to simplify visualisation and to identify major patterns as well as anomalies.

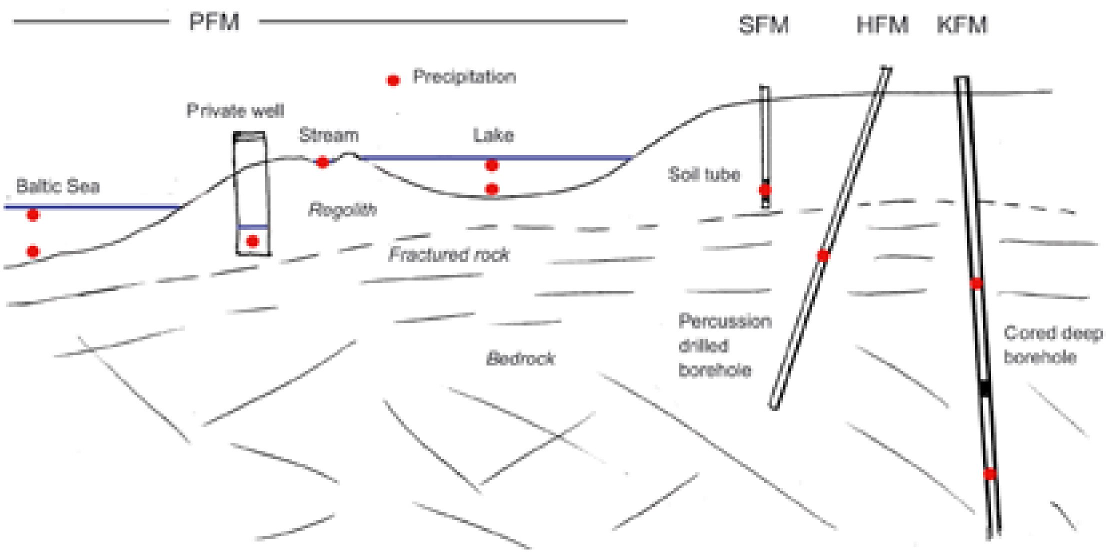

Figure 3-10. Schematic picture showing the different object types that are sampled for hydrochemistry in the Forsmark area. The red dots denote representative sampling levels.

Figure 3-11. *Surface water sampling points in the Forsmark area.*

Table 3-4. Listing of different parameter categories and representative parameters.

Representative parameter	Other parameters in category
pH	Conductivity
Cl	Na, K, Ca, Mg, HCO_3^- SO_4^{2-}
Sr	Li, I, F, Br
Si	SiO_2
Fe	Mn
S^{2-}	O_2
Tot-N	NH_4^+-N, $NO_{2/3}^-$-N, tot-P, PO_4^{3-}-P, TOC, DIC
DOC	
^2H	^3H, ^{18}O
^{13}C	
^{14}C	
^{34}S	
^{87}Sr	^{10}B, ^{37}Cl
Cu	Zn, Pb, Cd, Cr, Al, Ni, Hg, Co, V
La	Sc, Rb, Y, Zr, Mo, In, Sb, Cs, Ba, Hf, Tl, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu
U	Th
^{222}Rn	^{226}Ra, ^{238}U, ^{235}U, ^{234}U, ^{232}Th, ^{230}Th

In /Tröjbom et al. 2007/, simple two-variable plots are complemented by multivariate models such as the Ion Source Model. Multivariate statistical methods are dimension reducing techniques used for extracting relevant information from large data sets that contain many related parameters. At a catchment scale, empirical/statistical mass balance models are used in /Tröjbom et al. 2007/ to evaluate sources and sinks for individual elements in relation to hydrology and possible governing factors within the catchments.

3.6.2 Chemistry of biota

Terrestrial vegetation including roots, the uppermost soil layers, aquatic vegetation as well as terrestrial and aquatic fauna were sampled for chemical analyses /Hannu and Karlsson 2006/. The terrestrial fauna (small rodents) were sampled within the site investigation programme, whereas moose and fox were provided by local hunters. For all fauna, muscle tissues were prepared and analyzed for metals and CNP (carbon, nitrogen, phosphorous) using standard spectrometry methods /Hannu and Karlssson 2006/.

The elemental composition of biota, water and sediment from a shallow bay (Tixlanfjärden) in the Forsmark region are compiled by /Kumblad and Bradshaw in manus/. They present analyses of a number of different elements (Al, As, Ba, Br, C, Ca, Cd, Ce, Cl, Co, Cr, Cs, Cu, Dy, Er, Eu, F, Fe, Gd, Hg, Ho, I, K, Li, Lu, Mg, Mn, N, Na, Nd, Ni, P, Pb, Pm, Pr, Ra, Rb, S, Se, Si, Sm, Tb, Th, Ti, Tm, V, Yb, Zn, Zr) in all major functional components of the coastal ecosystem (phytoplankton, zooplankton, benthic microalgae, macroalgae, macrophytes, benthic herbivores, benthic filter feeders, benthic detrivores, planktivorous fish, benthic omnivorous fish, carnivorous fish, dissolved and particulate matter in the water and the bottom sediment collected during springtime in 2005).

3.7 Terrestrial ecosystems

3.7.1 General description

The description of the terrestrial ecosystem contains both qualitative data such as descriptions of which species are dominant in the area, as well as quantitative descriptions of a number of ecosystem properties that relate to biomass, production and energy budgets, i.e. consumption, egestion and respiration for animals, amphibians and birds. For information about the site-specificity of the data, where it is published and the methods used to estimate/calculate results, see /Löfgren (ed) 2008/.

The fauna has been investigated in a number of different studies, see section 4.2 in /Löfgren (ed) 2008/. The study aims can be summarised as 1) describing which species or functional groups are present in the area, 2) establishing reliable density estimates for larger animals and birds, and quantification of important pools/fluxes, which will be used for the ecosystem models and, 3) establishing a baseline for an ongoing monitoring programme that can be used to relate different kinds of disturbances to wild life population changes.

3.7.2 Ecosystem models

Field estimated local carbon balances for three ecosystems

Pools and fluxes of organic matter were investigated and compiled according to the component structure in Figure 3-12 at three localities. They represented vegetation types considered to be important both with respect to area coverage and as potential sinks for organic matter /section 6, Table 6-1 in Löfgren (ed) 2008/. Two conifer forests, which dominate the area, and one forested wetland, with alder and Norway spruce were studied. The aim was to describe the carbon balance using site-specific data when ever possible, but when such data were missing, literature data were used instead.

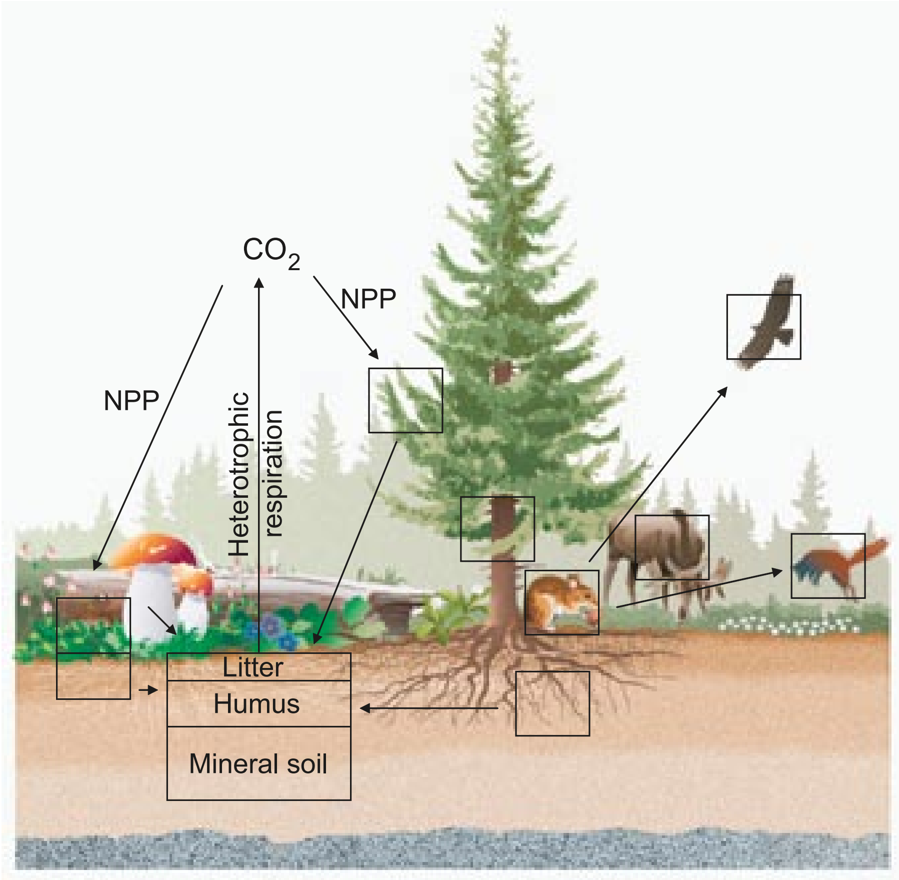

Figure 3‑12. *A conceptual description of pools and fluxes in an ecosystem, where black boxes symbolize pools of carbon/organic matter and arrows symbolise carbon/organic matter fluxes. Herbivores and carnivores were excluded at the local scale but included in the regional description.*

Tree-layer data for the different localities were derived from tree height and breast height diameter measured for ten representative trees at each locality /Tagesson 2006a/. Equations from /Marklund 1988/ were used to calculate fractions of green tissue, stem and living branches for Norway spruce (*Picea abies*) and silver birch (*Betula pendula*), while for alder (*Alnus glutinosa*) the equations presented in /Johansson 2000/ were used. The fractions of biomass present in the stumps, coarse roots and fine roots down to approximately 5 mm and between 5 mm and 2 mm were calculated using functions presented in /Petersson and Ståhl 2006/. Birch root functions were also used for alder. Fine root biomass estimates for diameters < 2 mm were available for each locality /Persson and Stadenberg 2007a/.

The mean biomass and standard deviation were estimated for each tree compartment based on the sampled trees. Above-ground litter fall was estimated at the localities during two consecutive years /Mjöfors et al. 2007/. Fine root turnover was estimated at the Norway spruce stand during one year (diameter fractions less than 1 mm) /Persson and Stadenberg 2007b/. In the calculations, we assumed the annual fine root production at all the three localities to be equal to the standing biomass for the fraction < 2 mm. Net stem increment was not measured at the localities, but was obtained from the National Forest Inventory database for a regional area around the site, where a number of criteria, such as age and height, were used to fit estimates to the three localities (See Table 6-3 in /Löfgren (ed) 2008/). Annual increment of leaf/needle and fine root biomass were assumed to be zero.

The above-ground (AG) biomass and net primary production (NPP) for the field and bottom layers were investigated by removing and measuring the biomass at the time of peak biomass, and using estimates of moss shoot elongation in 2004 /Löfgren 2005/.The below-ground (BG) biomass of fine roots was estimated by /Persson and Stadenberg 2007a/. Litter production was assumed to equal the above-ground NPP plus the below-ground Ø < 2 mm root fraction, which was assumed to be replaced during the year, plus the bottom layer production, implying an overall balance in relation to the field and bottom layer biomass production. Estimates of biomass and NPP for ectomycorrhizal (EM) mycelia were based on a study by /Wallander et al. 2004/ in a Norway spruce forest in southern Sweden.

Woody debris, such as standing and fallen logs, was quantified by /Andersson 2004/ in all vegetation types with a tree layer according to the vegetation map. The litter layer was investigated, as described in /Löfgren 2005/. The soil organic carbon pool was estimated for each locality making eight lateral transects of one humic and three mineral soils down to approximately one metre below the surface in each replicate, using the same methodology as the National Forest Soil Inventory /Lundin et al. 2004/. Soil respiration was measured in 2005/2006, in the different vegetation types in Forsmark, using a closed chamber technique, along with measurements of soil temperature and soil moisture /Tagesson 2006b, 2007/.

Estimates of regional carbon balances by dynamic modelling

The dynamic vegetation model LPJ-GUESS /Sitch et al. 2003/ was used to make a regional description of carbon balances for a number of different vegetation types dominating the investigation area. Some areas (sea shore, wetlands and forested wetlands) were not covered due to the extensive work required to adapt the model for these vegetation types. For these cases, ground-based measurements as well as literature data were presented /Chapter 8 in Löfgren (ed) 2008/.

The model was driven by climate data (temperature, precipitation and solar radiation) that was put together to describe a period of 100 years. Reference data describing the period between 1901 and 1960 were calculated with data from Örskär and the NORDKLIM climate stations Uppsala, Stockholm and Svenska högarna. The other model parameters, such as soil and vegetation characteristics, were set to correspond to the conditions at the site (see Chapter 7 in /Löfgren (ed) 2008/).

The model results cover the vegetation types; young (25 y) and old (80 y) stands of Norway spruce, Scots pine, deciduous trees (pedunculate oak (*Quercus robur*) and silver birch (*Betula pendula*)), mixed forests, dry pine on acid rocks, meadows and arable land. The model result was validated against ground-based estimates, which confirmed that estimated carbon balances are realistic in relation to measurements. Estimates of carbon balances for 2005 for the different vegetation types were made using the model /Table 7-4 in Löfgren (ed) 2008/. Furthermore, the simulated vegetation dynamics after a clear-cut were studied for up to 400 years by repeating the 100 years of climate data.

Food web

The biomass for all mammals, birds, amphibians and reptiles were estimated based on their densities in the area together with calculations of their production, consumption, egestion and respiration. The calculations are based on the field metabolic rate for each species /Nagy et al. 1999/. The fauna is more difficult to associate to specific habitats, but for some species or functional groups an attempt was made to distribute their consumption in the landscape, either by using their habitat preferences or their feeding preferences, or both.

3.7.3 Mass-balance models

Mass balance models describing the in- and outputs of a large number of elements, at the scale of catchments, were constructed in accordance with the conceptual illustration in Figure 3-13. The estimated inputs was atmospheric deposition and the output was horizontal transport by water. The element content was also estimated for four pools within each catchment. The regional ecosystem description of organic matter was combined with estimates of site-specific element concentrations within different pools to estimate these four pools /Hannu and Karlsson 2006/. The content in the pools describing the soil was the total content, meaning that a fraction

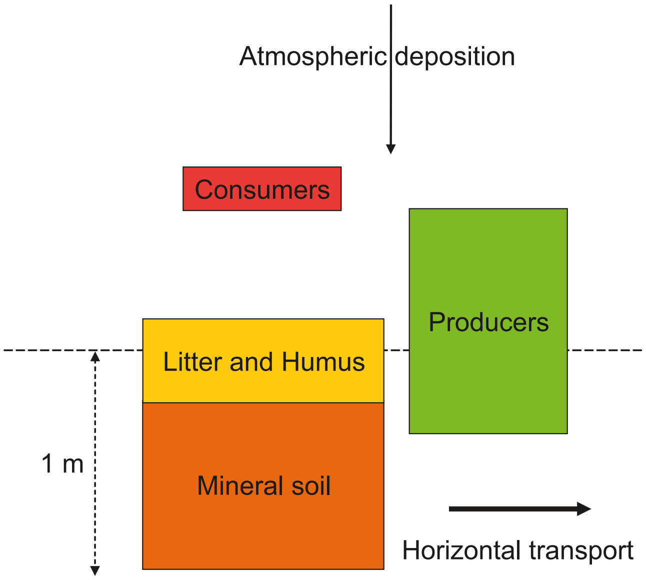

Figure 3-13. *The conceptual mass-balance model of the pools and fluxes that are used to describe terrestrial catchments.*

of the pool is non-available to the biota. By using the ratio between carbon and a specific element for pools and fluxes within ecosystems, it was possible to estimate their elemental contents and concentrations. Here, the mass balance for phosphorus is presented, but see /Chapter 9 in Löfgren (ed) 2008/ for a detailed presentation of uranium, thorium and iodine, and other elements and underlying assumptions for the calculations. In the case of phosphorus, which is a well-described element, also some internal fluxes such as weathering and demand by the vegetation was included to further elaborate and discuss the resulting mass balances. The atmospheric wet deposition at the site was estimated to be 0.012 gP $m^{-2}y^{-1}$. (Sicada, 2006-10-26), whereas the weathering was estimated using literature data (0.009 gP $m^{-2}y^{-1}$ for forest soils /Olsson and Melkerud 1989/ and 10 times higher for fine sediments /Ulén and Snäll 1998/). The transport of phosphorus in surface water was estimated from concomitant measurements of concentrations and discharge in streams of Forsmark /Appendix F in Tröjbom et al. 2007/.

Wetlands were not covered in the regional estimates obtained using LPJ-GUESS and was parameterised using field-estimated site data and, in some cases, literature data /Chapter 9 in Löfgren (ed) 2008/.

3.8 Limnic ecosystems

The limnic system includes both lakes and running water. Lakes can be regarded as sediment traps where accumulation of particles, nutrients and trace elements occurs, and where biological processes such as primary production, consumption and respiration may have a considerable impact on the accumulation and transport of matter. Streams is principally regarded as transport routes, where deposition and accumulation of matter are of minor importance, and where biological processes for long-term accumulation of matter are insignificant. On a short time scale elements may be trapped in streams, but at high discharge events, trapped elements are resuspended and transported further downstream and annual retention is small or nonexistent /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. This simplified view of the limnic ecosystem has been used in ecosystem and mass balance models in this report.

3.8.1 General description

An extensive amount of chemical, hydrological and biological data (including biomass data on phytoplankton, microphytobenthos, macrophytes, macroalgae, bacterioplankton, benthic bacteria, zooplankton, benthic fauna and fish) have been used in the description of the Forsmark lakes and streams.

3.8.2 Ecosystem models

Ecosystem models have been produced to describe the flows of carbon between and within the lake ecosystems for three lakes in Forsmark. In ecosystem models, major functional groups and flows of elements or energy between them, are included. In this report, the ecosystem carbon model for Eckarfjärden is presented and compared between the lakes in Forsmark.

The lake ecosystem was divided into three major habitats; the pelagic, littoral and profundal. The pelagic habitat is defined as the open water body. The littoral habitat is defined as the benthic area reached by enough light to enable photosynthesis. Finally, the profundal habitat is defined as the benthic habitat below the photic zone. The lakes in the Forsmark area are all very shallow and have clear water with moderate water colour. These conditions enable light to penetrate the entire benthic habitat in all lakes and, consequently, no profundal habitats are present in these lakes. The reed belts surrounding the Forsmark lakes are partially dried out during summer and are considered as wetlands rather than lake littoral. Thus, the reed belts are included in the terrestrial description and are not further described here. Biota in lakes is distinguished into seven functional groups according to feeding and habitat preferences (Table 3-5).

Site-specific data on the biomass of the functional groups and on primary production of phytoplankton and benthic primary producers are used in the ecosystem carbon model. No site-specific data on respiration and consumption are available, but these processes have been estimated from biomass values with the aid of conversion factors. For a detailed description of the conceptual ecosystem model, see /Nordén et al. 2008/.

3.8.3 Mass balance models

The mass balance model gives an overview of major fluxes of different elements to and from the lake ecosystem. The following inputs to and outputs from the lake ecosystem were defined:

- Inflow from the catchment (via inlets, direct drainage and groundwater).
- Deposition (input from atmospheric deposition, e.g. in rain).
- Outflow via outlets.
- Output by sediment accumulation.

Table 3-5. Functional groups in the lake ecosystems. The column to the right is shaded to illustrate that profundal habitat is absent in the Forsmark lakes.

	Pelagic	Littoral	Profundal
Primary producers	Phytoplankton	Benthic primary producers	
Consumers	Bacterioplankton	Benthic bacteria	Benthic bacteria
	Zooplankton	Benthic fauna	Benthic fauna
	Fish		

In the carbon mass balance two additional fluxes were identified, output by birds feeding in the lake and input/output of carbon dioxide (CO_2) across the air-water interface as a result of the balance of carbon dioxide dissolved in the lake water and present in the atmosphere. We have no site data to estimate atmospheric exchange of elements other than carbon. For some elements i.e. nitrogen and iodine, this exchange could be substantial but for most elements it should be of minor importance. The reason for not including the outflow via bird consumption for elements other than carbon is that this process is of minor importance for carbon and, therefore, can be neglected for other elements.

Data to estimate all four fluxes in the mass balances are available only for 16 elements (C, Ca, Cl, Fe, I, K, Mg, Mn, N, Na, P, S, Si, Sr, Th, U). For another 31 elements, the only flux missing is the deposition from atmosphere, a flux contributing with a minor part of total inflow for all elements for which data are available /Nordén et al. 2008/. In this report, we present the carbon mass balance for Lake Eckarfjärden, the phosphorus mass balance for Lake Bolundsfjärden, and a discussion on the most important flows in the mean lake (mean of the five investigated lakes) for the 47 elements with at least three identified flows. In the conclusions, a comparison between five investigated lakes in the area is also discussed. As a complement to the mass balances, the chemical composition (64 elements) of important pools in the lake ecosystem have been described, e.g. biota, sediment and water. For a detailed description of the conceptual model for the mass balances, see /Nordén et al. 2008/.

3.9 Marine ecosystem

The marine ecosystem at Forsmark comprises the marine area included in the regional model area in Forsmark. The studied area has been divided in 28 sub-basins, based on today's bathymetry and the projected pattern of future drainage areas arising in consequense of land uplift /Brydsten 2006/. Specifically since it was necessary to distinguish sub-basins in relation to their future terrestrial drainage characteristics, so that a site-evolution model could be constructed for radiological impact evaluation, in which radionuclide accumulation in each sub-basin and the subsequent radiological impacts of that accumulation in an evolving environment could be properly evaluated. The basins are presented in Figure 3-14 together with the digital elevation model for the marine area at Forsmark. The basin delimitations were made to conform to the overall strategy of the project to assess the long-term safety of a deep repository of nuclear waste. The detailed method for identification of basin delimitations is described in /Brydsten 2006/. Physical and chemical characteristics for the basins are presented in Chapter 4 and 5 in /Wijnbladh et al. 2008/.

3.9.1 General description

Large amounts of various site-specific data, mainly from the site investigation, regarding chemistry, hydrology, oceanography, climate, regolith and biota have been used in the description of the marine ecosystem at Forsmark, extensively described in Chapter 3 and 5 in /Wijnbladh et al. 2008/.

3.9.2 Ecosystem model

The data from the marine ecosystem and its overall characteristics, was conceptualized in an ecosystem model, using carbon as a proxy. The carbon ecosystem model was used for quantifying pools and fluxes of matter in the marine basins in the Forsmark area.

The ecosystem model is based on a food web consisting of biotic pools (primary producers and consumers), abiotic pools (particulate and dissolved matter) and fluxes of matter in the ecosystem (primary production, respiration, consumption, sedimentation, advection and runoff). The pools (abiotic and biotic) used in model calculations represent the spatial distribution in the marine model area of each component in the ecosystem model. The classification scheme

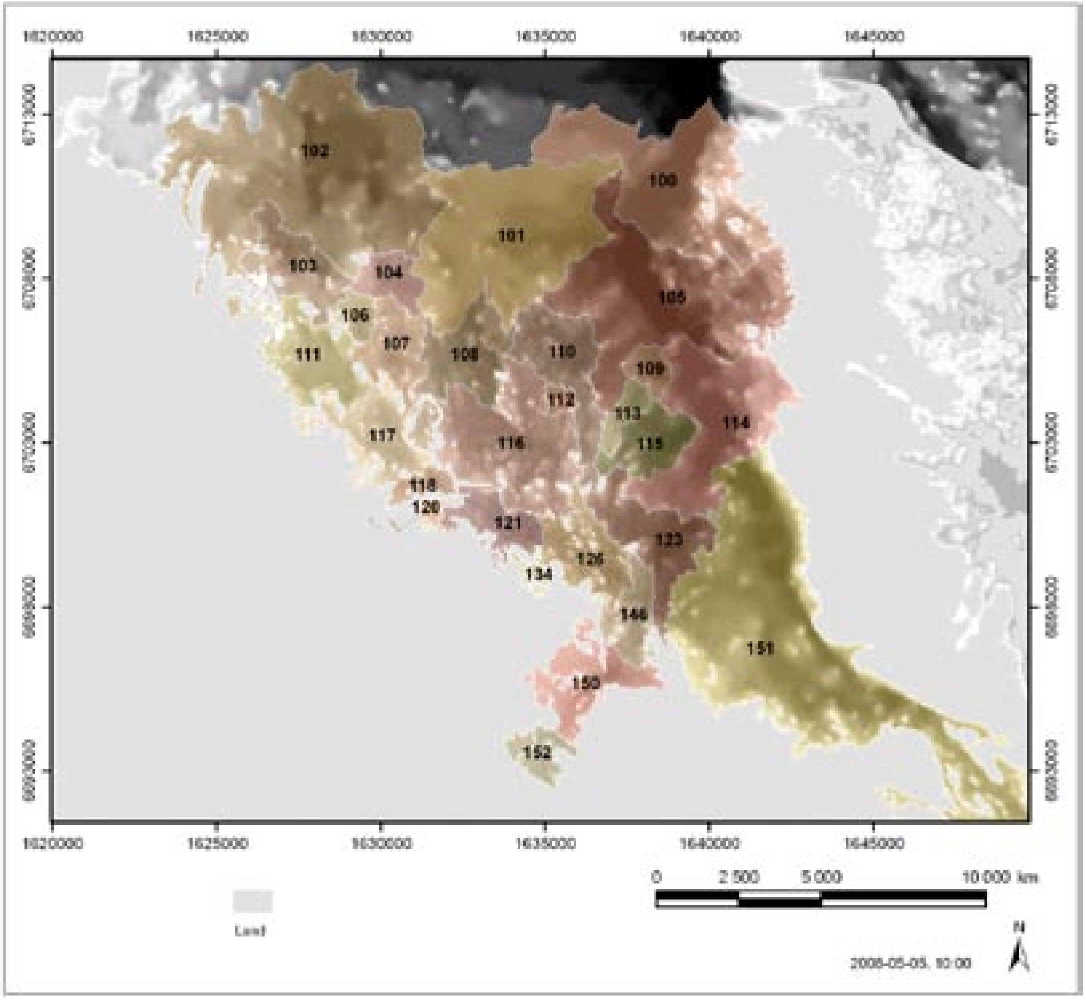

Figure 3-14. *Marine basins and bathymetry at Forsmark. The identification numbers of the marine basins in the marine model area are shown in black.*

of which groups to use and how to allocate the organisms among them was similar to the model structure used by /Kumblad et al. 2003/, but with some modifications, see Figure 3-15. The origin of the data used and any further treatment of those data regarding biomass and the distributions of the biotic and abiotic pools used in the calculations are extensively described in /Chapter 4 in Wijnbladh et al. 2008/.

The model was calculated on a spatial domain consisting of 1,500 × 1,500 grid-cells each of 20 m × 20 m size, thus covering an area of 30 × 30 km. This grid was used in modelling the fluxes of matter within delimited basins and the surrounding environment, comprising land ecosystems and the adjacent sea. The system was assumed to be in a steady, non-seasonal state and all input data were based on annual mean values. The model is non-dynamic and there are no feedbacks between processes in the system, but the processes within each unit, or functional group, are driven by independent data on biomass, concentrations of matter, irradiance and temperature measured in field. The parameters used in the calculations were interpolated to the 20 m grid using various methods described in detail in Chapter 4 in /Wijnbladh et al. 2008/.

3.9.3 Mass balances

Mass balances for 43 elements were calculated to identify the major pools and fluxes. Although consumption and respiration were included in carbon balances, these processes were not known for other element balances and hence not included. Fluxes and processes included in the mass balances are shown in Table 3-6.

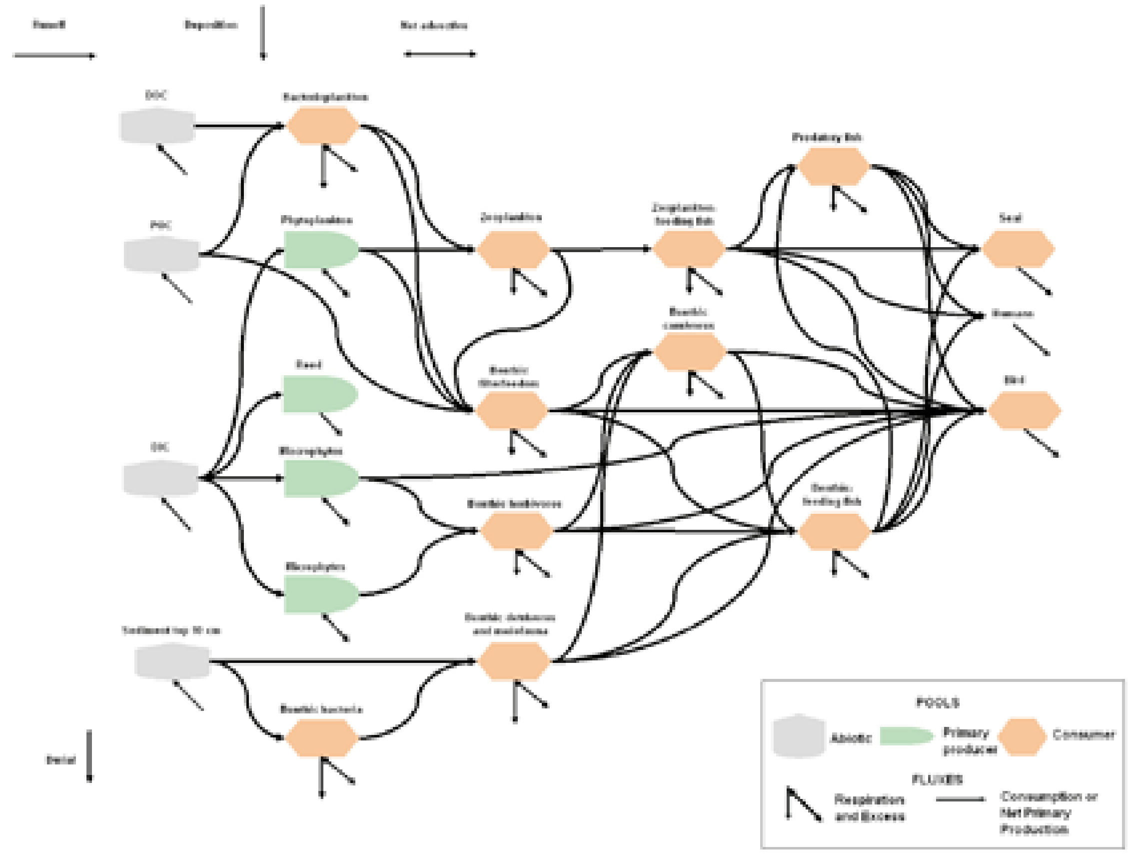

Figure 3-15. Conceptual illustration of the food web-based model for the marine ecosystem at Forsmark. Boxes and arrows denote pools and fluxes of matter respectively.

Table 3-6. Pools and fluxes of potential importance for the mass balance models of carbon and other elements in the marine system in Forsmark. Pools and fluxes marked with X are considered.

Fluxes to the system	Process	Mass balance carbon, remarks	Mass balance other elements, remarks
In through water	Runoff	X	X
In through water	Advective flow	X	X
In from atmosphere	Net Primary Production	X	Not applicable
In from atmosphere	Precipitation, deposition	X	Considered for some elements
In from atmosphere	Gas exchange atmosphere/ water	X	Not considered
Diffusive inflow	E.g. migration of organisms	Not considered	Not considered
Fluxes from the system			
Out through water	Advective flow	X	N, P, I, Th and U
Out to atmosphere	Respiration	X	Not applicable
Out to atmosphere	Evaporation/transpiration/ volatilisation	Not considered	Not considered
Diffusive outflow	E.g. migration of organisms	Not considered	Not considered
Accumulation	Burial	X	X
Pools			Considered for most elements
Producers		X	X
Consumers		X	X
Regolith_upper		X	X
Regolith_deep		Not considered	Not considered
Particulate		X	X
Dissolved		X	X

3.10 Human population and land use

The human population description is based on the results presented in the report "Human population and activities in Forsmark" /Miliander et al. 2004/. Most of the data included in /Miliander et al. 2004/ were obtained from Statistics Sweden (*Sw: SCB*). Since the population in Forsmark (area definition in /Miliander et al. 2004/) is low, the statistics for the Forsmark area are not publicly available, due to considerations of personal privacy. The description in this report is therefore based on statistics for the Forsmark parish, since many of the data were available at the parish level.

Other data sources such as the National Board of Fisheries (*Sw: Fiskeriverket*), the County Administrative Board of Uppsala (*Sw: Länsstyrelsen i Uppsala län*) and the Swedish Association for Hunting and Wildlife Management (*Sw: Svenska Jägareförbundet*) were also used. Wherever possible, the data were collected for a time series of ten years. However, ten year data was not available for all variables, so shorter time series were used as well. For more detailed information and discussion of the various issues relating to human population data and processing, please refer to /Miliander et al. 2004/.

3.10.1 Human consumption

The human consumption of crops (barley) and animal products (beef, milk and game-meat), originating from different drainage areas in Forsmark has been calculated. The figures are input data for the terrestrial ecosystem carbon budget in /Löfgren (ed) 2008/. Two different cases have been studied relating to production of beef and milk. First, a regional generic case based on meat production in the Forsmark parish as reported in /Miliander et al. 2004/. Secondly, a potentially self-sustainable case based on literature data regarding the maximum livestock density that an area intended for fodder production and grazing can hold. In this report, we only describe results from the regional generic case.

According to the agricultural statistics there is one agricultural enterprise (farm) in use within the Forsmark area. It is known that this farm has beef cattle. For reasons of privacy, there are no publicly available data concerning the production at this single farm. When calculating animal production in the Forsmark area, the densities of domestic animals in the Forsmark parish have been applied to the Forsmark area. The number of slaughtered cattle and the meat production are given in /Miliander et al. 2004/. The meat production is the part of the slaughtered/carcass weight that is consumed, i.e. the utilised carcass weight. The conversion factors between live weight, carcass weight and utilised carcass weight are given in /Löfgren (ed) 2008/.

The carbon content of mammals is 11.7% of the total (live) weight (44.9% of the dry weight) according to site-specific analyses of chemical composition of deposits and biota at Forsmark and Simpevarp /Hannu and Karlsson 2006, Engdahl et al. 2006/. The carbon content in milk and eggs can be estimated from the content of proteins, carbohydrates and lipids /Altman and Dittmer 1964, Dyson 1978, Rouwenhorst et al. 1991/. The contents of proteins, carbohydrates and lipids have been found in the Nutrient Database from the United States Department of Agriculture /USDA 2007/. The carbon content in milk (2% milk fat) is estimated to 5.1% and in egg to 14% (egg 50 g, raw).

There are no site-specific yield statistics available for crop production in the Forsmark parish. However, there are statistics available describing the standard yields for the yield survey districts (SKO areas). Forsmark is situated in SKO area 0322 /SCB 2007/. The amount of carbon in barley is estimated as 0.46 gC/g dw, as for the green field layer, in /Fridriksson and Öhr 2003/. The dry weight is 86% of the fresh weight according to /SCB 2007/. Thorough descriptions and evaluations of the input data and the methods used for calculating the human consumption of dry matter and carbon are presented in /Löfgren (ed) 2008/.

4 Resulting models

4.1 Historical development in Forsmark

This section is a brief summary of relevant parts of the background report R-08-19 /Söderbäck (ed) 2008/, which gives a comprehensive account of the geological evolution, palaeoclimate and historic development of both the Forsmark and Laxemar-Simpevarp areas. Here, only the parts of the report describing the Quaternary development of the surface system at Forsmark are summarised. A detailed reference list is given in the background report and here only a few, central references are included in the text.

4.1.1 Palaeoclimate and geological development during the Quaternary period

The Quaternary climate is characterized by large, sometimes rapid, changes in global temperature. Ice sheets covered larger areas during the cold periods than at present. The Forsmark area has consequently been covered by glacier ice repeatedly, although the total number of glaciations covering the model areas is not known. The cold glacial periods have been much longer than the warmer interglacial periods, which are characterized by a climate similar to the present. However, long ice-free periods have also existed during the glacials. During these ice-free periods the climate was colder than today and tundra conditions probably prevailed in large parts of Sweden. It can consequently be assumed that permafrost has prevailed in the model area for long periods of time. The latest glaciation started c. 115,000 years ago, and there is geological evidence of at least two periods thereafter when a large part of Sweden was free of ice. The exact timing and duration of these ice-free periods are, however, unknown. The onset of the latest glacial coverage in the model areas is not known, whereas the timing of the latest deglaciation is rather well established along the Baltic basin coast.

The present interglacial, the Holocene, started at the deglaciation of Mid-Sweden when the ice margin had not yet reached Forsmark. The climate during the deglaciation became successively warmer, although some periods of regression did occur. In southern Sweden, the warmer climate caused a gradual change from tundra vegetation to a forest dominated by decidious trees. The Mid-Holocene climate was characterized by temperatures a few degrees higher than today. The forests in southern Sweden have subsequently become dominated by coniferous forest.

The development of the Baltic Sea following the latest deglaciation has been characterized by ongoing shoreline displacement (Figure 4-1). At the deglaciation around 8800 BC, Forsmark was situated c. 150 m below the local sea level, and the first parts of the regional model area emerged from the sea around 500 years BC. The interaction between isostatic recovery and eustatic sea-level variations has caused a varying depth of water in the straits connecting the Baltic Sea with the Atlantic Ocean in the west, which has in turn caused varying salinity throughout the Holocene (Figure 4-2). At 4000–3000 BC, the salinity of the Baltic Basin was almost twice as high as it is today.

The development history of the Baltic Sea since the latest deglaciation has been divided into four main stages /Fredén (ed) 2002/, summarised in Table 4-1. Three of these stages; Yoldia, Ancylus and Littorina, are named after molluscs, which reflect the salinity of the stages. Freshwater conditions prevailed during most of the deglaciation of Sweden. The first Baltic Sea stage, the Baltic Ice Lake, was characterized by freshwater conditions, whereas weak brackish conditions prevailed c. 9300–9100 BC, during the middle part of the Yoldia Sea stage. However, since the Forsmark area was covered by glacier ice until c. 8800 BC, the first Baltic stage that affected the area was the freshwater Ancylus Lake stage, which lasted until the onset of the brackish Littorina Sea stage around 7500 BC /Fredén (ed) 2002/. Variations in salinity during the Littorina Sea stage have mainly been caused by variations in freshwater input and changes of the cross-sectional areas in the Danish Straits /cf. Westman et al. 1999/. Salinity was probably

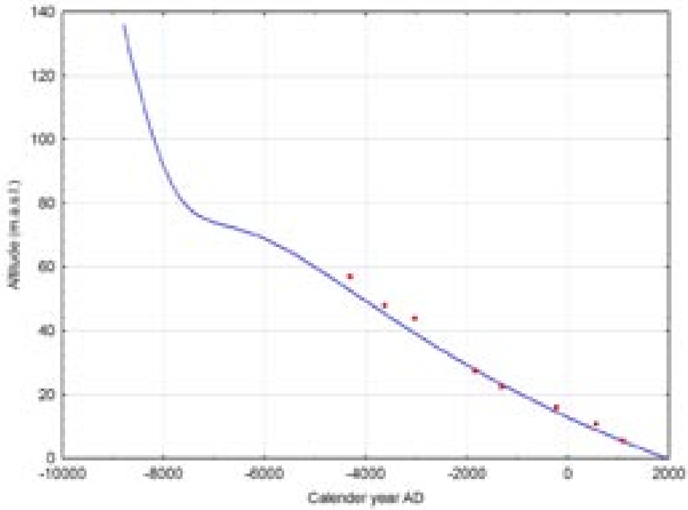

Figure 4-1. *Shoreline displacement curve for the Forsmark area after the latest deglaciation. The red symbols are from dating of the isolation events of lakes and mires /Hedenström and Risberg 2003/. The blue solid curve was calculated using a mathematical model /Påsse 2001/. m.a.s.l.= metre above present sea level.*

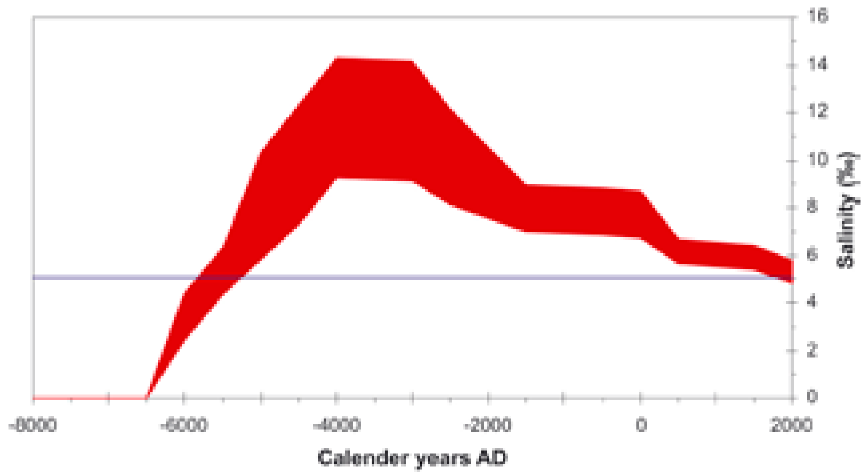

Figure 4-2. *Estimated range for the salinity of sea water in the open Bothnian Sea during the past c. 9,000 years. Maximum and minimum estimates are derived from /Westman et al. 1999/ and /Gustafsson 2004a,b/. The present salinity in the area is shown by the horizontal reference line.*

Table 4-1. The four main stages of the Baltic Sea. The Littorina Sea here includes the entire period from the first influences of brackish water 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

low during the first c. 1,000 years of the Littorina Sea stage but started to increase at 6500 BC. The most saline period occurred at 4500–3000 BC when the surface water salinity in the Baltic proper (south of Åland) was 10–15‰, compared with approximately 7‰ today /Westman et al. 1999/.

It has been suggested that all known loose deposits in the model area were deposited during the last phase of the latest glaciation, and during and after the following deglaciation, see Chapter 4 in /Söderbäck 2008/. In Forsmark, a till unit consisting of overconsolidated silty-clayey till was deposited during an earlier phase of the latest glaciation. The possibility of the occurrence of older deposits cannot be excluded, however, and there are indications of older deposits in neighbouring areas.

Till and glaciofluvial material were deposited directly by the ice sheet and by glacial meltwater, respectively. The Forsmark regional model area is situated below the highest shoreline and was consequently covered by water after the latest deglaciation at 8800 BC. During the deglaciation, glacial clay was deposited in the lowest topographical areas. The following shoreline displacement has had a great impact on the distribution and relocation of fine-grained Quaternary deposits. The most exposed areas have been subjected to wave washing and currents on the bottom. Sand and gravel have consequently been eroded from older deposits, transported and deposited at more sheltered locations. Periods of erosion have occurred also at sheltered locations, which have caused erosion of fine-grained deposits such as glacial clay. Shoreline displacement is an ongoing process and new areas are currently exposed to erosion, whereas sheltered bays with conditions favourable for deposition of clay gyttja have formed in other areas.

4.1.2 Development of ecosystems during the late Quaternary period

Long-term ecosystem development in near-coastal areas of Fennoscandia is driven mainly by two different factors; climate change and shoreline displacement. In addition, human activities have also strongly influenced the development of both terrestrial and aquatic ecosystems, especially during the last few millennia.

Shortly after the latest ice retreat, which started in southernmost Sweden c. 15,000 BC, the landscape was free of vegetation and can be characterized as polar desert. Relatively soon after the deglaciation, the ice-free areas were colonised by flora and fauna and in southern Sweden the landscape was covered by a sparse birch forest. Thereafter, the climate has oscillated between colder and warmer periods. During the cold period called Younger Dryas (c. 11,000–9500 BC), large areas of the deglaciated parts of Sweden were again affected by permafrost and much of the previously established flora and fauna disappeared. From the onset of the Holocene (c. 9500 BC) and thereafter, southern Sweden has been more or less covered by forests, although the species composition has varied due to climatic changes. Most of the present mammal fauna was established in southern Sweden during the early Holocene. During the last few thousand years, the composition of the vegetation has changed not only to due to climatic changes, but also due to human activities which have decreased the areas covered by forest. In southern Sweden, the introduction of agriculture and the subsequent opening of the landscape started c. 3000 BC.

In coastal areas like Forsmark, the shoreline displacement has strongly affected ecosystem development and still causes a continuous change in the abiotic environment. As a result of an overall regressive shoreline displacement, the sea bottom is uplifted and transformed into new terrestrial areas or to freshwater lakes (Figure 4-3). The starting conditions for ecosystem succession from the original near-shore sea bottom are strongly dependent on the topographical conditions. Thus, sheltered bays are accumulating organic and fine-grained inorganic material, whereas the finer fractions are washed out from more wave-exposed shorelines with a large fetch. During the process of shoreline displacement, a sea bay may either be isolated from the sea at an early stage and thereafter gradually turned into a lake as the water becomes fresh, or it may remain a bay until the shoreline displacement turns it into a wetland.

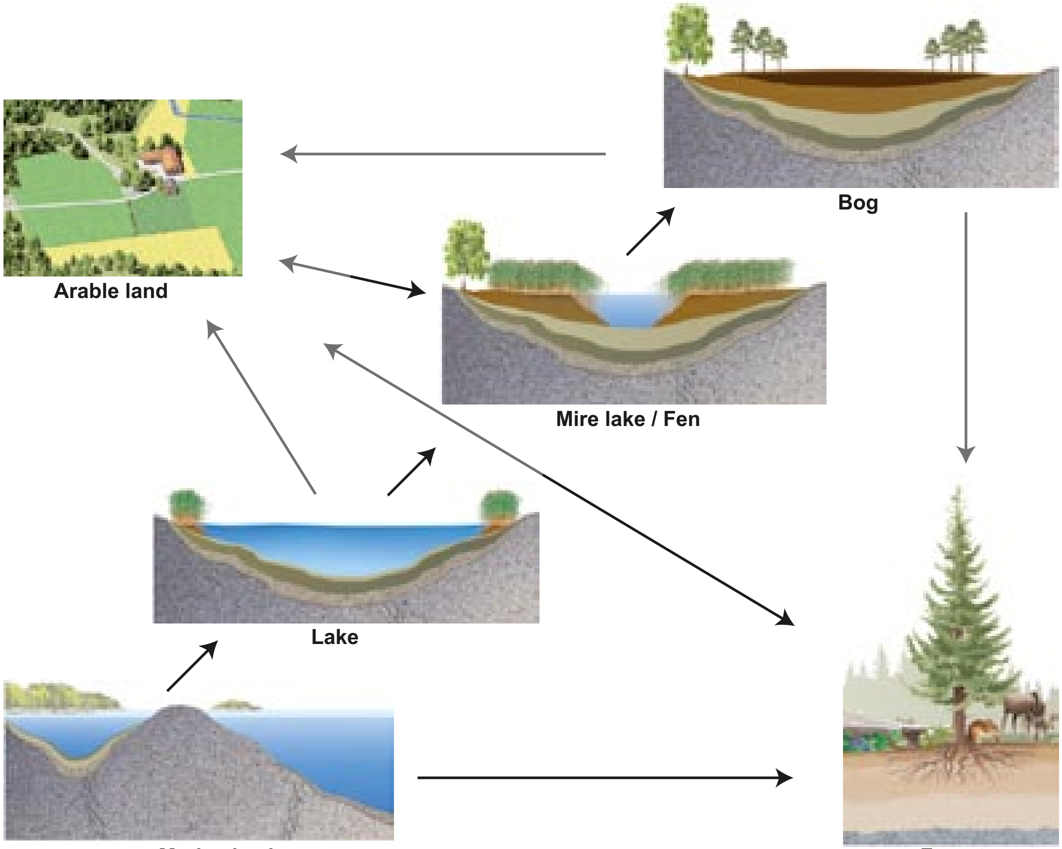

Figure 4-3. A schematic illustration of the major ecosystems that may be found at certain points during the temporal development, where the original sea bottom slowly is turned into an inland area due to shoreline displacement. Black arrows indicate natural succession, whereas grey arrows indicate human-induced changes to provide new agricultural land or improved forestry. Agricultural land may be abandoned and will then develop into forest or, if the hydrological conditions are suitable, into a fen. A forest may be "slashed and burned" and used as agricultural land.

After isolation from the sea, the lake ecosystem gradually matures in an ontogenetic process which includes subsequent sedimentation and deposition of substances originating from the surrounding catchment or produced within the lake. Hence, the long-term ultimate fate for all lakes is an inevitable fill-up and conversion to either a wetland or a more dry land area, the final result depending on local hydrological and climatic conditions. In Forsmark, all present-day lakes have developed into oligotrophic hardwater lakes, characteristic of the area.

Mires are formed basically through three different processes; terrestrialisation, paludification and primary mire formation. Terrestrialisation is the filling-in of shallow lakes by sedimentation and establishment of vegetation. Paludification, which is the predominant way 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 types of processes are likely to occur in the Forsmark area, but peatland filling in lakes (terrestrialisation) is probably the most common type of peatland development in the investigation area. 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.

4.1.3 Human population and land use

The human prehistorical period in the Forsmark region (an investigated area around Forsmark including six parishes, together covering c. 1,000 km^2 /cf. Berg et al. 2006/) is relatively short, since Forsmark was covered with water until c. 500 years BC. Accordingly, the Forsmark region was not permanently settled until the end of the prehistoric period. In the register of prehistoric remains made by the National Heritage Board, there are about 30 places with one or several prehistorical or cultural remains registered in the investigated region. There are, however, many prehistoric settlements further inland in the northern parts of Uppland. The oldest known remains in the Forsmark region are graves from the Iron Age, today situated 10–15 metres above sea level, but when built situated at the coastline.

The oldest information on settlements in the region is the tax register from 1312, which includes three of the investigated parishes. This source indicates that the region was relatively densely populated in the early medieval period. Between 1312 and 1550 there seems to have been a substantial decrease in the number of settlement units in the region, probably as an effect of the recurrent plague epidemics after 1349 /Berg et al. 2006/. During the medieval period, the Forsmark region was characterized by small villages, and new settlements were created in the peripheral areas of the older ones. The investigated parishes show a dominance of freeholders at the end of the medieval period and the share of farms belonging to the nobility was small.

During the early modern period (i.e. 1550–1750 AD), the establishment of the iron industry in the Forsmark region dramatically affected the surrounding landscape. Production was geared towards the needs of the industry; charcoal production, mining, and the production of fodder for animals used in the industry. The ownership structure also changed abruptly with the establishment of large estates. Similarly to many other places in Sweden, there was a strong population expansion. Many crofts were established in the forested areas around Forsmark, inhabited by people involved in the charcoal production. The population doubled or increased at an even faster rate between the 1570s and the 1750s.

The large estates in the Forsmark region expanded during the 18th century and, accordingly, the number of freehold farms decreased. The population increased dramatically from the 1780s up to the late 19th century. At the turn of the century, the increase ceased and during the latter part of the 20th century the rural population decreased. The number of people involved in agriculture decreased, and instead, the number of people employed in the industry and crafts was greater than before.

The extent of arable land in the region increased continuously from the colonisation of the area until around 1950. To increase the amount of hay that was fed to the farm animals, small farms and individual families carried out hay-making with the reeds and grasses on wetland areas. These areas were often distant and hard to reach and were thus mainly used by poor families that needed to feed their animals. Until the middle of the 19th century there were large wetland areas in the woodlands. From the beginning of the 18th century and onwards, much of the new agricultural land was gained from ditching of wetlands. Some of these areas are still cultivated whereas others are now deserted and, in some cases, have been turned into woodlands. From the early 1900s until the 1950s, most of the arable land in the Forsmark region was unchanged, but thereafter a significant part of the former open land has been abandoned and afforested.

4.2 Geometric models

4.2.1 Digital elevation model

The Forsmark DEM (see Figure 4-4) covers an area of approximately 30 × 30 kilometres, and a cell size of 20-metres, 1,501 rows, and 1,501 columns, and a total number of 2,253,001cells. The model area is relatively flat so the range in elevation is only approximately 109 metres with the highest point at 51.1 metres above sea level at the south-west part of the DEM, and the deepest sea point at –58.8 metres in the northern part. The mean elevation in the DEM is only 2 metres. The model area is covered by 58% land and 42% sea. The flat landscape is also shown in the statistics of the slope where the mean slope is 1.47 degrees, and 97.3% of the cells have slopes lower than 5 degrees and 2.6% have slopes between 5 and 10 degrees. Almost all of the cells with slopes steeper than 10 degrees (0.1%) are man-made such as the inlet channel to the nuclear power plant or piers and wharfs close to the facility for disposal of short-lived low- and intermediate-level waste (SFR) /Strömgren and Brydsten 2008/.

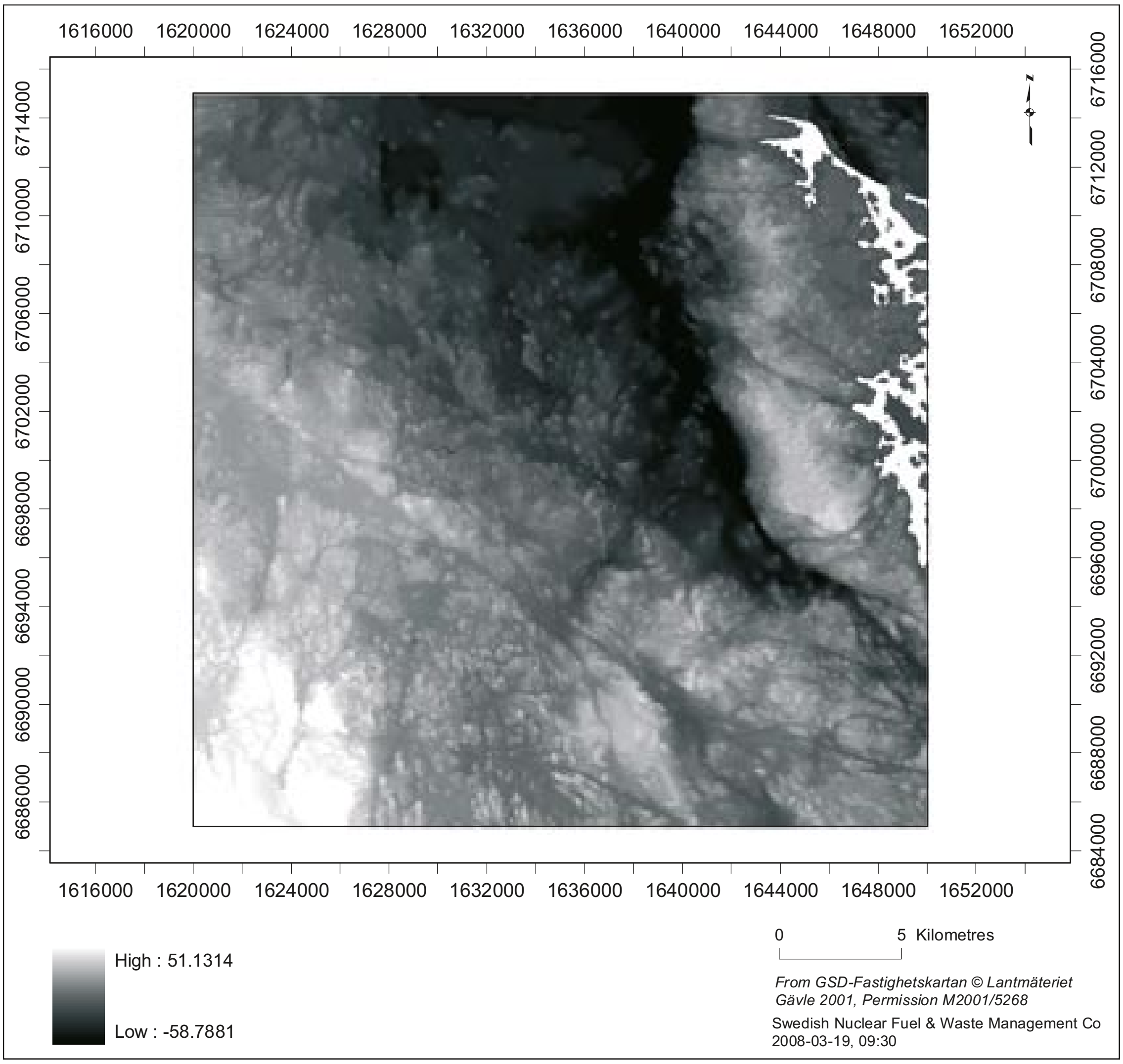

Figure 4-4*. The 20-metre digital elevation model for the Forsmark area describing the land surface, lake bottoms, and sea bottom.*

4.2.2 Regolith depth model

The regolith depth model (RDM) is presented in Figure 4-5. Figure 4-6 shows the central area. The regolith depth within the model varies between 0.1 and 42 m. Areas with thin regolith and frequent bedrock outcrops are e.g. the coastal zone and the islands, including the shoreline close to Gräsö Island. Generally, the regolith is deeper in the marine area where the average regolith depth is c. 8 m, whereas the average regolith depth in the terrestrial area is approximately 4 m. The input data and modelling processes for constructing the RDM are presented in /Hedenström et al. 2008/.

The maximum regolith depth in the model is about 42 m, recorded in the southwest-northeast groove outside the entrance to Kallrigafjärden. The majority of the observations with regolith depth > 20 m are located within the coastal area. The average and median regolith depth of the interpolated and adjusted model are shown in Table 4-2.

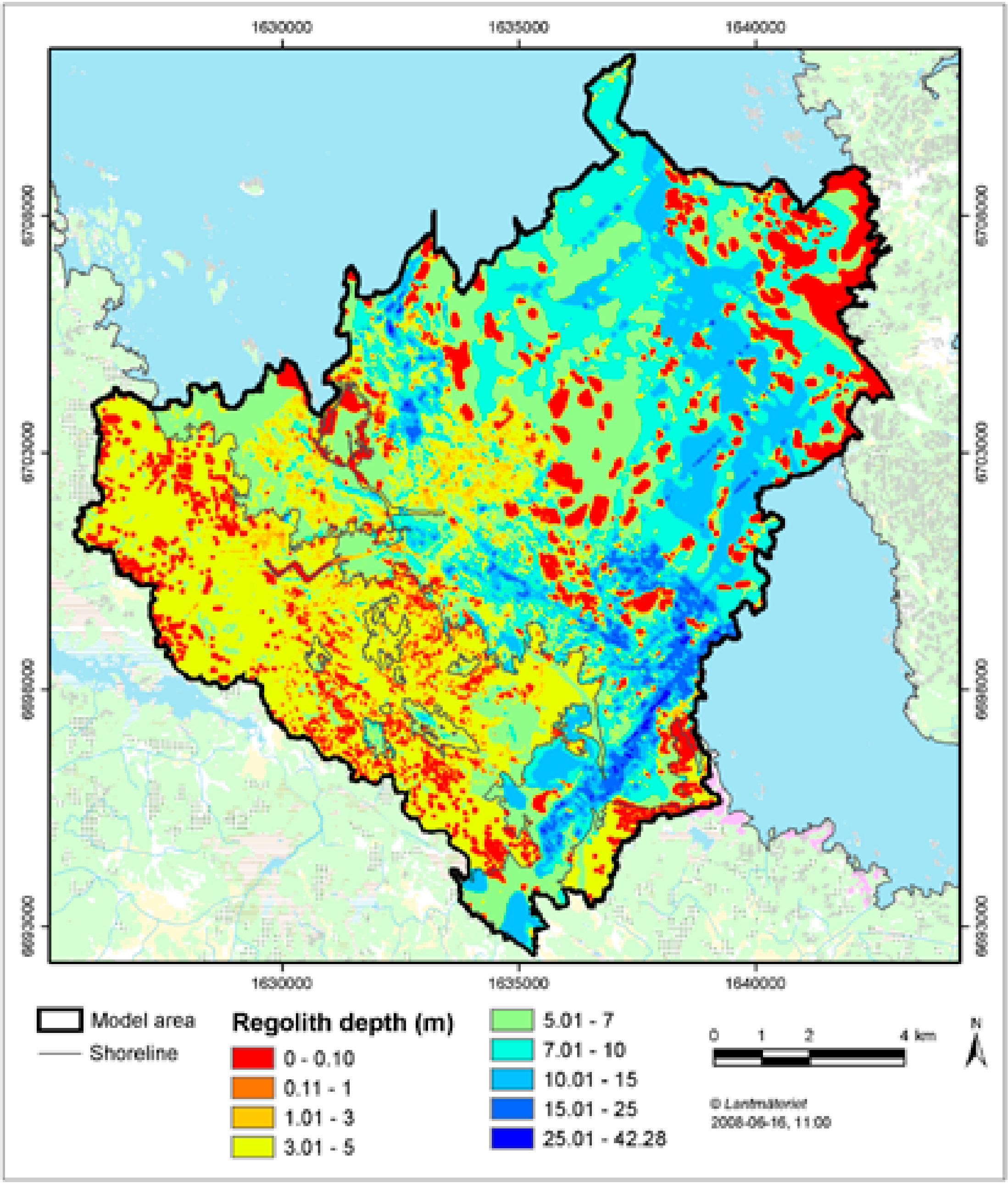

Figure 4-5. *Total modelled regolith depth at Forsmark.*

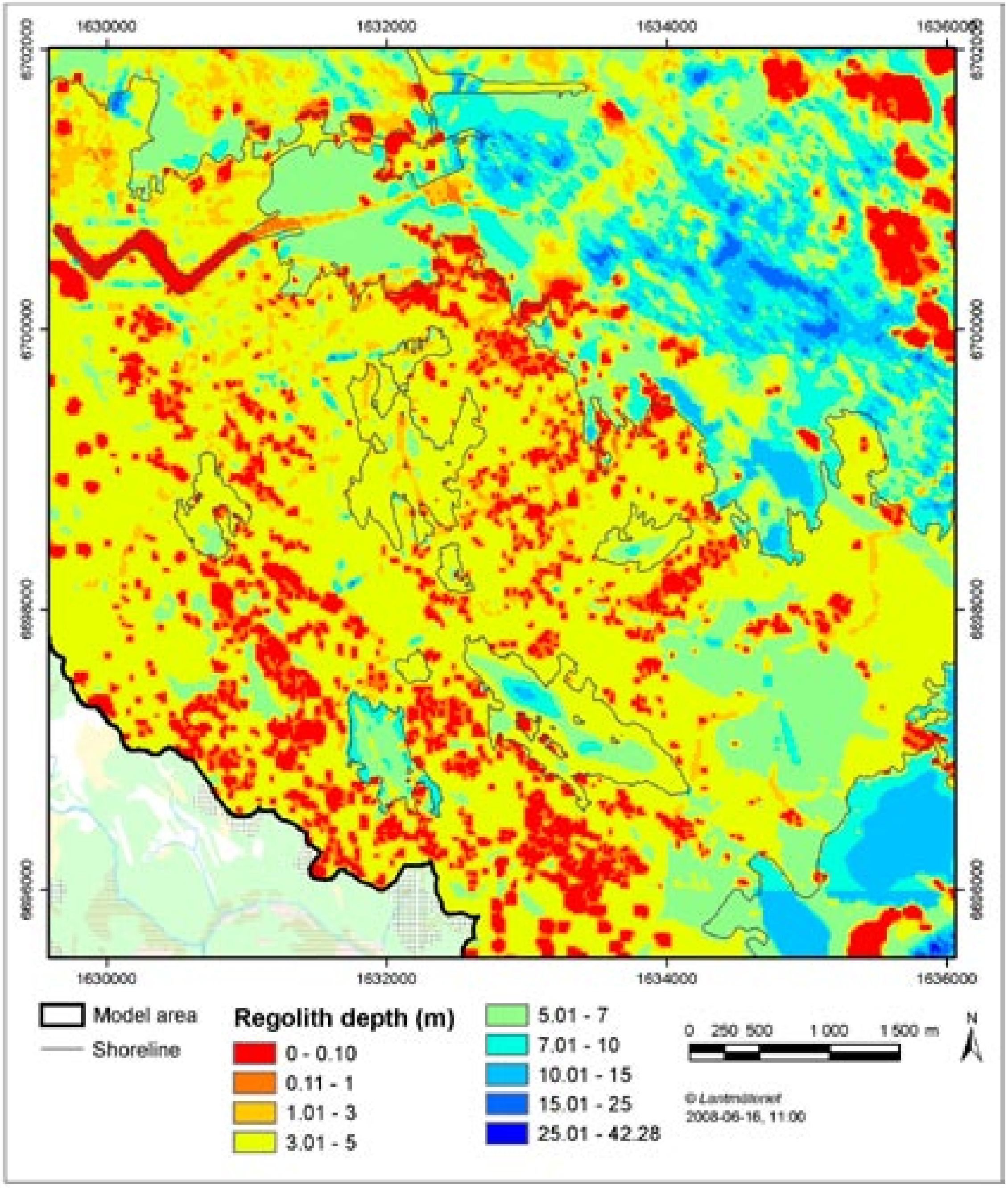

Figure 4-6. Total modelled regolith depth in the central parts of the Forsmark area.

Table 4-2. Average and median total regolith depth, from /Hedenström et al. 2008/.

Type of data	Average QD depth (m)	Standard deviation of average QD depth (m)	Median QD depth (m)
Whole model (including bedrock outcrops)	5.63	4.07	5.68
Whole model except bedrock outcrops	6.51	3.67	6.09

Table 4-3 below shows the average and median regolith depths, based on input data from the different data sources. Generally, the input data give slightly lower average and median regolith depths than are derived from the interpolated surfaces where also the bedrock outcrops (i.e. a QD depth of 0.1 m) are included. The average depth from the model excluding bedrock outcrops agree approximately with the average values from the input data.

Within the terrestrial parts of the investigated area, the area at Storskäret, which is covered with clayey till, has a generally deeper regolith than the remaining terrestrial areas. A zone with relatively deep regolith and few bedrock outcrops in the terrestrial area can be followed from the inlet of Lake Fiskarfjärden, including the lake basin and further to the NW. This depression in the bedrock has the same direction as several of the major bedrock lineaments in the Forsmark area. When extracting the regolith from the DEM, the elevation of the bedrock surface is presented (Figure 4-7). A comparison with the > 3 km lineaments at Forsmark /Stephens et al. 2007/ shows that at least the major lineaments, predominantly with a NW-SE strike, can be detected as depressions in the bedrock.

Below, two illustrative profiles are shown, selected to include representative examples from the model. Any other profile may be generated using the GeoModel tool. The profiles show the observation points that fall within 200 m of the profile. This means that boreholes and observation points situated up to 100 m from the line in either direction will be included in the graph. In some of the illustrated profiles, the elevations of observation points and depths of geological units may therefore differ from the modelled layers displayed in the profiles, since the modelled layers apply on the line along the profile.

Table 4-3. Average, median and maximum regolith depth calculated from different sources of input data, from /Hedenström et al. 2008/.

Type of data	Number of observations	Average QD depth (m)	Median QD depth (m)	Maximum QD depth (m)
Corings and excavations				
Organic and in-organic sediment mapping, peat land mapping, Ocean sediment core sampling.	1	5.47	5.47	5.47
Quaternary deposit mapping and stratigraphic observations, Neotectonic stratigraphic observations.	23	3.95	3.46	11.64
SGU's well archive.	5	2.13	1.56	12.02
Cored, percussion and probing boreholes, monitoring well in soil.	116	4.84	4.22	16.01
Geophysical data				
Refraction seismic measurement data.	6,853	3.98	3.64	29.88
Ground penetrating radar measurement data.	439	3.38	3.12	8.79
Continuous Vertical Electrical Soundings (CVES).	264	6.25	5.84	18.60
Seismic and sediment echo sounding data.	147,151	8.65	6.93	43.78
Reflexion seismic.	421	3.46	2.75	11.11
Total.	155,273	8.41	6.65	43.78

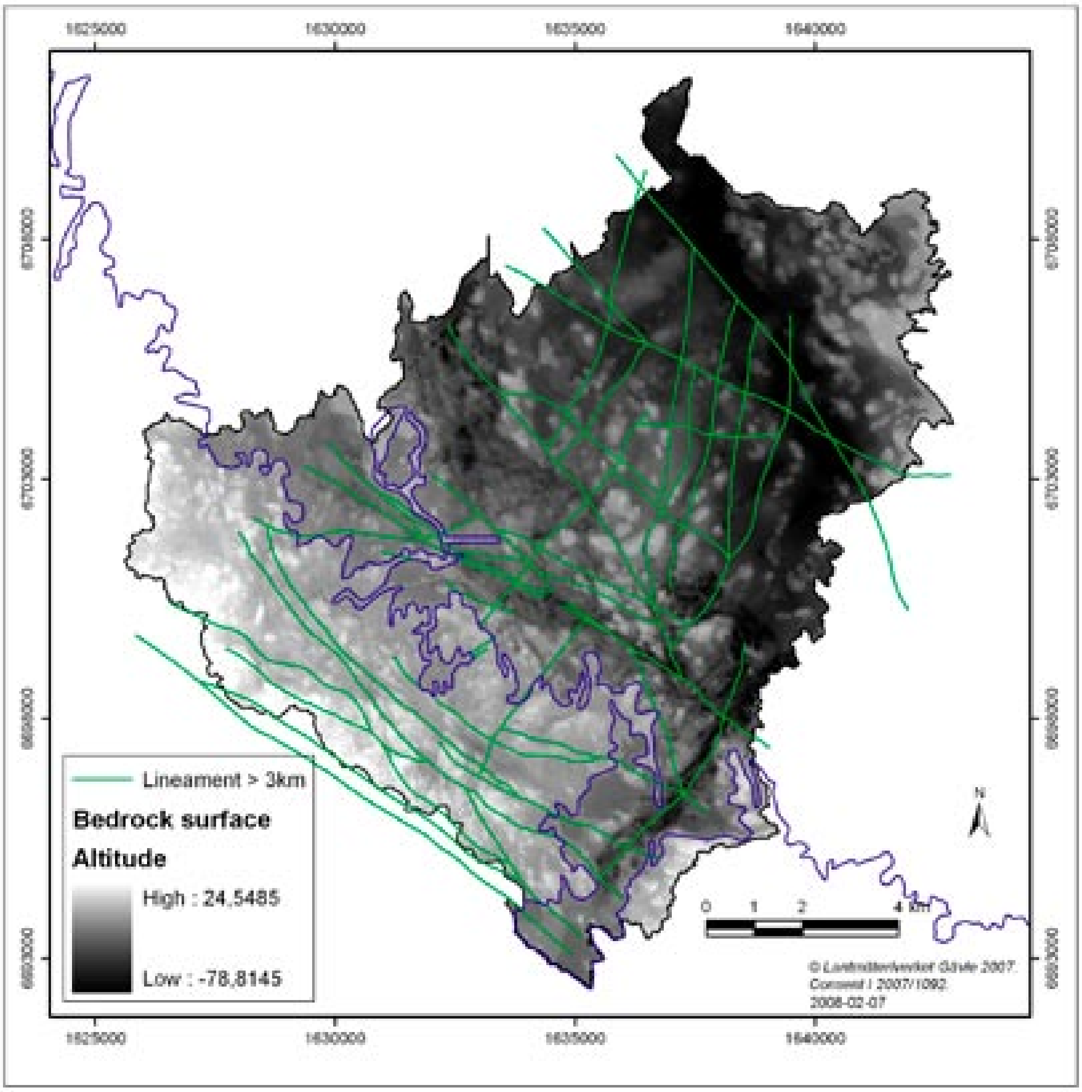

Figure 4-7. *The modelled bedrock surface at Forsmark with a resolution of 20 m. Purple line show the coastline and green lines are lineaments longer than 3 km, from /Hedenström et al. 2008, Stephens et al. 2007/.*

The profile that describes the stratigraphical distribution of the layers and lake sediment lenses in Lake Bolundsfjärden is presented in Figure 4-8. The lenses containing the water-laid sediments are barely visible. This is partly the result of the elongated profile but it also reflects the fact that the organic sediments are thin in this basin /cf. Hedenström 2004a/.

The profile crossing the glaciofluvial esker is displayed in Figure 4-9. A comparison with the conceptual model (section 3.3.2) shows a discrepancy in the shape of the bedrock under the glaciofluvial esker. Since too few observations are available, average depth values are used, resulting in a profile in which the bedrock topography follows the ground elevation. In fact, it is most probably that the glaciofluvial sediments are thicker at the crest and gradually thinner at the edges. The presented shape of the esker and bedrock surface is the result of the concept of using average depth values for all areas where glaciofluvial sediment is presented in the geological map. In /Appendix 1 in Hedenström et al. 2008/, additional profiles are presented.

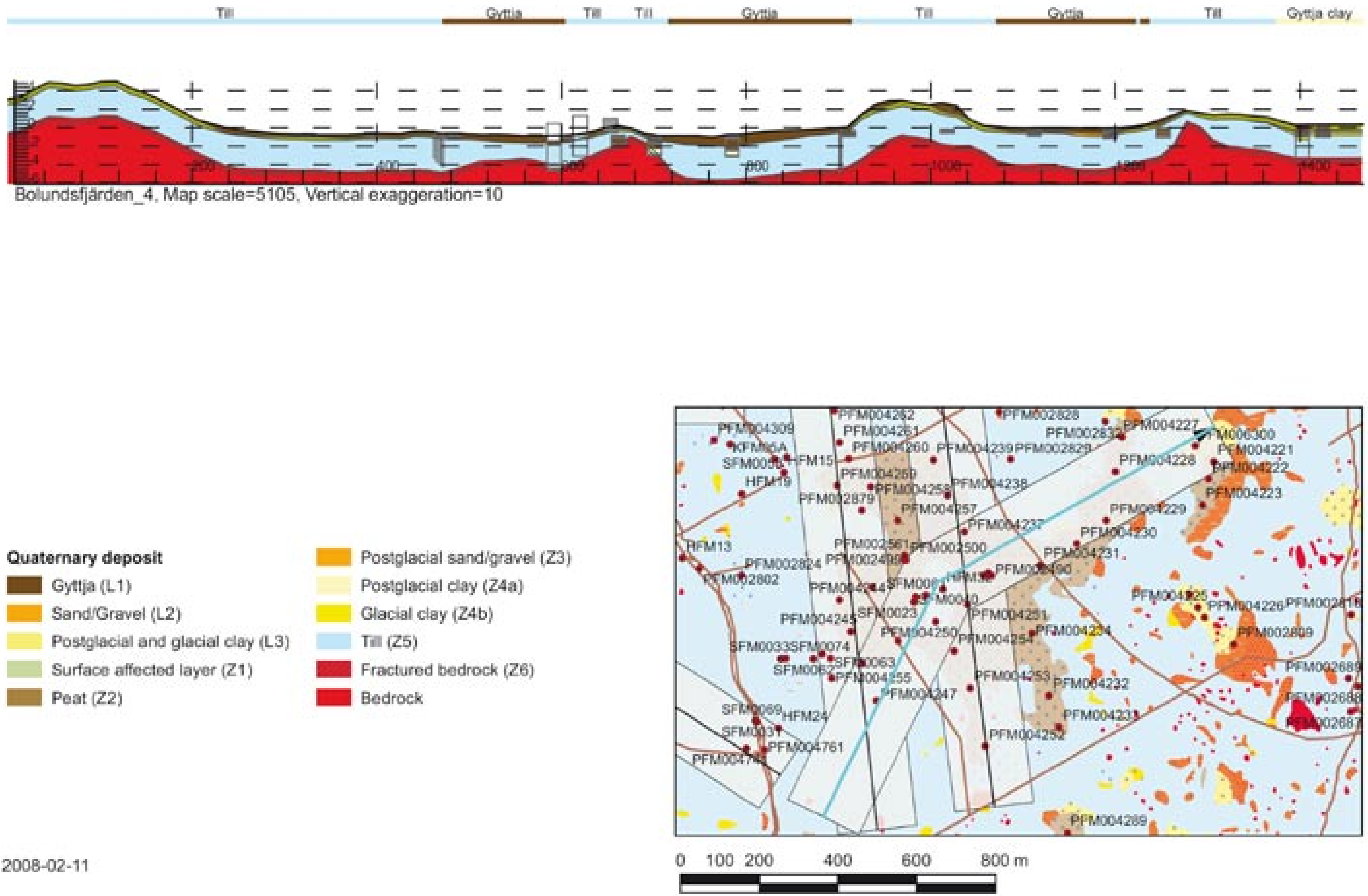

Figure 4-8. *Stratigraphical section along the Bolundsfjärden profile. For location of the profile, see the blue line (from /Hedenström et al. 2008/).*

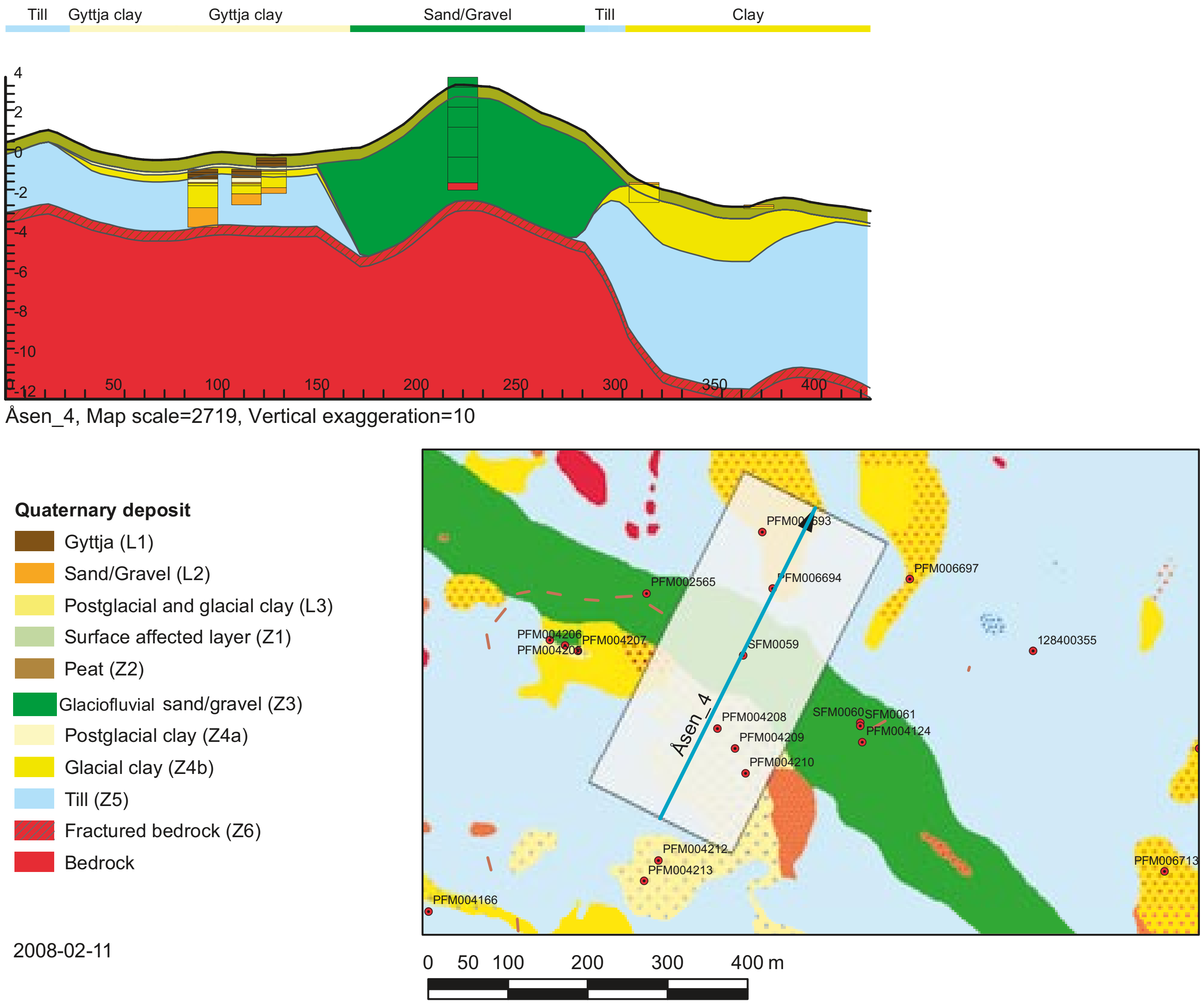

Figure 4-9. Stratigraphical section along the Börstilåsen profile. For location of the profile, see the blue line (from /Hedenström et al. 2008/).

4.3 Hydrology and hydrogeology

Comprehensive hydrological and near-surface hydrogeological field investigatigations have been conducted within the Forsmark site investigation, including monitoring of meteorological data, surface water levels and discharge, and groundwater levels in Quaternary deposits (QD), as well as hydraulic characterization of the QD (slug tests, pumping tests, permeameter tests on undisturbed core samples, and water retention analyses). Below, a summary is given of the conceptual modelling and the quantitative flow modelling of the hydrology and near-surface hydrogeology in Forsmark. For detailed presentations the reader is referred to /Johansson 2008, Johansson and Öhman 2008, Bosson et al. 2008/.

4.3.1 Hydrological and hydrogeological setting

The study area is characterized by small-scale topograpic variations and is almost entirely located below 20 m.a.s.l. Till is the dominant QD, whereas granite is the dominant rock type. The main lakes are Lake Fiskarfjärden (0.752 km^2), Lake Bolundsfjärden (0.609 km^2), Lake Eckarfjärden (0.282 km^2) and Lake Gällsboträsket (0.185 km^2). The lakes are shallow with mean depths 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 of very high sea water levels.

Wetlands are frequent and cover between 25% and 35% of some of the delineated sub-catchments. No major watercourses flow through the central part of the site investigatation 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.

In Table 4-4, best estimates of hydraulic properties of Quaternary deposits at Forsmark are shown. When sufficient site specific data are available these are used as a basis for the best estimate, whereas when site-specific data are scarce or missing generic data are used as support for the estimates. Due to the influence of soil-forming processes on the uppermost part of the soil profile, a differentiation of the hydraulic properties has been made between the upper 0.6 m of the profile and the deeper part of the profile for some of the QD. The change in hydraulic properties in the uppermost part of the soil profile is gradual towards depth. The division into two distinct layers was made to facilitate the transfer of the conceptual model to the three-dimensional numerical flow models.

The hydraulic conductivities (K) given in Table 4-4 are horizontal conductivities. The only vertical K-values from till are from the laboratory permeameter tests. The geometric mean of the samples taken from depths larger than one metre was approximately $4.4 \cdot 10^{-8}$ m/s while the geometric mean of till from the slug tests, representing horizontal hydraulic conductivites, was $1.3 \cdot 10^{-6}$ m/s, i.e. a K_h/K_v ratio of about 30 (K_h is the horizontal and K_v the vertical hydraulic conductivity). However, this result should be used with caution since the scales of the tests are different. The vertical K-values for gyttja and peat/gyttja/clay obtained from leakage coefficients from the pumping tests were approximately $1 \cdot 10^{-8}$ m/s, which is about 30 times lower than the K_h-values given for these deposits in Table 4-4.

From regional data, the mean annual precipitation in the Forsmark site investigation area has been estimated to be 559 mm (standard deviation: 106 mm) for the period 1961–1990 by the Swedish Meteorological and Hydrological Institute (SMHI). If the full three-year period of April 15, 2004, until April 14, 2007, of local measurements at Forsmark is considered, the corrected mean precipitation was 546 mm/y while the mean specific discharge of the largest catchment of 5.6 km^2 was 154 mm/y. Based on a comparison of groundwater and surface water levels at the start and end of the period it was concluded that these storages were a little smaller at the end of the period; the difference corresponded to c. –5 mm/y.

Table 4-4. Best estimates of hydraulic parameters of Quaternary deposits in Forsmark based on site-specific data and generic data when site-specific data are scarce or missing.

Deposit	K_h (m/s)	Total porosity (–)	Specific yield (–)
Peat	Depth < 0.6 m: $1\cdot10^{-6}$ Depth > 0.6 m: $3\cdot10^{-7}$	Depth < 0.6 m: 0.60 Depth > 0.6 m: 0.40	Depth < 0.6 m: 0.20 Depth > 0.6 m: 0.05
Gyttja Clay-gyttja, Gytttja-clay	$3\cdot10^{-7}$	0.50	0.03
Glaciofluvial and postglacial sand	$1.5\cdot10^{-4}$	0.35	0.20
Glacial and postglacial clay	Depth < 0.6 m: $1\cdot10^{-6}$ Depth > 0.6 m: $1.5\cdot10^{-8}$	Depth < 0.6 m: 0.55 Depth > 0.6 m: 0.45	Depth < 0.6 m: 0.05 Depth > 0.6 m: 0.03
Till	Depth < 0.6 m: $1.5\cdot10^{-5}$ (fine-grained and coarse)	Depth < 0.6 m: 0.35	Depth < 0.6 m: 0.15
	Depth > 0.6 m: Fine-grained: $1\cdot10^{-8}$ Coarse: $1.5\cdot10^{-6}$	Depth > 0.6 m: 0.25	Depth > 0.6 m: Fine-grained: 0.03 Coarse: 0.05
Till/bedrock interface	$1.5\cdot10^{-5}$	0.25	0.05

The mean of the locally measured precipitation was 13 mm/y lower than the 30-year normal precipitation estimated by SMHI. Since approximately 2/3 of the precipitation goes to evapotranspiration, the precipitation deficit should correspond to a discharge deficit of approximately 5 mm/y. These estimates of storage changes and precipitation deficit indicate that the measured 3-year mean discharge should be close the long-term normal discharge. A rough estimate of the long-term overall water balance of the area is as follows: precipitation = 560 mm/y, actual evapotranspiration = 400–410 mm/y, and runoff = 150–160 mm/y.

Figure 4-10 shows the overall conceptual model of the surface hydrology and near-surface hydrogeology, which is discussed in the following sections (and also in Chapter 5). This conceptual model was developed based on joint interpretations of hydrological-hydrogeological data from Quaternary deposits and bedrock, including groundwater flow modelling. In particular, evaluations of time series data on groundwater levels in different parts of the hydrogeological system were found to be very important for the development of the conceptual model.

4.3.2 Boundary conditions

The meteorological conditions constitute the top boundary condition of the hydrological and near-surface hydrogeological system. Water is added to the system by rainfall and snowmelt and abstracted by evapotranspiration and runoff (discharge). For long-term averages of precipitation, evapotranspiration and runoff, see above.

The strong correlation between the topography of the ground surface and the groundwater level in the QD means that surface water and groundwater divides for the QD can be assumed to coincide. For the south-western boundary of the model area it can be assumed that the water divides of the flow systems involving the near-surface bedrock follow the surface water divide of River Forsmarksån, i.e. the topography can be used for delineation of the inland boundary (see also Chapter 5 for a description of hydrogeological boundary conditions). From the conclusion that groundwater divides for the shallow groundwater systems limited to the QD (till), where the major part of the water flow takes place, coincide with the surface water divides, follows that such systems only may have a lateral boundary to the sea in the near-shore areas between the outlets from the major catchments to the sea, the so-called "rest catchments".

For the flow systems involving also the near-surface bedrock, the situation is different due to the highly transmissive horizontal and sub-horizontal fracture zones extending below the sea /Follin et al. 2008/, see Figure 4-10. The vertical contact between these zones and the sea (via outcropping or indirectly via vertical fractures and till/sediments) will determine the

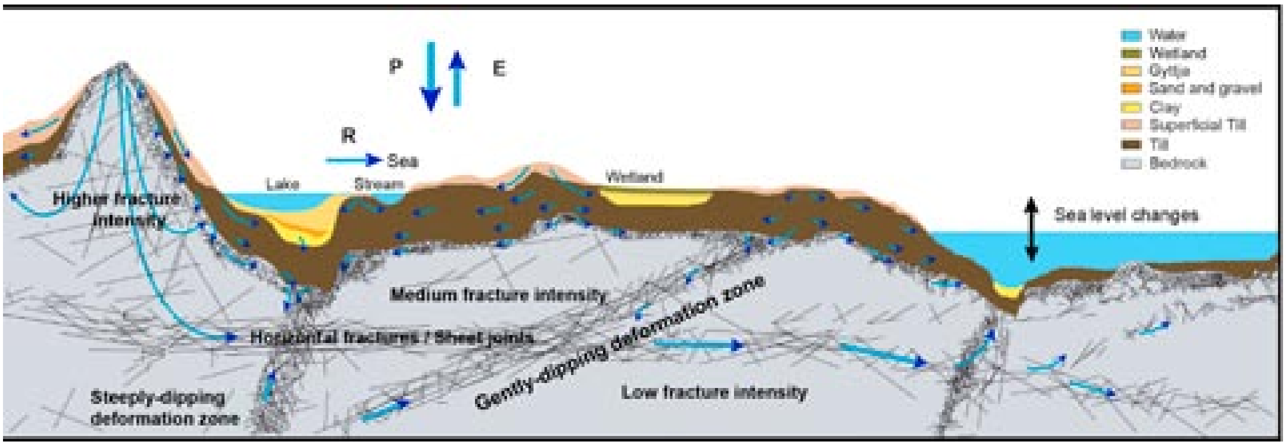

***Figure 4-10.** Section illustrating the conceptual hydrogeological model of the Quaternary deposits and the upper bedrock at the Forsmark site; figure taken from /Follin et al. 2007/.*

boundary conditions of these systems. The bottom boundary for the near-surface hydrogeology is somewhat arbitrarily set to 150 m.b.s.l., which is based on the vanishing of the highly transmissive horizontal fractures/sheet joints below this depth (see Chapter 5). According to the hydrogeological modelling of the deep bedrock, the vertical flow at this depth is very small. In a 5 km by 5 km control area in the central part of the site investigation area, the average net downward flow was calculated to c. 0.1 mm/y /Follin et al. 2007/.

4.3.3 Infiltration and groundwater recharge

The infiltration capacity exceeds the rainfall and snowmelt intensity with few exceptions. The highest recorded daily rainfall and snowmelt of 27 and 9 mm equal $3 \cdot 10^{-7}$ and $1 \cdot 10^{-7}$ m/s, respectively, which can be compared with the measured saturated hydraulic conductivity of approximately $1.5 \cdot 10^{-5}$ m/s of the uppermost part of the till dominating the area. Unsaturated (Hortonian) overland flow may appear over short distances, mainly on agricultural land covered with clayey till and on frozen ground where the soil water content is high during freezing. Also on outcropping bedrock unsaturated overland flow may appear, but only over very short distances before the water reaches open fractures or the contact zone between bedrock and QD. However, due to the flat terrain and the shallow groundwater levels, overland flow takes place in areas where the groundwater level reaches the ground surface.

The shallow groundwater levels suggest that there is a strong interaction between evapotranspiration, soil moisture and groundwater flow. The groundwater levels in many monitoring wells were within one metre below the ground surface all the year, and the groundwater levels were on average less than 0.7 m below the ground surface for 50% of the time. The annual variation in the groundwater levels is mostly less than one metre in discharge areas, and 1.5 m in typical recharge areas. Diurnal fluctuations of the groundwater levels, driven by evapotranspiration cycles, were evident in many of the groundwater wells in QD.

4.3.4 Sub-flow systems and discharge

Similarly to the external boundaries of the model area, the internal surface water divides and the groundwater divides of the groundwater systems restricted to QD are assumed to coincide. The strong correlation between the mean groundwater levels observed in the till and the ground elevation means that the average vertical hydraulic flux at some point below the surface is less than the net infiltration into the saturated zone of the till. The decrease in hydraulic conductivity with depth and the anisotropy of the till with ($K_v < K_h$) are plausible explanations, but a contribution from a contrast in vertical hydraulic conductivity between the till and the bedrock is also possible (with the uppermost bedrock having a lower K_v).

The small-scale topography and the hydraulic conductivity profile of the till that is dominant in the area imply that many small catchments will be formed with local, shallow groundwater flow systems in the QD and that most of the groundwater will move along these shallow flow paths. In Figure 4-11 the distribution of recharge and discharge areas in the QD, as calculated in the hydrological modelling with the MIKE SHE tool /Bosson et al. 2008/, is shown. In this context, the mean groundwater head difference between the two uppermost calculation layers is used for the definition of recharge and discharge areas, i.e. areas where the head was higher in the top layer than in the layer below were defined as recharge areas and *vice versa* for discharge areas.

The permeability and storage characteristics of the till profile mean that very little water needs to be added to raise the groundwater table to a depth of approximately one metre. A groundwater recharge of 10 mm will give an increase in the groundwater level of approximately 20 cm. During periods of abundant groundwater recharge, the groundwater level in most recharge areas will reach the shallow part of the QD-profile, where the hydraulic conductivity is much higher, and a significant lateral groundwater flow will take place. However, the transmissivity of this upper layer is so high that the groundwater level does not reach much closer to the ground surface than 0.5 m in typical recharge areas.

The local, small-scale recharge and discharge areas, involving groundwater flow systems restricted to QD, will overlie the more large-scale flow systems associated with groundwater flow at greater depths. Interestingly, the groundwater level in the till seems to be considerably higher than in the bedrock in the central part of the site investigation area (i.e. within the "target area" where the repository is planned to be located). The differences between the levels in the till and the bedrock are generally much larger than between different sections in the bedrock boreholes sealed off by packers. However, the groundwater levels in most bedrock boreholes are still above the QD/rock interface under undisturbed conditions, indicating that no unsaturated zone exists below the interface.

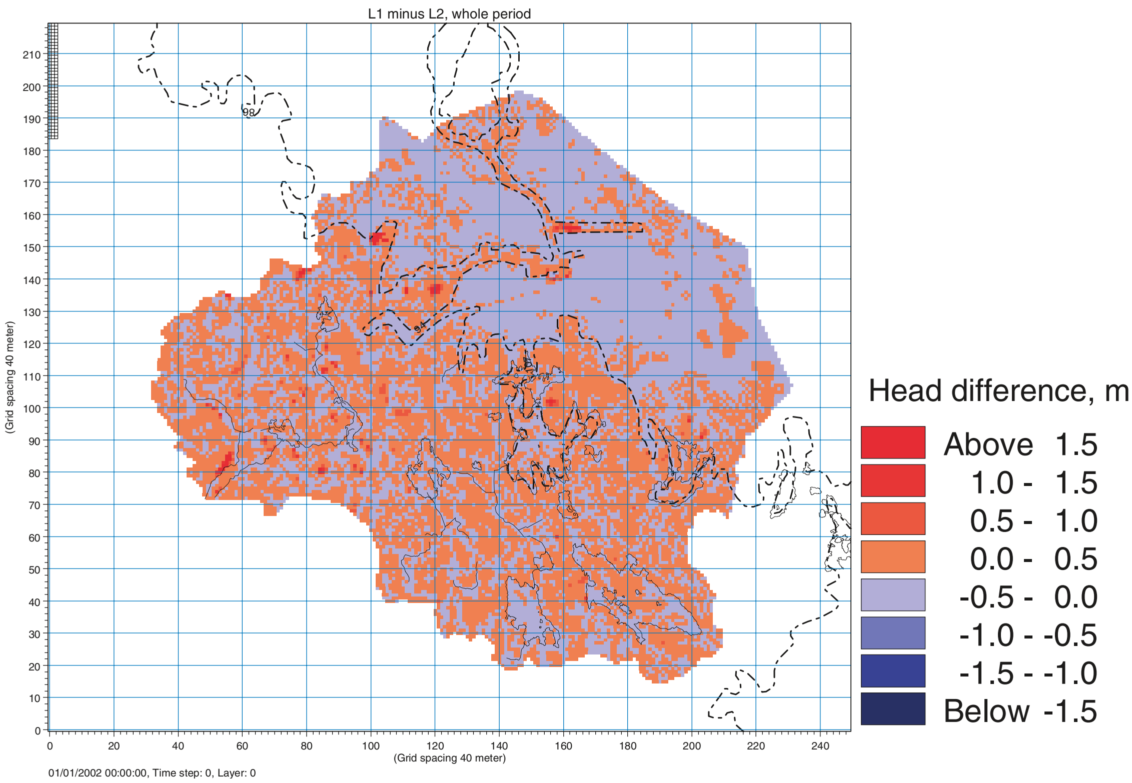

***Figure 4-11**. The mean head difference between the MIKE SHE model calculation layers 1 and 2 in Quaternary deposits under dry conditions; positive values (red areas) indicate recharge areas and negative values (blue to purple) discharge areas.*

The groundwater level variations in the till and the bedrock are correlated. The natural groundwater level fluctuations are, however, smaller in the bedrock, but still controlled primarily by the annual precipitation and evapotranspiration cycles. The conditions prevailing within the target area in the north-western part of the candidate area, with a lower groundwater level in bedrock than in QD, imply that the groundwater flow has a downward component at the studied sites. This means that there is an inflow from the till to the bedrock. The difference between the levels in till and bedrock indicates limited hydraulic contact between QD and rock. A probable explanation for the low levels measured in the bedrock boreholes is that these intersect some of the highly conductive horizontal to sub-horizontal fractures shown to exist in the shallow bedrock (see Chapter 5).

The highly transmissive shallow bedrock acts as a drain for water coming from above as well as from below. 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.

Interestingly, in the middle of Lake Bolundsfjärden, the lake level and the groundwater level in till are considerably higher than the levels in the bedrock down to 200 m depth, indicating a downward flow gradient from the lake and QD to the bedrock. The groundwater level in the bedrock below Lake Bolundsfjärden was even below the sea level during the dry summer and autumn of 2006. Two possible, perhaps superimposed, phenomena could explain this: (i) the groundwater level in the bedrock is indirectly influenced by evapotranspiration extracting water from the groundwater zone in the QD inducing an upward flow from the bedrock, and/or (ii) the borehole is influenced by the drainage pumping in the SFR facility (approximately 6 L/s). An influence from evapotranspiration requires that the groundwater level in the bedrock is above the QD/rock interface, which is the case in the low-lying areas surrounding Lake Bolundsfjärden, so that no unsaturated zone exists in the bedrock.

An influence from the pumping at SFR requires a good hydraulic contact all the way to SFR (Figure 1-2). From a pumping test in HFM33, immediately west of SFR, it is known that quick and strong responses were observed in e.g. HFM02 (c. 0.3 m) and HFM15 (c. 0.1 m) located c. 1.5 km from the pumping well. The pumping rate in HFM33 was approximately 3.8 L/s; this test is described in /Gokall-Norman and Ludvigson 2008, Follin et al. 2008/.

In the MIKE SHE numerical modelling of the near-surface hydrology, there was a general problem with too high simulated groundwater levels in the bedrock, whereas there was a good agreement with the measured groundwater levels in the Quaternary deposits. Furthermore, with the original parameter settings the model was unable to simulate the drawdowns in the pumping test in the percussion-drilled borehole HFM14, causing fast and extensive measured responses in monitoring wells in bedrock more than one km from the borehole. To overcome these problems, several tests were conducted with different combinations of increased horizontal hydraulic conductivity of the bedrock and decreased vertical hydraulic conductivity of the bedrock and the Quaternary deposits, and a decreased specific storage of the bedrock compared with the data set obtained from the bedrock hydrogeology modelling.

One outcome of these tests was that the specific storage coefficient had to be lowered considerably from the values used initially (varying from $1\cdot10^{-7}$ m^{-1} to $1\cdot10^{-5}$ m^{-1}) to obtain a good match between measured and simulated responses in the pumping test. In the final calibrated MIKE SHE model, a value of $5\cdot10^{-8}$ m^{-1} was used. Furthermore, an increase of the horizontal hydraulic conductivity of the sheet joints, as implemented in the model in the upper bedrock, by a factor 10, and a decrease of the vertical hydraulic conductivity of the upper 200 m of the bedrock by a factor 10 were found necessary to obtain a good fit between measured and simulated pumping test responses. Decreases of the vertical hydraulic conductivity of the Quaternary deposits also turned out to have only a marginal effect on the groundwater levels.

The problem with the generally too high groundwater levels in the upper rock was only partly solved by the parameter changes made. As a final test, the pumping for the drainage of the SFR facility was introduced in the model in a quite simplistic manner, as a well screened between c. 40 and 140 m depth. Furthermore, the drainage of the Forsmark nuclear plant reactor buildings 1 and 2 by pumping of c. 1–2 L/s at c. 20 m depth was included in the model. The introduction of these sinks, with the influence of the SFR drainage dominating, improved the agreement between measured and simulated groundwater levels in the bedrock considerably. The mean absolute error and mean error for all the considered monitoring sections in rock changed from 0.68 m to 0.41 m and from –0.65 m to –0.05 m, respectively (negative mean errors indicate that the simulated levels are too high). Most of the monitoring wells showed errors of c. 0.2 m.

The calculated annual water balance for each layer in the saturated zone is presented in Figure 4-12, which shows results obtained from model runs with and without pumping in SFR. The numbers shown in the figure are spatially and temporally averaged specific fluxes representing the terrestrial part of the model area only. The net average annual groundwater recharge from the unsaturated zone to the uppermost calculation layer containing the Quaternary deposits was 124 mm. The inflow to the second calculation layer in QD, at 2.5 m depth, was c. 45 mm/y. There were many local recharge and discharge areas within this layer; 41 mm/y was transported back to the uppermost QD layer. Only c. 11 mm was flowing down to the uppermost bedrock (calculation layer 3), and the downward net flux across the QD/rock interface was only 2–4 mm/y.

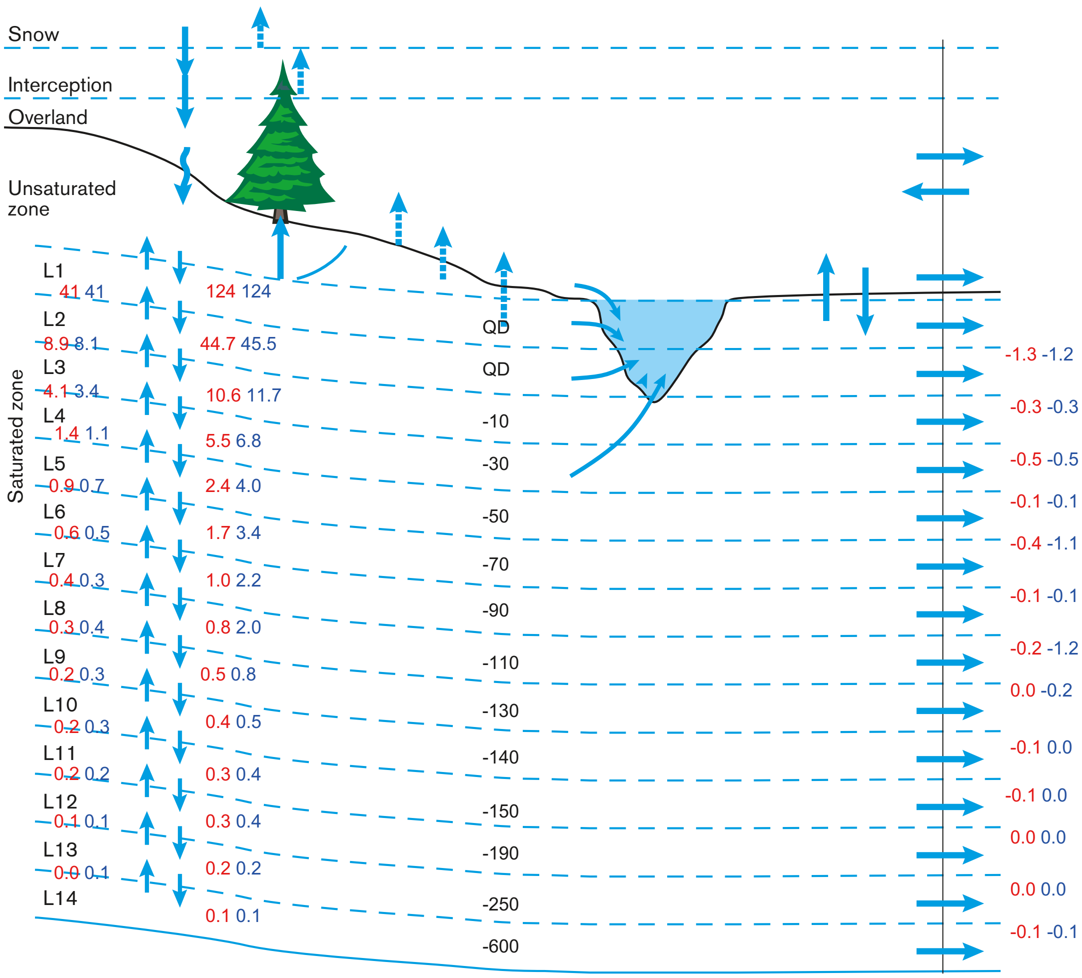

Figure 4-12*. Average water balance for each layer in the saturated zone /Bosson et al. 2008/, expressed as annual specific fluxes in mm/year from layer to layer and through the boundary at the coastline (negative for outflow). The red figures represent the calculation without SFR and blue figures the one with the SFR drainage activiated. Note that only the net flux is shown for the recharge into the saturated zone (124 mm/year), whereas upward and downward components otherwise are reported (e.g. 8.9/8.1 and 10.6/11.7 belong to the same layer interface). The mean lower level of each calculation layer is shown in the middle of the figure.*

In the uppermost c. 100 m there was a slight increase of the downward flow when the SFR drainage was included in the simulation. The pumping was active down to 140 m.b.s.l. and the results show that below this level the influence of SFR was insignificant (the SFR pumping has a stronger influence on the flow in the bedrock below the sea, but this area is not included in water balance in the figure). The net vertical groundwater flux at the level of 150 m.b.s.l. was c. 0.1 mm/y (see above), which agreed well with the corresponding bedrock modelling result. However, the magnitudes of the upward and downward flow components were somewhat lower in the MIKE SHE model, which probably was due to the above-mentioned reduction of the vertical hydraulic conductivity in the upper part of the bedrock.

The flow systems around and below the lakes appear to be quite complex. The lake water level/groundwater level relationships, under natural as well as disturbed conditions, indicate that the lake sediments and the underlying till have low vertical hydraulic conductivities. If the hydraulic contact had been good, the conditions with groundwater level drawdown from evapotranspiration extending below the lakes, and the quick and extensive drawdowns extending below Lake Bolundsfjärden and the sea during pumping tests in the bedrock, would not prevail. Furthermore, the groundwaters below the lakes have relict marine chemical signatures, whereas groundwaters in the riparian zones are fresh.

The gradients between different model compartments in the flow model are crucial for any kind of transport analyses. The conditions around the lakes are of specific interest, because the lakes may act as discharge areas for sub-flow systems restricted to QD and also for sub-systems involving the bedrock to different depths. In Figure 4-13 a calculated profile of groundwater heads in a west-east cross-section across Lake Bolundsfjärden simulated by MIKE SHE is shown (with the SFR drainage included in the simulation).

According to the modelling results, also Lake Bolundsfjärden acts as discharge area for the upper parts of the system, including also the uppermost part of the bedrock, during periods of wet conditions. However, observed data do not support this, because the observed heads in the bedrock below the lake are lower than the simulated levels even when the effect of SFR is considered in the model. The simulated gradients in the upper graph in Figure 4-13 show that layer 4 (c. 10–30 m.b.s.l.), being part of the high-conductive horizontal fractures/sheet joints in this area, transports water from the higher-altitude areas around the lake and under the lake.

Under dry conditions, the effects of transpiration on the gradients in the littoral zones are pronounced in the Lake Bolundsfjärden area, see the lower graph in Figure 4-13. On the eastern side of the lake, a significant upward gradient is simulated by the model. This means that according to the model results the transpiration processes together with the capillary forces are important sinks, not only for the QD but also for the upper bedrock. In particular these sinks are important for the littoral zones around the lake.

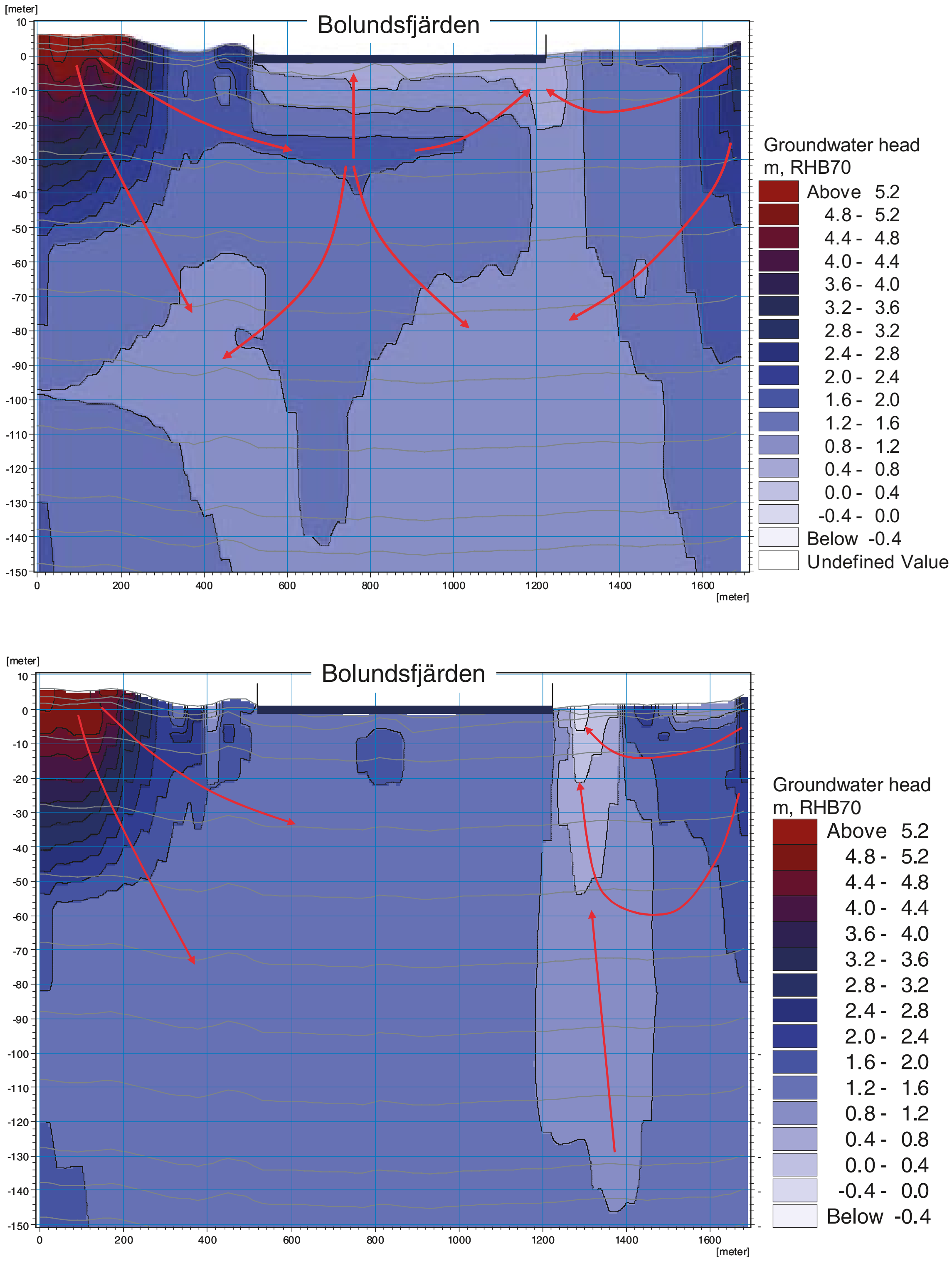

Figure 4-13*. Simulated groundwater heads in a west-east profile across Lake Bolundsfjärden for a wet period (April 2006, upper graph) and a dry period (August 2006, lower graph) /Bosson et al. 2008/.*

4.4 Regolith and Quaternary geology

Below follows a descriptive summary of the Quaternary geology and the distribution and properties of regolith in the Forsmark area. The description consists of an overview of the spatial distribution and properties of the different units and sub-domains defined at Forsmark. The modelled regolith depth is presented in section 4.2. A description of the regolith depth model is found in /Hedenström et al. 2008/. For a detailed description of the properties and distribution of the regolith at Forsmark, see /Hedenström and Sohlenius 2008/ and for the geological and historical development of the site, see section 4.1 of this report and Chapter 4 and 6 in /Söderbäck (ed) 2008/. The area described in this chapter is equivalent to the model area for regolith depth (Figure 4-5).

The regolith in Forsmark, as in general along the coast of northern Uppland, is characterized by a flat upper surface, young and un-weathered soils, high content of calcium carbonate in gravel and fine fractions, and the occurrence of till with high clay content. The soil profiles are typically poorly developed and dominated by Regosols, Gleysols and Histosols /Lundin et al. 2004/. The results from corings, excavations and geophysical investigations at the Forsmark site indicate that the till fills depressions and small-scale crevasses in the bedrock leaving a flat surface.

4.4.1 Distribution

Quaternary deposits cover c. 90% of the ground surface within the model domain (Table 4-5). The spatial distribution of the regolith is controlled by the bedrock morphology. The more elevated areas in the south-western part are dominated by till and bedrock outcrops, whereas the fine-grained sediments are more prevalent at lower altitudes, mainly in deeper areas offshore (Figure 4-14). Exposed bedrock or bedrock with only a thin regolith (< 0.5 m) occupies c. 9% of the area in the regional model area and only c. 5% of the central part (Table 4-5). Areas with a low frequency of outcrops are the eastern part of Storskäret, west of Lake Bolundsfjärden, and the major part of the deep marine area. Areas with a high frequency of bedrock outcrops are north of Lake Bruksdammen and along the present shoreline and on several of the small islands. Many of the bedrock outcrops show clear signs of glacial erosion (Figure 4-15) abraded on the northern side, indicating active ice with a dominant flow direction from 350–360°, whereas an older ice movement direction from the northwest is preserved on lee side positions /Sohlenius et al. 2004/.

Till

Glacial till is the dominant Quaternary deposit in the Forsmark area. Till covers 65% of the terrestrial areas and 30% of the marine area (Table 4-5). Compared with a national database covering 85,000 km^2 of SGU local Ae maps covering areas in southern Sweden (SGU 2006), the distribution of Quaternary deposits at Forsmark has two significant differences. The Forsmark area has less clay and silt (8% compared with 20%) and more till (65% compared with 41%) as compared with the national averages. A comparison with the surface coverage in the Laxemar-Simpevarp area shows a significantly higher proportion of bare bedrock at Laxemar-Simpevarp (35%), compared with Forsmark (13%) as well as national values (15%).

The distribution of till at Forsmark is characterized by heterogeneity in textural composition and spatial distribution. Two main characteristics of the till at Forsmark are 1) the occurrence of a clayey till/boulder clay in the eastern part and 2) the generally high content of calcium carbonate in the fine- and gravel fractions of the till. High content of calcium carbonate is recorded in a majority of the glacial deposits in the area /Hedenström and Sohlenius 2008/. The calcium carbonate in the till material has its origin from Palaeozoic limestone on the bottom of the Bothnian Sea north of Forsmark, eroded, incorporated and deposited by glaciers /Persson 1992/.

Table 4-5. The proportions (%) of the areas covered with different Quaternary deposits and bedrock exposures, totally and in subareas of the Forsmark area. The subareas are described in Figure 2-3 in /Hedenström et al. 2008/. Terrestrial refers to all areas excluding those covered by water. Detailed terrestrial refers to the central part of the model area /Sohlenius et al. 2004/.

	All areas	Terrestrial	Detailed terrestrial	Marine area
Bedrock exposures	9	13	5	6
Glacial clay	25	4	4	41
Postglacial clay (including gyttja clay and gyttja)	11	4	4	17
Postglacial sand and gravel	4	2	4	6
Till total (sandy/clayey)	48.5 (46/2.5)	65 (58/7)	74 (63/11)	30
Glaciofluvial sediment	0.5	1	2	0
Peat	1	8	3	–
Artificial fill	1	3	4	–

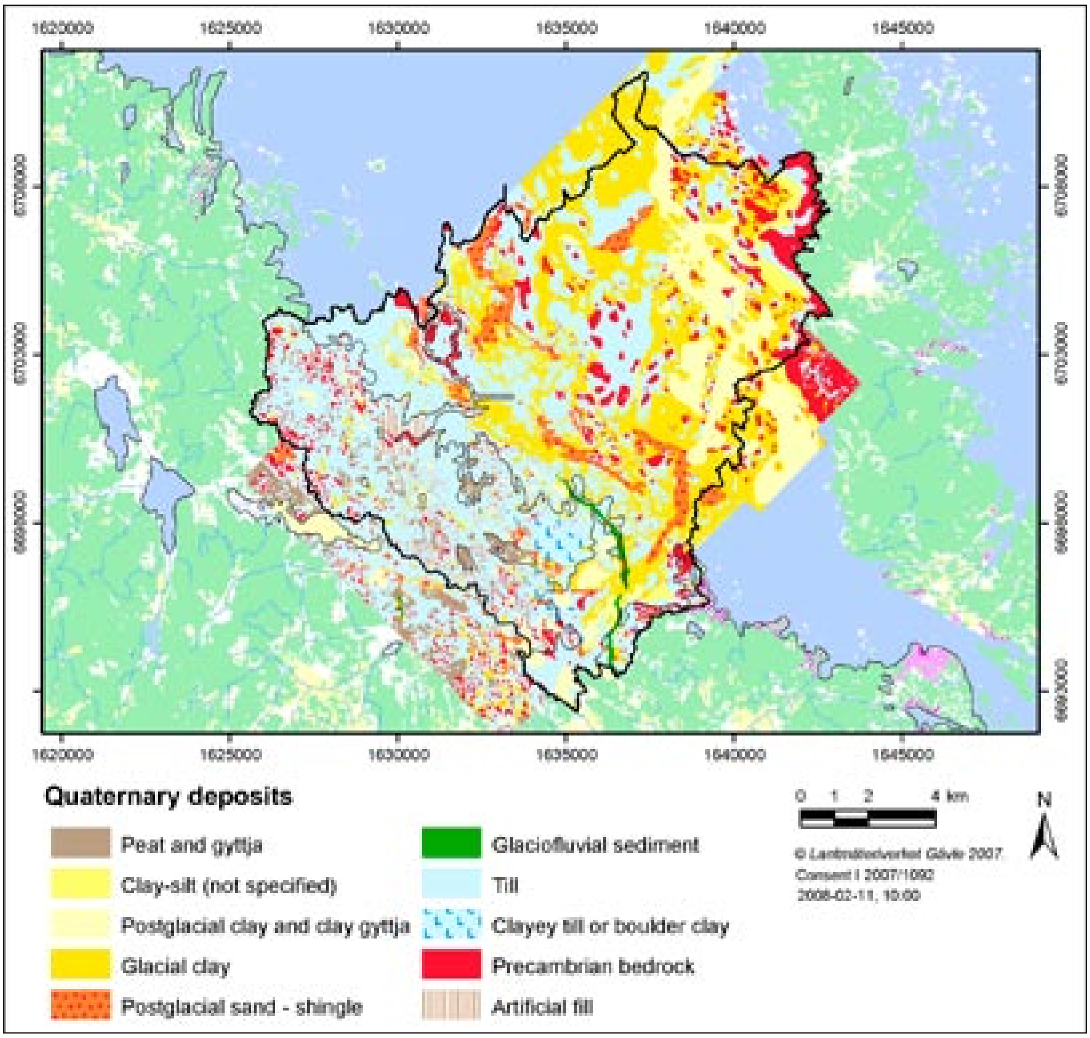

Figure 4-14. Map showing the distribution of the Quaternary deposits in the Forsmark area (from /Hedenström et al. 2008/). The map is a compilation of six different geological maps, originally presented at different scales (cf. Figure 3-7). It should be noted that the areas presently covered by water (under lakes, streams and in the sea) are presented ignoring the water cover. The black line shows the extension of the regolith depth model.

***Figure 4-15.** The bedrock at Forsmark often shows clear signs of glacial abrasion, especially the outcrops that are recently uplifted from the sea. The majority of the glacial striae have a direction from the north, the right side of the picture, probably representing the youngest ice movement direction.*

Based on the grain-size composition of the matrix and the boulder frequency in the surface layer, the till in the terrestrial area has been divided into three areas (Figure 4-16).

- Till area I constitutes the major part of the Forsmark terrestrial area, especially in the western and southern parts of the model area. In this area, sandy till with a medium frequency of superficial boulders dominates. The topography is generally flat or gently undulating with numerous exposed, often small, bedrock outcrops at the highest altitudes and close to the coast (Figure 4-17). The average depth to bedrock within Till area I is 3.5 m.
- Till area II is dominated by clayey till and boulder clay, i.e. a clay content > 5% of the matrix. The major part of the arable land in Forsmark is located within this area at Storskäret (Figure 4-18). The frequency of bedrock outcrops is low in areas with clayey till. The boulder frequency is generally low, but stones are frequently found in heaps within the arable land. The average depth of the clayey till/boulder clay is 5.8 m /Hedenström et al. 2008/.
- Till area III lies in the eastern part of the investigated area, close to the Börstilåsen esker. It is characterized by a high frequency of large boulders with a volume often > 1 m^3 (Figure 4-19). This subdomain is part of a regional zone of till with a high frequency of large boulders following the coast south to Östhammar and further south /Persson 1992/. The major part of till area III is situated within the Kallriga nature reserve and in the coastal marine area; hence, no excavations or corings have been performed.

The stratigraphical relation between the till units is more complex than the surface distribution /Sundh et al. 2004/. Sandy till has been observed on top of clayey or silty till in the western part, whereas the reverse has been recorded in the east. At the transition between Till areas I and II, the two till types have been nested into each other in a more or less random way /Hedenström and Sohlenius 2008/. A unit consisting of a hard clayey till has been observed under sandy till at several sites within Till area I (Figure 4-16).

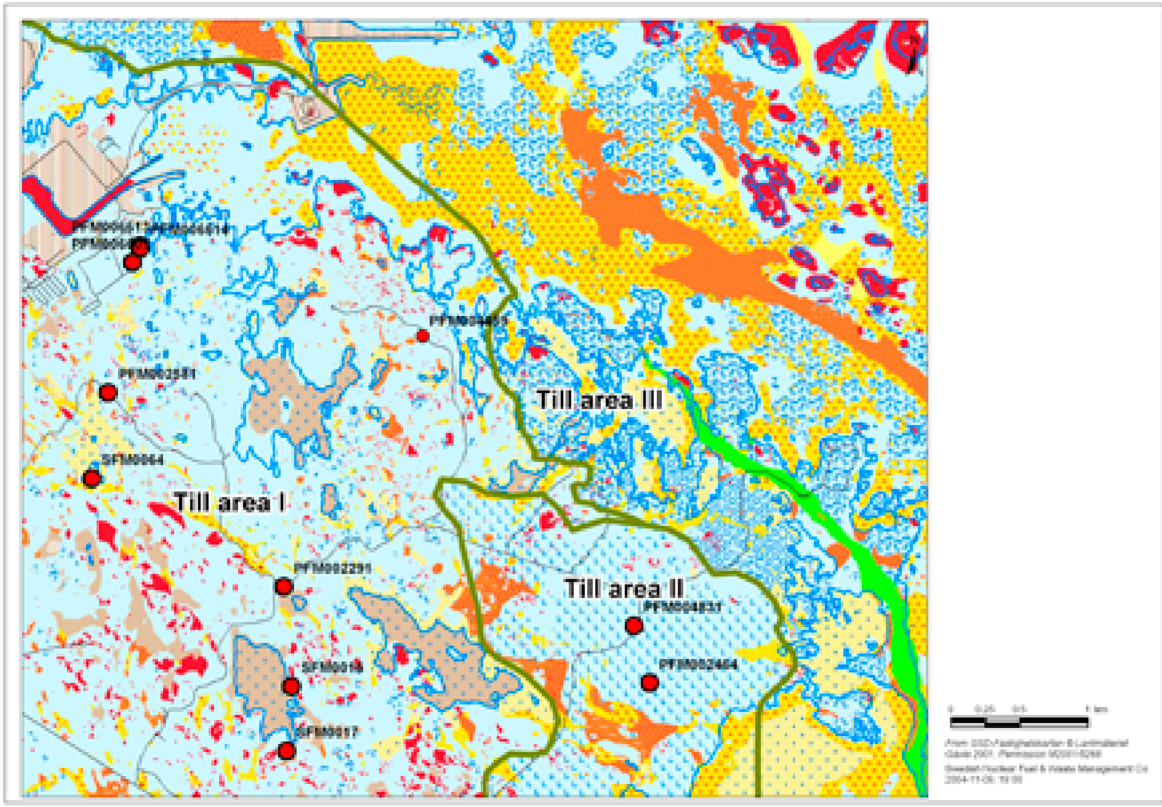

***Figure 4-16**. Distribution of the three till areas (delimited by green lines) at Forsmark and sites (shown as red dots) where a hard clayey till has been observed below a sandy till unit (from /Hedenström and Sohlenius 2008/).*

***Figure 4-17**. Till area I in Forsmark is dominated by managed forest.*

***Figure 4-18**. The arable land at Storskäret is located within Till area II. The frequency of boulders is low but stones, often well rounded, are frequent at the surface.*

***Figure 4-19**. Dense occurrence of angular, large boulders is characteristic for Till area III.*

Glaciofluvial sediments

Glaciofluvial sediments in Forsmark are limited to one small esker, the Börstilåsen esker, which passes through the south-eastern part of the model area, covering 1% of the terrestrial area (Table 4-5). The Börstilåsen esker is the largest glaciofluvial deposit in the Östhammar region and can be followed from Harg situated c. 30 km south of Forsmark. Information from the site shows that c. 5–7 m of glaciofluvial sand, gravel and stones are located directly on the bedrock (Figure 4-20).

The distal glaciofluvial sediments, represented by glacial clay and silt, were deposited in stagnant water at some distance from the retreating inland ice, generally superimposed on till. The major part of the glacial clay is found in the offshore area, especially in the areas with a water depth of > 6 metres. In the marine area, the average depth of glacial clay is c. 3 m /Elhammer and Sandkvist 2005/. In the terrestrial area, the locations covered with glacial clay are mainly local depressions such as the bottom of lakes and small ponds (Figure 4-21). Generally, glacial clay in terrestrial areas, especially those not associated with the larger lakes, is often only a few dm thick and is probably remnants after erosion on the bottom of the sea.

***Figure 4-20**. The glaciofluvial sediment at the crest of the Börstilåsen esker. The sediment is coarse, dominated by gravel deposited directly on bedrock. The photograph was taken in November 2003, during the drilling at SFM0060.*

***Figure 4-21**. Example of a varved glacial clay collected in a small pond close to the Börstilåsen esker.*

Postglacial sediments

The postglacial Quaternary deposits in Forsmark are of three main types: postglacial sand and gravel, clay gyttja, and gyttja and peat. After the deglaciation and formation of the glacial deposits, the Forsmark area has been situated below the Baltic until the last few thousand years. Thus, the formation, erosion and relocation of postglacial deposits have mainly been taking place on the bottom and in the water column of the Baltic. These processes are still active in the areas presently located below sea level as reflected in the accumulation of postglacial clay in the protected and deeper areas. In the terrestrial areas, postglacial sediments and peat are formed in the many wetlands, ponds and lakes.

Postglacial sand and gravel have been observed during the geological mapping of the terrestrial and marine areas as well as in corings in lakes and mires /Sohlenius et al. 2004, Elhammer and Sandqvist 2004, Hedenström 2004b/. The postglacial gravel and sand often superimposed on the glacial clay and are interpreted to mainly represent deposition after erosion and transport by currents on the sea floor and are therefore often referred to as postglacial sand instead of wave-washed sediment. However, although frequently occurring, postglacial sand and gravel only cover 2% of the Forsmark area (Table 4-5). Stratigraphical information showed that the average depth of postglacial sand and gravel is 22 cm in the terrestrial and lacustrine areas and 0.9 m in the marine area.

Postglacial clay, including clay gyttja and gyttja clay, is predominantly found in the deeper parts of valleys on the sea floor (Figure 4-14). The average depth of postglacial clay in the marine area is 0.9 m /Elhammer and Sandkvist 2005/. The ongoing isostatic uplift transfers sedimentary basins to sheltered positions, favouring the accumulation of organic sediments.

Organic deposits occur frequently but do not cover a large area (Table 4-5). Both peat and clay gyttja-gyttja clay was identified in the wetlands. Based on the surface distribution of organic deposits, the terrestrial area has been subdivided into two general domains (Figure 4-22). One in the south-western part (A) and one in the north-east (B). The difference in composition of the organic deposits in these two areas is basically a result of how long time has passed since their emergence from the sea. The youngest mires at low altitudes typically have clay gyttja at the surface (domain B), e.g. along the shores of Lake Fiskarfjärden and Lake Gällsboträsket (Figure 4-23). Peat is found most frequently in the south-western part of the area, i.e. the most elevated parts that have been above sea level long enough for infilling of basins and peat to form (domain A). Actual peatlands in the Forsmark area, found in domain A, are generally young and nutrient rich. Bogs do occur but are few and still young, while rich fens are the dominant type of wetlands /Fredriksson 2004/. Stenrösmossen and the mire at Rönningarna are two examples of mires, which, at least partly, are developed into bogs with an average peat layer depth of 1.4 m. The mire at Rönningarna consists of a central part characterized as a pine bog covered with e.g. *Ledum palustre*, *Myrica gale* and *Sphagnum spp*. (Figure 4-24), whereas the distal areas of the mire are characterized as a fen dominated by richer and more nutrient demanding vegetation.

The ongoing isostatic uplift results in the emergence of new land areas, which transfer the coastal basins to a sheltered position, favouring the accumulation of clay gyttja and gyttja. Gyttja is formed in lakes and consists mainly of remnants from plants that had grown in the lake. In areas with calcareous soils, such as the Forsmark area, calcareous gyttja is formed when lime-saturated groundwater enters the lake and/or by biological precipitation by algae. Many of the ponds and lakes in Forsmark are very shallow, often less than 1 m water depth at the deepest and will have only a short duration as a lake/pond before the basin is filled in and developed into a wetland cf. /Brydsten 2004/. Some of the shallow basins are in fact hard to classify as either lake or wetland, i.e. Kungsträsket and Stocksjön. Based on the sedimentary strata, the basins may instead be divided into two main groups: presence or absence of clay in the bottom of the sedimentary basin. An inventory of small and shallow basins located in the central part of the candidate area showed that approximately half of the investigated sites had a layer of clay under the organic sediment (Figure 4-25). Regarding the three larger lakes, Lake Eckarfjärden and Lake Fiskarfjärden have continuous layers of clay whereas in Lake Bolundsfjärden, the postglacial sediments are partly located directly on till /Hedenström 2004a/.

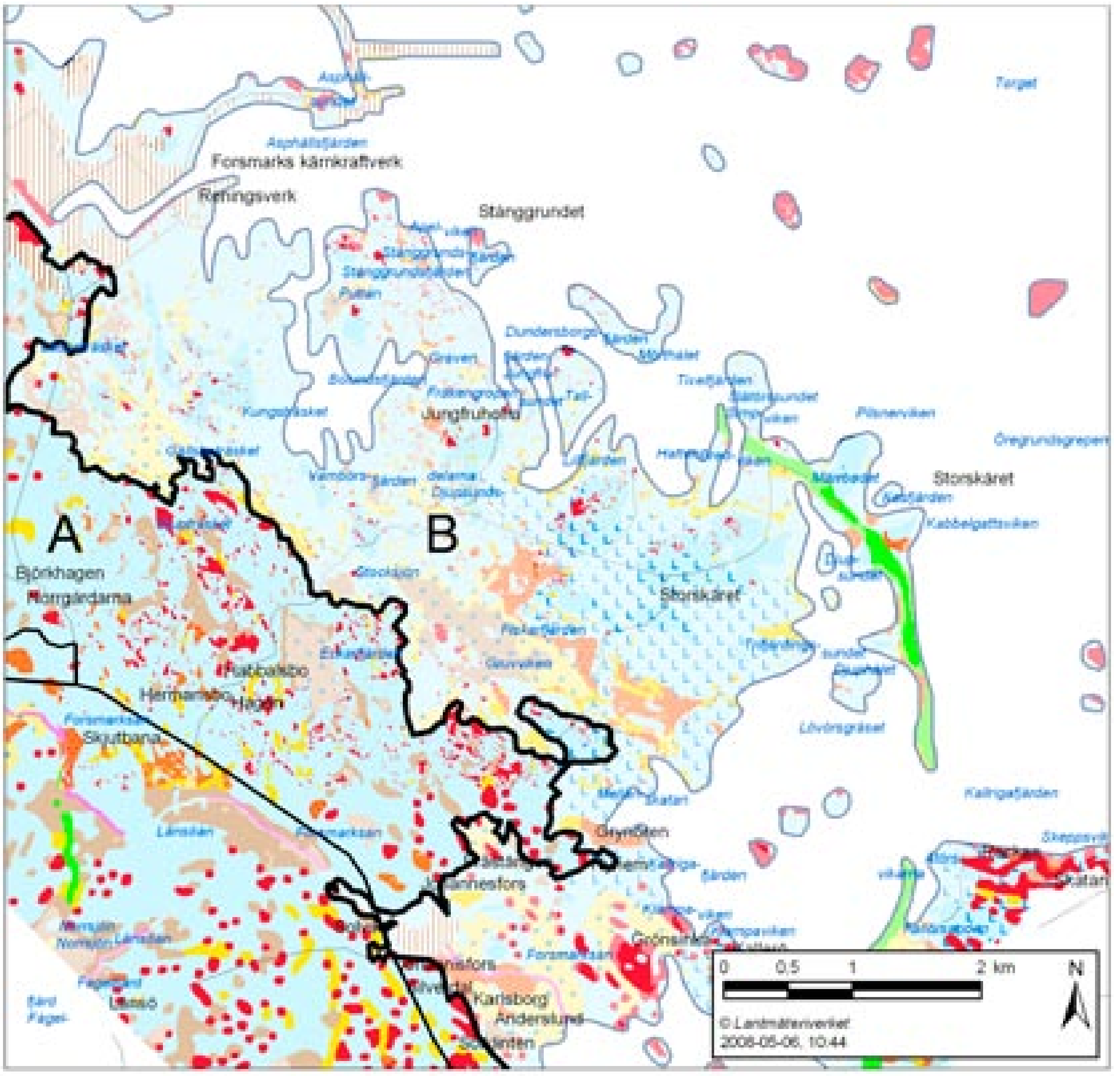

***Figure 4-22**. The two general domains, A (older) and B (younger) for organic deposits at Forsmark (from /Hedenström and Sohlenius 2008/).*

***Figure 4-23**. At Gällsboträsket (PFM002727), the surface layer is covered with clay gyttja, associated with organic domain B. The lake is, to a large extent, overgrown with reed (from /Sohlenius et al. 2004/).*

***Figure 4-24**. The mire at Rönningarna is one of the peatlands within organic domain A. The mire is located at 11 m.a.s.l. Radiocarbon dating of the transition between clay and peat shows that peat formations started at c. 380 AD /Sternbeck et al. 2006/. The central part of the mire is characterized as a pine bog whereas the distal part is a minerotrophic fen.*

Figure 4-25. *Map showing the sites investigated and the type of bottom substrate found under mires in the central part of the Forsmark candidate area (from /Lokranz and Hedenström 2006/).*

The distribution of sediments in the lakes and ponds of the Forsmark region is fairly uniform. Generally, the sediment sequences are thin. In a majority of the lakes investigated, the total thickness of the water-laid sediments (not including glacial till) was less than 2 m /Hedenström 2004a/. Only in three basins (Eckarfjärden, Fiskarfjärden and the small pond close to Börstilåsen) > 4 m sediments was retrieved when coring /Hedenström 2004a/.The maximum coring depth in the area was 8.8 m (including 0.5 m water), recorded in the north-western part of Lake Fiskarfjärden (PFM004195). A generalised outline of stratigraphical units in the investigated sediments at Forsmark is presented in Table 4-6. It should be noted, however, that not all strata were present in every basin.

Artificial fill

There are two areas with artificial fill within the Forsmark regional model area (Figure 4-14). The largest one is the area around the nuclear power plant where the fill material consists mainly of blast bedrock and Quaternary deposits excavated from the sea bottom. At an excavation south of reactor Forsmark 3, 2 m of artificial fill was exposed on top of the bedrock. The sediment had an appearance very similar to the till from the area. A grain-size composition analysis of a sample collected at 1.2 m depth from a pit in the fill material was analysed and classified as sandy till. The other area with artificial fill material is located at Johannisfors, in the south-eastern part of the regional model area. These types of deposits are known to contain pollutants, mainly heavy metals, originating from the pulp production. The deposit at Johannisfors consists of calcareous waste material (Swedish *mesa*) from an old pulp mill. The mill was closed after a fire in 1932 and since then no industrial activity has been performed at the site, although industrial activities such as iron manufacturing and timber preparation presided the pulp mill. The Johannisfors site has been the object for an inventory of the risk of pollutants in the filling material, performed by The County Administrative Board of Uppsala (*Sw: Länsstyrelsen Uppland)* /Jansson 2005/.

Table 4-6. The general stratigraphical distribution of Quaternary deposits in the Forsmark. It should be noted that all units are not present at all sites (from /Hedenström and Sohlenius 2008/).

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

Soil types

The soils in the Forsmark area are typically immature, poorly developed soil types on till or sedimentary parent material, which is influenced by calcareous material /Lundin et al. 2004/. The dominant soil-types are Regosols (Figure 4-26) but also six other soil classes occur. Soils influenced by water, e.g. Glaysols and Histosols, are also frequent. Typical soils for Sweden are Podsols, but this soil-type has not yet developed in Forsmark. The poor soil development is a result of young age; this is because most of the candidate area emerged from the sea during the last 1,500 years.

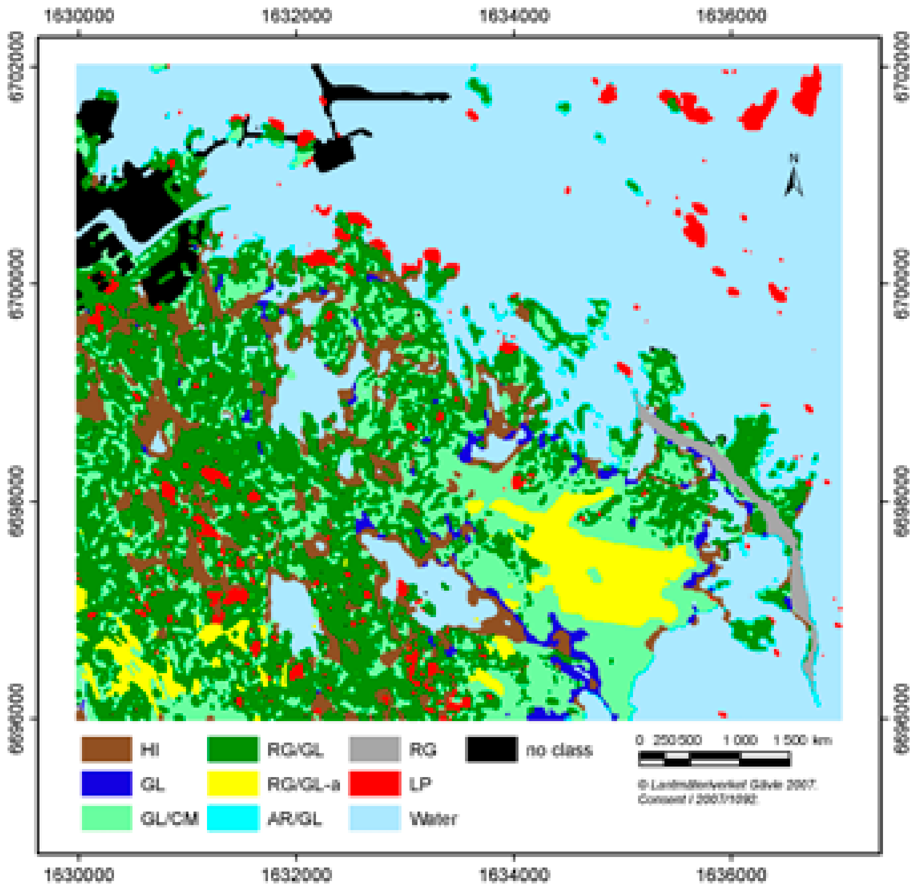

Figure 4-26. The spatial distribution of soil types in the Forsmark regional model area (updated after /Lundin et al. 2004/). HI = Histosol, GL = Gleysol, CM = Cambisol, RG = Regosol, AR = Arenosol, LP = Leptosol, a = arable land.

4.4.2 Properties

Physical properties

The physical properties of the regolith include grain size distribution, hydraulic conductivity, bulk density, porosity for the Quaternary deposits in Forsmark. Some values are calculated, for example hydraulic conductivity, whereas the majority are based on measurements from the site. Additionally, some values are derived from the literature, when site-specific values are missing. For the hydraulic properties based on measurements at the site, see section 4.3 and Chapter 5.

Table 4-7 presents a summary of grain size distributions, sorting coefficients (D60/D10) and calcium carbonate contents of the different minerogenic deposits from the terrestrial area. The clay content in till samples is between 0.9% (sandy till) and 25.9% (boulder clay) and the $CaCO_3$ is between 1% (clayey till) and 34% (sandy till). The higher the sorting coefficient (D60/D10) is, the more poorly sorted are the minerogenic deposits.

The bulk density of the upper 60 cm of the regolith was investigated in a number of horizons in the soil type inventory /Lundin et al. 2004/. In the upper horizon (0–10 cm), bulk density is low, 0.4–1.5 g/cm^3. The density increases downward to 1.4–2.3 g/cm^3 (50–60 cm) /Lundin et al. 2004/. Bulk density measured in two trenches located in Till area I was 1.5–2 g/cm^3 in the top soil layers, whereas it was 1.9 and 2.3 g/cm^3, in the deeper layers respectively (Table 4-8). Porosity was c. 30–40% at the surface and c. 10–20% at c. 2 m depth.

Properties of the Quaternary deposits from the coastal area are presented in Table 4-9 and for wetlands in Table 4-10. The contents of carbon, nitrogen, sulphur and phosphorous in marine and lacustrine sediments and in peat are presented in Table 4-11. In general, the porosity is higher (37–90%) in the water-laid sediments than in the till, while the bulk density is generally lower in the organic sediments.

Table 4-7. Summary of some physical parameters of the most common minerogenic deposits from the terrestrial area at Forsmark.

Deposit	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	D60/D10	$CaCO_3$ (%)
Sandy and sandy silty till (Till area I) n=66	22.1 (±7.8)	50.8 (±10.1)	23.5 (±8.9)	3.6 (±1.1)	46.4 (±29.5)	19.1 (±5.7)
Clayey till and boulder clay (Till area II) n=103	15.8 (±8.1)	41.2 (±6.8)	32.3 (±7.2)	10.8 (±4.4)	104.0 (±155.4)	23.4 (±6.6)
Gravely till n=15	44.8 (±8.8)	40.7 (±10.7)	12.7 (±5.4)	2.4 (±1.1)	132.6 (±105.7)	17.5 (±5.3)
Gravel n=5	53.1 (±6.7)	44.2 (±6.1)	1.5 (±1.2)	1.2 (±1.1)	16.8 (±4.1)	
Sand n=15	16.9 (±16.2)	68.0 (±14.1)	13.0 (±15.4)	2.7 (±2.2)	10.6 (±8.1)	
Silt n=4	0.2 (±0.5)	15.9 (±13.7)	68.9 (12.6)	15.0 (±6.8)	9.9	
Clay n=30	0.6 (±1.8)	3.0 (±7.2)	41.6 (±16.1)	54.8 (±13.8)		18.0 (±13.3)

Table 4-8. Soil physical parameters as measured at different horizons in two large trenches within till area I . Depth from/to ground level (data from Lundin et al. 2005).

IDCODE	Depth from (m)	Depth to (m)	QD	Dry bulk density (g/cm^3)	Rel pore vol (%)	Water content (%)	K (m/s)
PFM004455	0.10	0.15	Gravely sand	1.60	37.9	3.6	$5.8\cdot10^{-5}$
PFM004455	0.20	0.25	Sandy till	1.60	42.0	8.3	$3.7\cdot10^{-5}$
PFM004455	0.50	0.55	Sandy till	1.90	31.0	7.4	$1.9\cdot10^{-7}$
PFM004455	0.80	0.85	Sandy till	2.00	24.3	10.4	$1.2\cdot10^{-7}$
PFM004455	1.20	1.25	Sandy till	2.00	27.1	11.7	$2.3\cdot10^{-8}$
PFM004455	1.70	1.75	Sandy till	1.90	29.8	17.1	$1.2\cdot10^{-7}$
PFM004455	2.50	2.55	Clayey sandy till	2.10	23.0	14.4	$9.3\cdot10^{-8}$
PFM004458	0.05	0.10	Sandy till	2.00	26.0	15.7	$1.3\cdot10^{-6}$
PFM004458	0.20	0.25	Sandy till	1.90	27.3	13.4	$4.6\cdot10^{-7}$
PFM004458	0.50	0.55	Sandy till	2.10	22.6	15.6	$6.9\cdot10^{-7}$
PFM004458	0.80	0.85	Gravely till	2.10	22.2	15.3	$9.3\cdot10^{-7}$
PFM004458	1.20	1.25	Gravely till	2.20	18.3	14.9	$2.3\cdot10^{-7}$
PFM004458	1.70	1.75	Sandy till	2.20	16.3	15.1	$2.3\cdot10^{-8}$
PFM004458	2.50	2.55	Sandy till	2.20	17.0	13.3	$1.0\cdot10^{-7}$
PFM004459	3.50	3.55	Clayey sandy silty till	2.20	19.8	18.9	
PFM004460	0.05	0.10	Gravely sand	2.00	26.4	13.4	$3.0\cdot10^{-5}$
PFM004460	0.20	0.25	Boulder clay	1.60	40.2	37.1	$4.6\cdot10^{-7}$
PFM004460	0.50	0.55	Sandy till	2.10	21.9	14.9	$3.5\cdot10^{-8}$
PFM004460	0.80	0.85	Sandy till	2.10	20.7	16.0	$2.3\cdot10^{-8}$
PFM004460	1.20	1.25	Sandy till	2.20	17.0*	16.8	$1.2\cdot10^{-8}$
PFM004460	1.70	1.75	Sandy till	2.30	16.0*	15.9	$8.1\cdot10^{-9}$

* The values are corrected based on recommendations by Lars Lundin, SLU, September 2008.

Table 4-9. Results from the grain size and $CaCO_3$ analyses with calculated hydraulic conductivities from the coastal area /Ising 2006/. *Calculated from the grain size distribution curve according to Fair and Hatch.

Id code	Depth (m)	Deposit	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	*K-value (m/s)
PFM006073	4.13–4.18	Clay	0	10.9	42.7	46.4	20	
PFM006073	4.18–4.31	Clayey sandy till	17.7	42.5	26.3	13.5	8	$2.7\cdot10^{-8}$
PFM006094	1.55–1.87	Sand	13.6	80.7	3.1	2.6	0.4	$3.0\cdot10^{-5}$
PFM006095	0.29–0.59	Sand	0	94.9	2.0	3.1	0.3	$4.2\cdot10^{-5}$
PFM006095	2.20–2.50	Clay	0	1.5	32.7	65.8	29	
PFM006095	2.76–3.00	Boulder clay	9.2	37.6	37.5	15.7	25	$1.7\cdot10^{-8}$
PFM006097	3.55–3.67	Clayey sandy till	17.7	42.4	26.7	13.2	10	$2.6\cdot10^{-8}$

Table 4-10. Analytic results of organic content, $CaCO_3$ content and K-values from two wetlands from organic domain B and one mire from organic domain A at Forsmark. K-values are calculated from grain size analyses /Lokranz and Hedenström 2006/. Colour codes are according to /Munsell 1975/. *Are based on textural analyses, others on ocular inspection.

Coring ID	Depth	Lithology *	*K-value (m/s) (Fair Hatch)	Loss of organic ignition (weight %)	Colour	$CaCO_3$-content Passon (%)
SFM0084	0.35–0.50	Gyttja		36.7	5Y3/1	1.5
Organic domain B	0.50–0.60	Gyttja		25.3	5Y3/2	0.9
	0.70–0.75	Gyttja		24.1	5Y3/2	2.5
	0.85–0.90	Clayey gyttja		20.7	5Y3/2	1.0
	0.95–1.00	Clayey gyttja		19.5	5Y3/2	1.1
	1.15–1.20	Clayey gyttja		21.9	2.5Y3/2	0.4
	1.20–1.25	Clayey gyttja		(7.8)	10YR5/1	35
	1.25–1.28	Clayey gyttja		9.8	5Y3/2	2.2
	1.40–1.50	Sand*	3.38 E–04*		5Y3/1	0.7
	1.55–1.70	Sandy gravel*	9.67 E–06*		5Y3/1	1.2
	1.85–1.90	Clay*			5Y4/1	7
SFM0091	0.55–0.64	Gyttja		30.1	5Y3/2	4.5
Organic domain B	0.68–0.75	Gyttja		20.5	5Y3/2	1.0
	0.85–0.90	Clayey gyttja		19.4	5Y3/2	0.4
	0.94–1.00	Clayey gyttja		17.5	5Y3/2	0.5
	1.18–1.24	Sandy gravel*	1.23 E–03*		5Y3/2	9
	1.26–1.31	Clay*			5Y4/1	35
SFM0094	0.9–1.30	Clayey sandy till*	5.06 E–07*		5Y5/2	26
Organic domain A	1.60–1.90	Clayey sandy till*	1.16 E–07*		5Y5/2	20
	2.20–2.70	Clayey sandy till*	9.09 E–08*		2.5Y5/2	21

Table 4-11. Distribution and average contents of C, N, S and P as recorded in marine and lacustrine sediments and peat at Forsmark.

Environment	Lithology	Relative age	C %	N %	S %	P %	Water content %	Porosity %	Bulk density g/cm³
Bog/Fen	Peat	Youngest	55	0.68	0.7	0.02	90	89.6	1.004
Freshwater lake	Gyttja	↑	18	1.4	1.9		93	90.1	1.031
Shallow Baltic basin	Clay gyttja	↑	6.2	0.6	1.6	0.09	86	79.2	1.085
Coast	Post-glacial sand and gravel						8.5	32	1.600–2.00
Postglacial Baltic basin	Post-glacial clay	↑	1.8						
Late glacial Baltic basin	Glacial clay	Oldest	1.0	0.11	0.76		53	37.8	1.40

Chemical properties

Chemical properties of the regolith are presented in section 4.5.5 below.

Properties of the soil horizons

Analyses of $CaCO_3$ in the fine fraction of the till have been performed on > 200 samples during the site investigations. Almost all samples contained $CaCO_3$, even in the upper layers /Hedenström and Sohlenius 2008/. However, the upper 55 cm of the soil profiles, /Lundin et al. 2004/ showed that leaching of $CaCO_3$ occurs in the surface.

A regional study of leaching of calcium carbonate in till from northern Uppland /Ingmar and Morenborg 1976/ showed that the depth of the carbonate-free, leached zone increased from a few dm at sites close to the sea level up to 3 – > 6 m at inland sites. The occurrence of calcium carbonate high up in the soil horizons at Forsmark shows that the soil profiles still are unweathered. This is especially valid for locations in the central part of the candidate area at low altitudes. For sites located at altitudes of only a few metres, too little time has been available for leaching to take place.

The calcareous soil material has yielded nutrient-rich conditions, which can be observed in the rich and diverse flora of the area. This can also be seen in the predominant humus forms of mull type and of the intermediate moder type, which indicate a rich soil fauna. Because of the young age of the soils, the Forsmark area exhibits less soil of Podsol type than most similar areas in Sweden. Instead, the typical soil types are the less developed Regosol soils, together with Gleysols and Histosols, which are formed under moist conditions.

The pH map shown in Figure 4-27 is produced by extrapolations from soil studies at 16 sites, which represent eight land types /Lundin et al. 2004/. The soil pH is generally above or close to seven in mineral soil sampled 55–65 cm below the ground surface. The relatively high pH in the soils is an effect of calcium carbonate, which is present in most of the Quaternary deposits. The lowest pH values were recorded on the glaciofluvial esker, which may indicate the absence of fine-grained calcite in these deposits, since the esker consists of coarse material. Stones and gravel of limestone, however, are present in the esker.

The pH in the O-horizon in the Forsmark area is in general high, with values of around 6, whereas Sweden on average has values between 4 and 5. The humus layer is influenced by the underlying mineral soil and the pH value is 6.5 on average, to be compared with values of around 5 for most of Sweden.

Carbon concentrations in the humus layer are in accordance with ordinary Swedish conditions, but in the mineral soil the influence of $CaCO_3$ makes the concentration of carbon higher as compared with the average values for Sweden. There is also an increasing trend with depth, which mainly can be attributed to the $CaCO_3$ content, and deviates from ordinary forest soil conditions. Nitrogen concentrations in the soil agree fairly well with most parts of Sweden. However, the values are lower than usually observed in Uppsala County /Lundin et al. 2004/.

The root depth was measured at LFM00810. Most of the roots reached between 10 and 40 cm (average: 25 cm). Fine roots were found down to 57 cm below the ground surface and coarse roots were observed down to 25 cm depth /Lundin et al. 2005/.

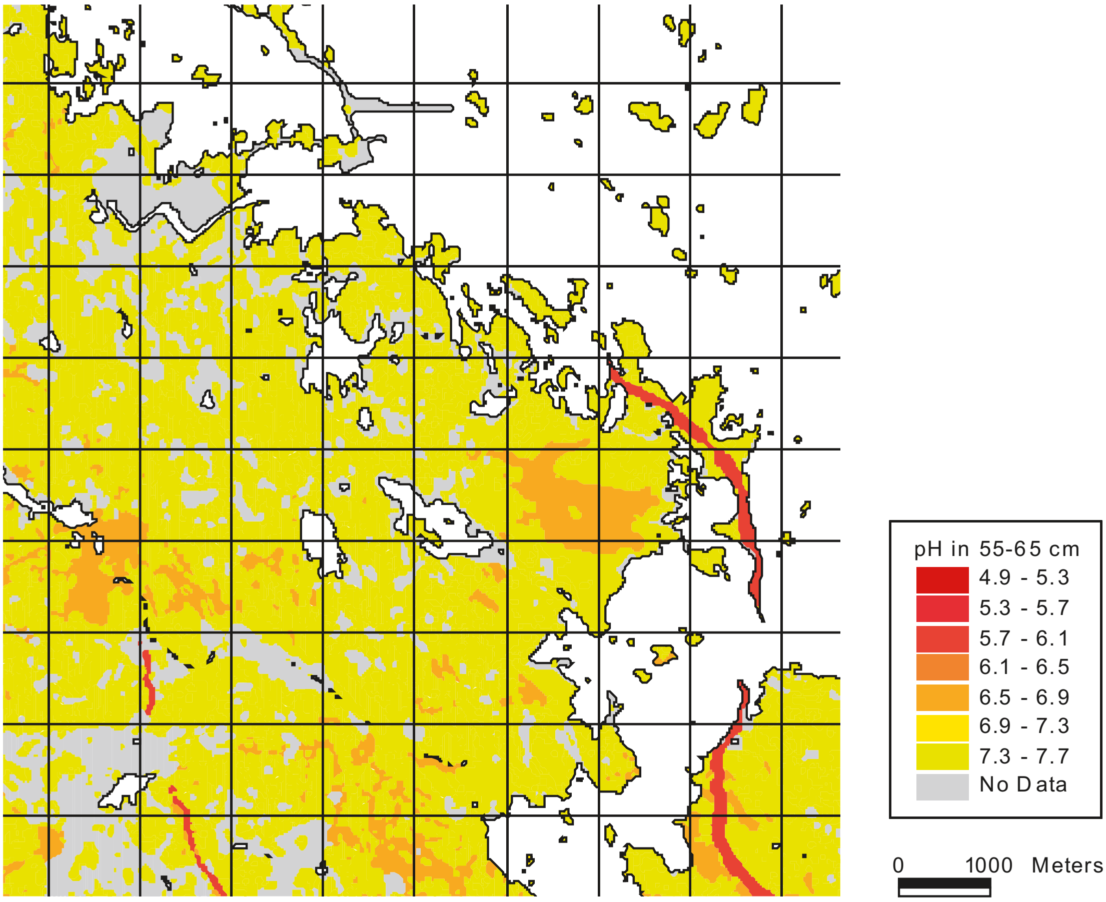

Figure 4-27. *Mineral soil pH at the depth 55–65 cm below the ground surface (from /Lundin et al. 2004/).*

4.5 Chemistry of water, regolith and biota

The flat topography and the recent withdrawal of the Baltic Sea due to the isostatic land uplift are two important factors determining the chemistry in the Forsmark area. Marine remnants in the regolith, as well as modern sea water intrusions, strongly influence the hydrochemistry, especially in areas at low altitude close to the coast. Accordingly, the surface waters and shallow groundwater in the Forsmark area are characterised by high contents of marine ions. Other characteristics of the surface waters in the area are high pH values and particularly high concentrations of calcium and bicarbonate. The main reason for this is the glacial remnants, mostly in the form of a till layer, which were deposited during the Weichselian glaciation and deglaciation /Fredén 2002/. The rich supply of Ca and the high alkalinity have a large impact on the structure of the whole ecosystem in the Forsmark area.

4.5.1 Characteristics of the hydrochemistry of the surface system

To generalise, the four major ion sources influencing the groundwater in the Forsmark area are 1) marine water (relict or modern), 2) deep saline groundwater, 3) weathering of local minerals and 4) bicarbonate of atmospheric CO_2 origin. In surface waters, calcite dissolution is an important additional ion source, contributing mainly Ca^{2+} and HCO_3^-.

Five major groundwater types may be identified in the Ion Source Model in Figure 4-28 according to the encircled groups of observations. It should be noted, however, that any classification in some way is an artefact, as most observations belong to continuous gradients between theoretical end-members. The following water types are introduced in order to facilitate interpretation:

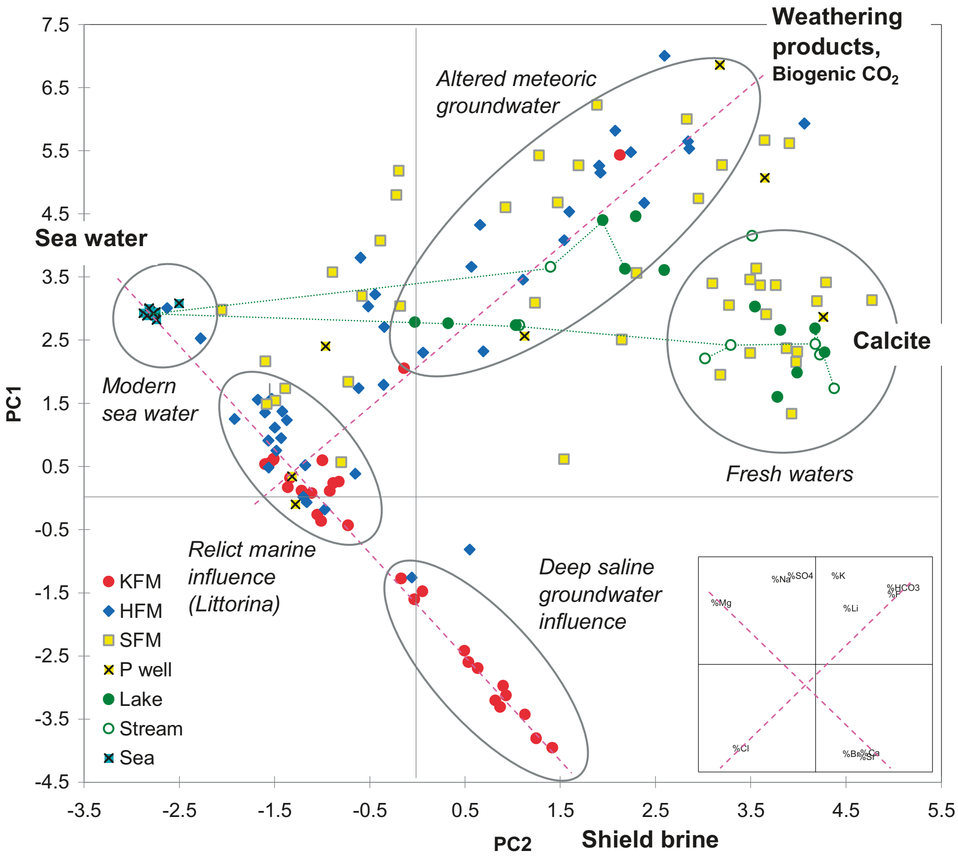

Figure 4-28. This multivariate model shows how the compositions in water samples relate to different ion sources, e.g. sea water, brine or other theoretic end-members. The axes represent principal components, which together comprise approximately 80% of the total variation. The different possible ion sources are marked in bold and possible groundwater types are marked in italics; for details, see /Tröjbom et al. 2007/.

- Modern sea water.
- Relict marine groundwater (mostly of Littorina origin).
- Deep saline groundwater significantly influenced by shield brine (shield brine is a highly saline groundwater present at great depths in the granitic environment of the Scandinavian shield).
- Altered meteoric groundwater is of meteoric origin, significantly altered by processes within the regolith.
- Freshwaters include both surface water and shallow groundwater, showing "immature" ion signatures mainly influenced by biogenic CO_2 and calcite dissolution.

The most apparent gradient is shown by a large number of observations ranging from modern sea water to the deep saline groundwater clearly influenced by shield brine. Most of the observations along this gradient are groundwater samples from the bedrock (percussion drilled boreholes, HFM, and cored boreholes, KFM). A few shallow observations in soil tubes and private wells also plot along this gradient (cf. deep discharge, Chapter 5).

Groundwater influenced by relict marine water is located on the intersection between the major gradients pointing at the ion sources sea water, shield brine and local weathering. The intermediate location of this group may be interpreted as if the ingoing ions mainly are a product of mixing of these major ion sources, i.e. relict sea water, mixed with deep saline groundwater and with a relatively small influence of local weathering products.

Altered meteoric groundwater shows a large spread, which probably reflects the great variety of processes influencing these waters, e.g. variations in mineralogy, mixing with modern or relict marine components, cation exchange reactions as well as influence from biogenic CO_2 and calcite dissolution. The shift of this group of the calcite-influenced fresh waters may be explained by cation exchange reactions in the regolith where e.g. Na^+ is exchanged with Ca^{2+}.

Freshwaters in the upstream part of catchments show influence from biogenic CO_2 and the calcite-rich overburden in the Forsmark area. The location of this group in the projection indicates a concomitant supply of Ca^{2+} and HCO_3^- (cf. Figure 4-28) due to calcite dissolution driven by H^+ of biogenic CO_2 origin.

The impact of Ca in the surface system is also reflected in the ecosystems of most lakes, which are characterized as oligotrophic hardwater lakes /Brunberg and Blomqvist 2000/.

4.5.2 Conceptual hydrochemical model with a palaeohydrologic perspective

In samples from the upper parts of the bedrock extending down to depths of several hundred metres, as well as in some shallow groundwater sampling points, a brackish groundwater type with a clear relict marine signature is preserved (Figure 4-28). Major ions in these groundwaters seem to originate mainly from a marine source, but at least to some extent, also from a deeper saline source. The isotopic characteristics of the water (i.e. ^2H, ^{18}O) also show a clear evaporation signature, reflecting the marine (Littorina, see section 4.1 in this report) origin of the water.

The development of the hydrochemistry in the Forsmark area since the latest deglaciation 11,000 years ago is outlined in a conceptual model /Tröjbom et al. 2007/. This model describes a generalised hydrological picture that, in combination with an understanding of hydrochemical processes, is important for the interpretation of past and present hydrological patterns in the surface system and in shallow groundwater in the bedrock.

The period from deglaciation until start of emergence from the sea

Ancylus stage: Shortly after the deglaciation (c. 9000 BC), the groundwater in the fractured bedrock consisted of a mixture of glacial water, old meteoric water and deep saline groundwater originating from the previous glacial period and earlier interglacials. After the withdrawal of the ice cover, glacial (Quaternary) deposits were exposed at the bottom of the freshwater lake which was formed by the melting glaciers. In the Forsmark area, these deposits also contained large amounts of limestone. During this period, when the Forsmark area was covered by the non-saline water of the Ancylus Lake (c. 9000–7500 BC), there was probably little exchange of water and elements through the regolith due to the lack of hydrological driving forces.

Littorina stage: When the Forsmark area was covered by the brackish Littorina Sea with increasing salinity (c. 7500–3000 BC), the difference in density between Littorina Sea water and the mixture of glacial melt water, old meteoric and deep saline groundwater in the bedrock gave conditions appropriate for a density turnover. This process may have resulted in infiltration of sea water through the bottom sediments and the minerogenic regolith.

The resulting mixing of Littorina Sea water and the primordial groundwater mixture gave the groundwater in the fractured bedrock a distinct marine signature with respect to ions such as Na^+, Cl^- and Mg^{2+}, as well as a typical marine evaporation signature of the water.

When the Forsmark area was still covered by Baltic Sea water after the Littorina salinity maximum (c. 3000–0 BC), there was no driving force transporting ions and water from the less saline sea water to the heavier, more saline groundwater in the bedrock. On the contrary, there was a possible discharge of groundwater from the fractured bedrock up-wards through the regolith, driven by the topographical gradient near the coast. This flow regime may have transported the Littorina-dominated groundwater from the fractured bedrock, as well as any residual ion signature of the primordial groundwater mixture (including deep saline signatures) of the bedrock, into the regolith.

The Forsmark area emerging from the sea

From around 0 BC until present date, when parts of the Forsmark area have emerged from the sea due to the isostatic uplift, the conditions in the regolith have been significantly altered. Recharge of meteoric water leads to a completely new flow pattern compared with the conditions prevailing when the area was submerged under sea water. This new situation results in local discharge in streams and lakes, as well as recharge through the regolith down to the upper parts of the fractured bedrock. The widespread and horizontally extended fracture systems, which are characteristic for the upper parts of the bedrock in the Forsmark area, effectively channel the recharging groundwater, as well as any potential discharge from deeper levels, to discharge points near or below the Baltic Sea.

The effective recharge into the lower parts of the regolith and further down into the upper parts of the bedrock is probably low, due to the low permeability of the till. This could result in a slow washout of marine remnants from the time submerged under the Baltic Sea. In areas with supposed low turnover, such as areas covered by clay layers with low permeability, relict marine ion signatures should be more pronounced in the shallow groundwater. One example of this is the area of Lake Gällsboträsket, which is characterized by relict marine signatures regarding the composition of major constituents. This pattern could, according to the conceptual model, be explained by influence from stagnant marine remnants formed under a previous hydrological regime and are preserved because of the stagnant conditions in these areas (Figure 4-29).

Aeration of the deposits by meteoric recharge and supply of organic carbon to the regolith due to the development of a biologically active layer give prerequisites for drastic alterations of the hydrochemical conditions in the shallow groundwater. Oxidation of sulphide minerals leads to

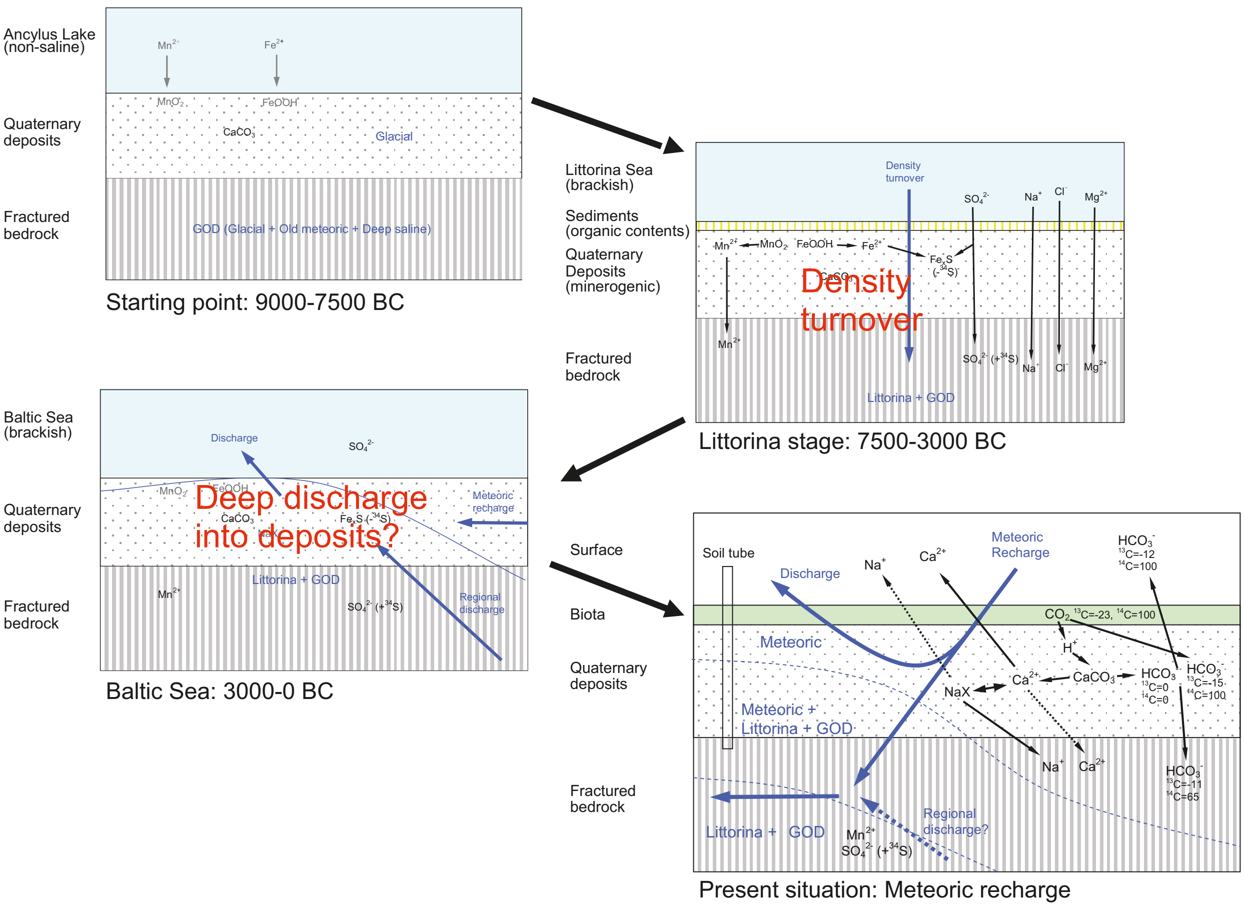

Figure 4-29. Conceptual model showing the surface chemistry in a palaeohydrological perspective. There are indications of an ongoing discharge, but that is most likely a local phenomenon in the area of Lake Gällsboträsket, according to rock-hydraulic simulations /Tröjbom et al. 2007/.

high concentrations of SO_4^{2-}, especially in discharge from clayey organic sediments. Increased supply of H^+, mostly derived from decomposition of biogenic carbon or oxidation of sulphide minerals, is the ultimate driving force for weathering reactions that take place in the regolith or bedrock.

The regolith in the Forsmark area is characterized by particularly high contents of calcite ($CaCO_3$), which in combination with rich supply of H^+ from organic carbon leads to an extensive dissolution of calcite in the till. Calcite dissolution releases large amounts of Ca^{2+} and HCO_3^- ions into the shallow groundwater system (Figure 4-30). Some Ca^{2+} is discharged into streams and lakes through the local hydrological recharge/discharge patterns, and contribute to the forming of the characteristic Ca-rich oligotrophic hard water lakes in the Forsmark area.

The rich supply of Ca^{2+} ions is also an important prerequisite and driving force for an extensive cation exchange that seem to take place in the regolith. Alkali cations such as Na^+ and K^+ are released into solution during weathering of silicates. These ions, which are the most mobile constituents of this important mineral group, are leached and replaced by hydrated cations such as Ca^{2+} and Mg^{2+}. The original silicates are thereby transformed to clay minerals /Kalinowski and Schweda 1996, 2007/. Groundwater with long residence time, e.g. groundwater that reaches down to the upper parts of the bedrock, may be considerably depleted in Ca^{2+} but enriched in e.g. Na^+, and shows therefore a more "mature" signature than groundwater found at more shallow depths.

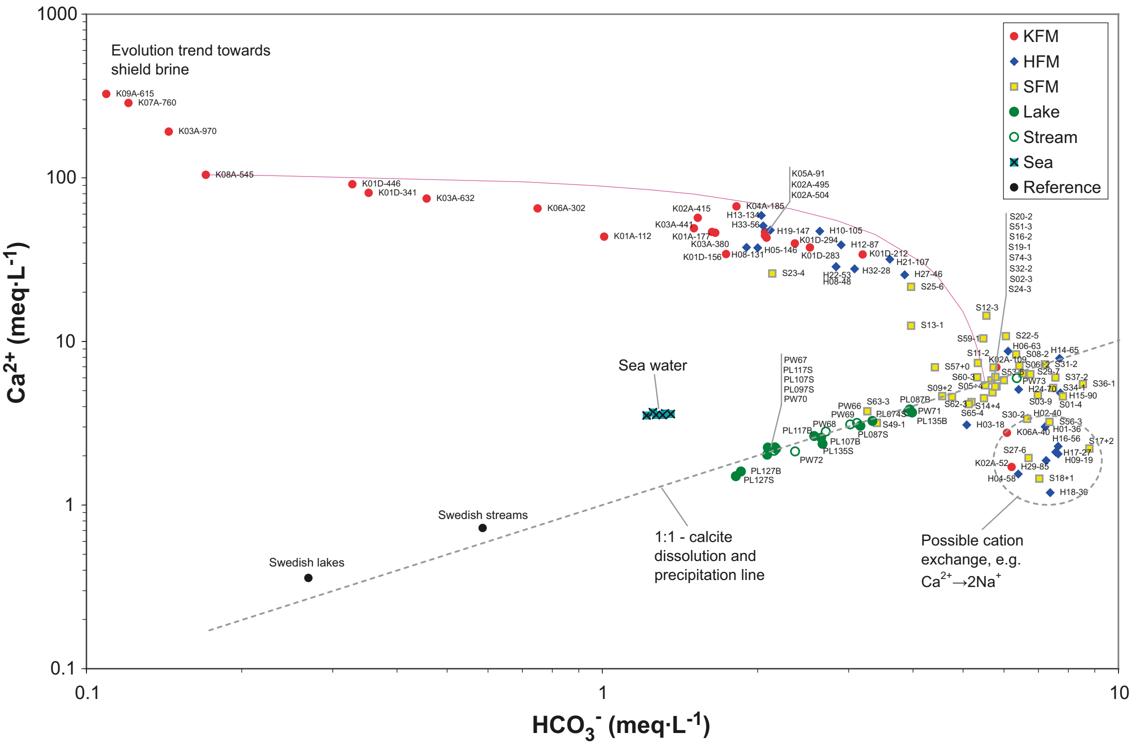

Figure 4-30. *Ca^{2+} versus HCO_3^- (meq L^{-1}). The grey dashed line shows the 1:1 molar charge relationship between Ca^{2+} and HCO_3^-.*

4.5.3 Evaluation of observations in relation to the conceptual model

The ongoing uplift after the latest glaciation, in combination with remnants from the past, are factors that have a great impact on the surface hydrochemistry observed in the Forsmark area. Large-scale marine gradients observed in the surface system are consistent with the conceptual model described above and with the palaeohydrological history; areas recently emerged from the Baltic Sea show stronger marine influences compared with areas located at higher topography (Figure 4-28). Discharges from Lake Eckarfjärden, located at c. 5 m.a.s.l. contain low concentrations of marine ions, whereas Lake Gällsboträsket, which was more recently separated from the Baltic and now is located at c. 2 m.a.s.l., still show significantly elevated concentrations of e.g. Na and Cl in discharges. At a smaller scale, for example in the area of Lake Bolundsfjärden, which was covered by the Baltic Sea less than a hundred years ago, there are marine gradients among shallow groundwater sampling points, probably reflecting different stages of washout of marine remnants by meteoric recharge.

In shallow groundwater in the regolith below the lakes, more or less stagnant conditions have preserved relict marine signatures even at relatively shallow depths. These signatures, which are generally found in the groundwater of the bedrock down to several hundred metres depth, reflects 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 are difficult to explain without a vertical discharge gradient at any time during the palaeohydrological history, especially as there are no hydrological indications of any deep discharge at the present date /Follin et al. 2008/.

The marine signature in the soil tubes located in the regolith below the lakes shows, similarly to the marine influence in the discharge from the lakes, a topographical gradient which probably reflects the time for influence from meteoric recharge. There are, however, exceptions to this general trend, reflecting the importance of the local recharge/discharge patterns. The presence of low-permeable deposits such as clay may be an important prerequisite for preserving hydrochemical signatures reflecting a previous hydrological regime. In the case of Lake Gällsboträsket, there are also indications that ongoing deep discharge from the Eckarfjärden deformation zone add deep signatures to the discharging surface water. Similar deep signatures are also present in one soil tube located in the vicinity of this lake (SFM0057), whereas groundwater samples from the till layer below the lake mainly correspond to relict marine signatures (cf. deep discharge in Chapter 5).

4.5.4 Evaluation of chemistry of biota

Elemental concentrations vary greatly between organisms and environmental components, depending on the function of the element, the habitat, ecosystem characteristics, trophic level and morphology (taxonomy) of the organism. The results from a study by /Kumblad and Bradshaw in manus/ show that food intake and metabolism strongly influence the elemental composition of organisms. Three studied macrophyte species had quite similar elemental composition despite their taxonomic differences, whereas the primary consumers were generally more similar to other primary producers than to secondary consumers. There is a marked difference between different trophic levels in the concentrations of many elements. Most elements exhibit lower concentrations in fish compared to other organisms, with the exceptions of C, N, P, Se and to less extent for K, Zn, S, Ca, Rb and Hg. Shell-bearing organisms showed the highest concentrations of Ca, and phytoplankton and benthic microalgae contained the highest levels of Si /Kumblad and Bradshaw in manus/.

The chemical results from the study of different types of flora and fauna are compiled in /Hannu and Karlsson 2006/. This study shows that fresh water mussel and tench have the highest concentrations of Se compared to the other species (including both flora and fauna) analysed. For more details and results of other elements, see /Hannu and Karlsson 2006/.

As well as being of ecological interest, these data will enable realistic predictions of radionuclide distributions in the environment in the event of their release from a future deep repository. This in turn will contribute to, for example, more reliable estimates of doses to organisms and humans from radionuclides potentially released from the repository.

4.5.5 Chemical properties of the regolith

Chemical properties of the regolith have been analysed in several activities and the most commonly occurring regolith and soil types are included. A statistical evaluation of chemical data from regolith samples was presented by /Tröjbom and Söderbäck 2006/. In this section, chemical properties of the different lithological units are described and the results are presented.

The geochemical distribution pattern of trace elements in till has been presented by /Sohlenius and Rudmark 2003, Hannu and Karlsson 2006/. When the median concentrations of elements in till from the Forsmark area are compared with Swedish reference data (SGU), the majority of the elements are within a factor 2 of the median values of the Swedish reference data /Tröjbom and Söderbäck 2006/. As described earlier, the till in Forsmark is characterized by high calcium carbonate content. The statistical comparison with national references confirms that Ca and Sr are the two exceptions where the contents in till in the Forsmark area are clearly higher than the Swedish reference data.

A comparison between the different till types shows that till with a clay content higher than 5% (Till area II, see Figure 4-16) has a slightly higher content of calcite (average content 23%, n=106) in the fine fraction (grain sizes < 63 μm) compared with the sandy till (average content 19%, n=66). Also the As content is high, probably due to the precipitation of Ca-arsenates, which is favoured by the occurrence of calcite /Nilsson 2003/.

Strontium occurs at concentrations about seven times higher in till at Forsmark than the Swedish reference. A similar enrichment is recorded in surface waters in the Forsmark area as compared with a sample of Swedish lakes /Tröjbom et al. 2007/. The high Sr concentrations in the surface waters are probably a secondary effect from the high content of Sr in the till in the area. Both Ca and Sr probably originate from the sedimentary bedrock of Gävlebukten. The analyses of heavy metals in basal till show that the contents of Cu, Pb and Zn in the till correspond to these of the local bedrock /Nilsson 2003/.

The geochemical analyses presented by /Sohlenius and Rudmark 2003/ show a positive correlation between the clay content and the contents of most elements in the eight samples analysed. The elements are probably leached out more effectively with HNO_3 from fine-grained material than from coarser material. The results from this investigation indicate to what degree different elements can be leached and taken up by biota in the natural soil environment.

In a statistical analysis, /Tröjbom and Söderbäck 2006/ showed that three sampling sites deviate in the chemical composition of till. SFM0016 and SFM0017 in the vicinity of Lake Eckarfjärden, and to some extent also SFM0057, show high contents of Al, Fe, Mg, Mn and somewhat low contents of Ca and S. Till from these sites also shows deviating contents of some of the trace elements. The Ag and Cd contents are especially low, whereas the contents of Bi, B, Ga, Sc, Sr, U, V, and Zn are more or less elevated at these sampling sites. It is of interest to note that these three sites have stratigraphy comprising a (hard) silty/clayey till under a sandy till (cf. Figure 4-16).

The stratigraphical and analytical investigations of lake sediments in the Forsmark area have resulted in a good knowledge of the waterlaid sediments /Bergström 2001, Hedenström and Risberg 2003, Hedenström 2003, 2004, Strömgren and Brunberg 2006/. The general stratigraphy presented for the marine and lacustrine lake sediments (Table 4-6) has been complemented by evaluations of some chemical and physical properties of the different units (Table 4-11). In all investigated lake sediments, the content of C, S and N shows an increasing trend from the oldest to the youngest sediments /Hedenström and Risberg 2003, Hedenström 2004a/. The total contents of C, S, and N are relatively low in the glacial clay.

Chemistry in peat

Stratigraphical and chemical characterization of peat has been carried out in three peatlands, AFM001245 (Stenrösmossen), AFM001246 (4 kilometres south-west of Forsmark) /Fredriksson 2004/ and the Rönningarna mire /Lokrantz and Hedenström 2006, Hannu and Karlsson 2006/. The chemical composition of the peat may be used for a better understanding of the groundwater chemistry of the area and to predict future land use of the peatlands.

Stenrösmossen (chosen for the further evaluation here) is a horizontal forest mire developed from a shallow stagnant water body, representative for a peatland in the model area. The main part of the mire is influenced by minerotrophic, nutrient-rich groundwater from surrounding regolith. Some of the results from /Fredriksson 2004/ have been summarised and compared with the mean and median values for Swedish peatlands /Hedenström and Sohlenius 2008/. The peat in Stenrösmossen is influenced by the occurrence of calcium carbonate in the surrounding regolith, which is reflected by a high content of calcium oxide (47% in ash).

The contents of trace elements in the peatlands are normal except for high concentrations of Pb and Zn. The reason for these anomalies is not known, and both peatlands are situated far from any present industrial activities. The concentrations of these elements in till are similar to national mean values.The mires are, however, situated in an area, which earlier had been subjected to mining and Forsmarks Bruk is situated only a few kilometres from the mires.

There is a relatively high content of sulphur in peat from Stenrösmossen. High sulphur contents are common in peatlands along the Baltic Sea coast. The sulphur may originate from brackish water which has remained since the site was covered by the sea. The high sulphur content makes it unlikely that peat from Stenrösmossen will be used as fuel.

4.6 Terrestrial ecosystems

4.6.1 General description

Vegetation

The terrestrial vegetation is strongly influenced by the characteristics of the Quaternary deposits and by human land use. The Forsmark area is fairly young as an effect of the land uplift and the small topographic variations /Söderbäck (ed) 2008/. The location at the sea makes the seashore a prominent feature in the east along with conifer forests, shallow lakes, mires and some agriculture land. Below follows a brief description of three major vegetation types within the investigation area, see Chapter 4 in /Löfgren (ed) 2008/ for more details.

Forests cover 73% of the land area in Forsmark and are dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) growing mainly on wave-washed till. The spruce becomes more abundant where a deeper soil cover is found along with more mesic-moist conditions. Outcrop is not a prevalent substrate in the Forsmark area, making pine forest on acid rocks quite scarce. The calcareous soil material provides nutrient-rich conditions, characterized by herbs and broad-leaved grasses along with a number of orchid species, and predominant humus forms of mull and intermediate moder types /Lundin et al. 2004/. The deciduous tree species are dominated by *Betula pendula*, *Alnus glutinosa* and *Sorbus acuparia*, but also *Acer platanoides* and *Fraxinus excelsior* are fairly common. The Forsmark area has a long history of forestry, which is seen today as a fairly high percentage of younger and older clear-cuts in different successional stages in the landscape. *B. pendula* 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.

Figure 4-31. *Herb-rich Norway spruce forest in the Forsmark regional model area.*

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. The mires are characterized by a high calcareous influence, which gives rise to extremely to intermediately rich fen types common in this area /Göthberg and Wahlman 2006, Jonsell and Jonsell 1995/. Although not yet so numerous, bogs are present in the inland and are continuously created due to land rise and mineral and nutrient leaching processes. Other important wetland types are the freshwater shores (wet meadows or marshes) and riparian deciduous forest swamps along streams that are inundated at least once a year by the stream and affected by overbank sedimentation. The flat topography in the area promotes the occurrence of small floodplains that are flooded during high-flow periods /Carlsson et al. 2005/. Such areas may be of importance for the retention of various substances that otherwise are transported by the water to the sea.

The agricultural land covers 5% of the land in the Forsmark area and is mainly located in the southeast part of the candidate area. The agricultural land is the arable crop land and the pastures or semi-natural grassland. The agricultural land area provides food for humans, either directly as crop production or as production of fodder for animals. Grasslands are used for grazing cattle or may be recently abandoned grasslands and both land uses are found close to settlements. The semi-natural grasslands were earlier intensively used, but are today mainly a part of the abandoned farmland following the nation-wide general regression of agricultural activities. The standard yield of the most important grain species, barley, is 167±4 gCm^2y^{-2} (mean and standard-deviation for year 2000–2007).

***Figure 4-32.** Wetland in Forsmark dominated by reed (Phragmites australis).*

***Figure 4-33.** The largest arable land area, Storskäret, in the southeast of the Forsmark regional model area.*

Fauna

From site investigations, it has been possible to estimate the population densities for most of the mammal and bird species, that are found in the Forsmark region. The mammals included in the surveys are listed in Table 4-12. The mean densities of the monitored species set out in Table 4-12 have been used in the carbon budget calculations. In Forsmark, moose and roe deer populations have decreased during the period of the investigations (2002–2007). The population density of hares, in forest and field, is higher than in 2002/2003. Hare populations have high inter-annual variation and the results are within the limits of what can be expected. The wild boar populations have increased at an amazing rate, a phenomenon that the area shares with many other parts of the country. Hovewer, the population growth is more rapid than the average rate in the county /Truvé 2007/. The most common bird species in Forsmark according to the breeding bird counts between 2002 and 2004 are listed in Table 4-13.

Table 4-12. Mammal species that have been monitored in Forsmark. The density estimates have been generated from the surveys that are listed in the table /Truvé and Cederlund 2005, Truvé 2007/.

Species English (Swedish)		Latin	Surveys in Forsmark
Herbivores (even-toed ungulates)	Moose (*Sw: Älg*)	*Alces alces*	Pellet: 2002, 2003, 2007 Aerial: 2002, 2004
	Roe deer (*Sw: Rådjur*)	*Capreolus capreolus*	Pellet: 2002, 2003, 2007
Herbivores (Lagomorphs)	European (common) hare (*Sw: Fälthare*)	*Lepus europaeus*	Pellet: 2002, 2003, 2007
	Mountain hare (*Sw: Skogshare*)	*Lepus timidus*	Pellet: 2002, 2003, 2007
Carnivores	Lynx (*Sw: Lo*)	*Lynx lynx*	Snowtracking: 2002
	Marten (*Sw: Mård*)	*Martes martes*	Snowtracking: 2002, 2007
	Red fox (*Sw: Rödräv*)	*Vulpes vulpes*	
Omnivores	Wild boar (*Sw: Vildsvin*)	*Sus scrofa*	Pellet: 2007
Rodents	Bank Vole (*Sw: Skogssork/ Ängssork*)	*Cletrionomus glareolus*	Trapping: spring and autumn 2003
	Field vole (*Sw: Åkersork*)	*Microtus agrestis*	Trapping: spring and autumn 2003
	Water vole (*Sw: Vattensork*)	*Arvicola terrestris*	Trapping: spring and autumn 2003
	Wood mouse (*Sw: Mindre skogsmus*)	*Apodemus sylvaticus*	Trapping: spring and autumn 2003
	Yellow necked mouse (*Sw: Större skogsmus*)	*Apodemus flavicollis*	Trapping: spring and autumn 2003
Insectivores	Common shrew (*Sw: Vanlig näbbmus*)	*Sorex araneus*	Trapping: spring and autumn 2003

Table 4-13. The 15 most common nesting species in the Forsmark regional area, presented as the total number of birds registered and the number of birds per km observed during transect surveys /Green 2005/.

Species English (Swedish)	Latin	Total number (2004)	Abundance (n/km) 2004	Abundance (n/km) 2003	Abundance (n/km) 2002
Willow Warbler (Lövsångare)	*Phylloscopus trochilus*	460	10.22	8.62	11.31
Chaffinch (Bofink)	*Fringilla coelebs*	444	9.87	13.27	11.36
Robin (Rödhake)	*Erithacus rubecula*	206	4.58	4.04	3.54
Common gull (Fiskmås)	*Larus canus*	198	4.40	4.09	1.36
Greylag goose (Grågås)	*Anser anser*	116	2.58	2.95	2.65
Song Thrush (Taltrast)	*Turdus philomelos*	98	2.18	3.83	1.81
Blackbird (Koltrast)	*Turdus merula*	87	1.93	2.26	2.46
Siskin (Grönsiska)	*Carduelis spinus*	74	1.64	1.81	3.57
Wood Pigeon (Ringduva)	*Columba palumbus*	67	1.49	1.05	1.01
Great Tit (Talgoxe)	*Parus major*	58	1.29	1.33	1.27
Goldcrest (Kungsfågel)	*Regulus regulus*	56	1.24	2.09	0.54
Tree pipit (Trädpiplärka)	*Anthus trivialis*	37	0.82	0.56	0.87
Yellowhammer (Gulsparv)	*Emberiza citrinella*	37	0.82	1.51	1.57
Pied flycatcher (Svartvit flugsnappare)	*Ficedula hypoleuca*	35	0.78	0.67	0.92
Jackdaw (Kaja)	*Corvus monedula*	35	0.78	3.29	1.29

4.6.2 Ecosystem models

Field-estimated local carbon balances for three ecosystems

All the three investigated forest localities were net carbon sinks, where most of the carbon accumulated in the vegetation (Table 4-14). NPP was between 429 and 537 g C $m^{-2}y^{-1}$. The forested wetland accumulated 74 g C $m^{-2}y^{-1}$ in the soil organic carbon pool, whereas the two forests were close to zero in regard to soil carbon balance. This investigation described the ecosystems more closely from a site-specific perspective and served as a baseline for comparison with the results of the dynamic modelling (section 4.1.3 and Chapter 7 in /Löfgren (ed) 2008/) and with more general literature data that may be used to describe pools and fluxes in long-term perspectives in the safety assessment.

The estimated pools and fluxes for the three localities were in agreement with similar studies. The standard deviations that were estimated and propagated through the calculations represent spatial variation for most of the properties, due to lack of time series. The large variation found for a number of properties on this rather small spatial scale indicates that there are a number of factors affecting these properties at a small scale, such as soil properties, topography, water availability etc. The large standard deviation of the Net Ecosystem Production (NEP) estimates mainly stems from the large standard deviation in the soil respiration estimates, which also suggests a high spatial variation at the scale measured.

Model-estimated carbon balances for a number of ecosystems

The LPJ-GUESS modelled vegetation types were all net sinks except for the clear-cut that was a carbon source, mainly due to decomposition of the large litter pool originating from the residues after the clear-cut. NPP was between 461 and 664 g C $m^{-2}y^{-1}$ for the forested vegetation types. A similar calculation of the NEP as above showed that all vegetation types were accumulating carbon in the Soil Organic Carbon (SOC) pool or were close to zero except for the dry pine forest and the previously mentioned clear-cut. The spatial variation of NPP was studied in the regional model area by combining remote sensing and dynamic vegetation modelling (Table 7-6 in /Löfgren (ed) 2008/). The temporal variation of a number of ecosystem properties was investigated by modelling 400 years of forest succession, where NPP is illustrated in Figure 4-34 showing the NPP for the most important tree species and the field layer separately.

Table 4-14. A description of carbon pools distinguished into functional units in the three investigated ecosystems at Forsmark. See also Figure 3-12 for the conceptualized ecosystem. Pools are in g C m⁻² and fluxes are in g C m⁻²y⁻¹ (mean±SD).

Functional groups and properties		Vegetation types Norway spruce	Old Norway spruce	Norway spruce – alder wetland
Tree layer				
Biomass	Needles/leaves	677±263	593±453	326±305
	Wood	6,577±2,051	9074±3,716	5,411±2,120
	Fine roots < 2mm	183±76	205±104	166±108
Net accumulation	Branches	26±4	23±10	20±9
	Stems	114±19	99±41	88±41
	Coarse roots	29±5	25±10	22±10
Litterfall		64±26	91±19	108±32
Root litter production < 2mm		183±76	205±104	166±108
Field and bottom layer				
Biomass	Leaves	8±6	20±12	3±3
	Bryophytes	38±16	38±16	43±47
	Roots < 10mm	29±35	98±115	22±47
Litter production		39±29	94±50	25±22
Soil Organic Carbon pool				
Litter pool		544±228	544±228	383±130
Humus		1,660	1,620	2,440
Mineral soil		530	5,330	1,720
Heterotrophic respiration		290±125	395±620	225±190
Total				
NPP		454±87	537±124	429±122
Litter production		285±85	390±117	299±114
Acc. in soil		–5±151	–5±631	74±222
Acc. in vegetation		169±20	147±44	130±93
NEP		164±153	142±632	204±226

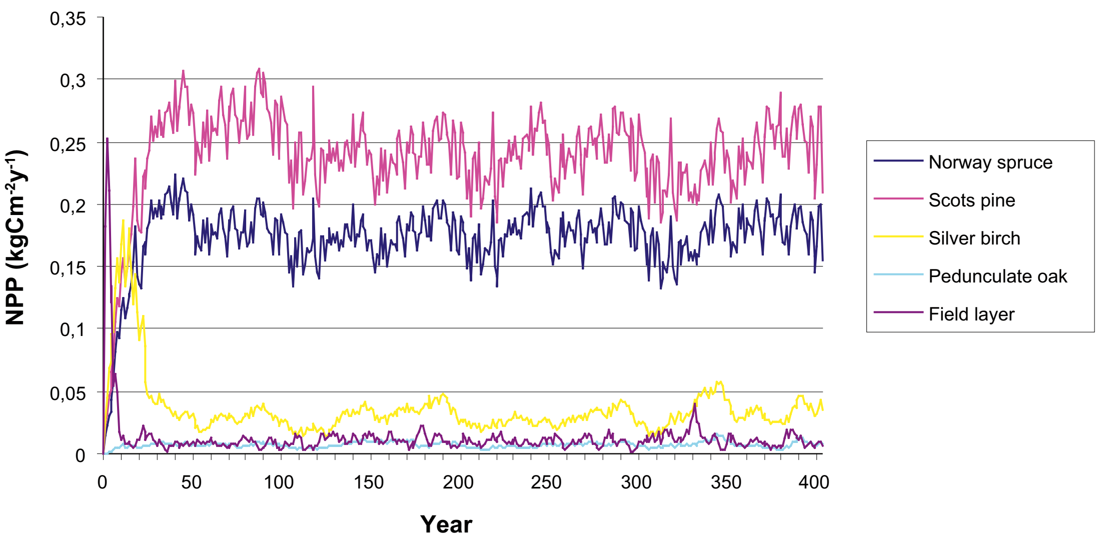

Figure 4-34. *Net primary production during a 400 y period of forest development starting after a clear-cut for Forsmark showing performance of four different tree species and the field layer during a 400 y period. The model was driven by climate data describing a 100 y period that was repeated. Values are given in kg C $m^{-2}y^{-1}$.*

Average values of carbon balances in a 100-y forest cycle, i.e. the time from clear-cut to felling of a managed forest are illustrated in Figure 4-35. There was a positive uptake of carbon allocated as biomass accumulation, i.e. more carbon was located to the vegetation than was lost as respiration.

Unlike very many other detailed models, requiring many input parameters, LPJ-GUESS simulates estimates of carbon and vegetation dynamics directly on the basis of the local climate. Net primary production and net ecosystem production were in the upper range of boreal forests, but not unrealistic in comparison with field data and literature values. Temporal variations in carbon balances were also estimated and compared with literature estimates. This variation was also realistically estimated. One limitation that most likely influenced the modelled results for the investigated areas was that anthropogenic influences were not included. The investigation area consists of managed forests, and sites are prepared by for example chopping, ditching, thinning, competition control and fertilization. Another limitation was the estimation of the SOC pool, which was substantially overestimated, due to young soils at both sites, i.e. there had been no time to build up a quasi-equilibrium amount of SOC. Still, the model gave a good description of carbon balances in both investigation areas and carbon balances were realistically estimated in comparison with field estimates and literature values.

Food web

Estimations of biomass, production, consumption, egestion and respiration for mammals are presented in Table 4-15. Estimations for birds, amphibians and reptiles are presented in section 4.2 and in Chapter 8 in /Löfgren (ed) 2008/. The figures are used to construct food webs, which are used to estimate fluxes across different trophic levels, e.g. herbivores to carnivores (see Figure 4-36).

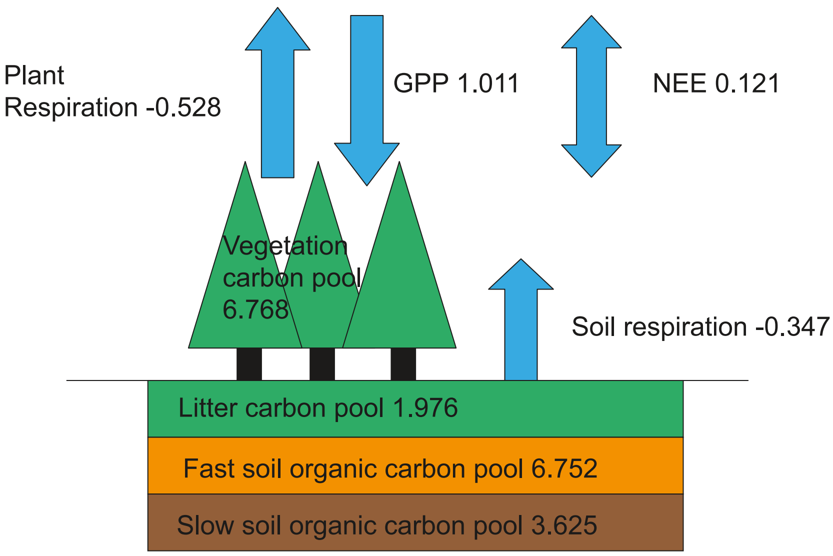

***Figure 4-35.** A summary of mean carbon pools and fluxes for a 100-y forest cycle in Forsmark from planting to felling. The positive mean Net Ecosystem Emission (NEE) suggests an annual accumulation of carbon during the forest cycle. Values are given in kg C m^{-2} for the carbon pools and kg C $m^{-2}y^{-1}$ for the carbon fluxes.*

Table 4-15. General figures per unit area describing number densities, biomass, production, consumption, egestion and respiration for the mammals in the Forsmark area.

Mammal species		Habitat	Density	Biomass (standing stock)		Production	Consumption	Egestion (Feaces)	Respiration
			Number per km^2	Body mass g/ind	Biomass C mgC/m^2/y	Prod C mgC/m^2/y	Consump C mgC/m^2/y	Faeces C mgC/m^2/y	Resp. C mgC/m^2/y
Herbivores (Eventoed ungulates)	Moose	Forest+Field	1.0	300,000	36	7.0	397	174	216
	Roe deer	Forest+Field	7.3	25,000	21	10	574	251	312
Herbivores (Lago-morphs)	European hare	Field	0.7	3,800	0.3	0.3	16	7	9
	Mountaine hare	Forest	1.1	3,000	0.4	0.4	22	9.6	12.1
Herbivores (domestic)	Cattle	Field area (seed area excluded)	66	527,000/200,000	3,443	1,160	199,857	85,339	106,016
	Cattle (milkprod.)					7,343			
	Sheep	Field area (seed area excluded)	31	66,000/46,000	203	79	8,480	3,621	4,780
Carnivores	Marten	Forest	0.84	1,250	0.123	0.202	8.3	1.83	6.2
	Red fox	Forest+Field	0.20	6,000	0.14	0.18	7.4	1.7	5.6
	Lynx	Forest	0.035	30,000	0.12	0.12	5.11	1.14	3.85
Omnivorous	Wild boar	Forest+Field	0.043	60,000	0.3	0.11	5	1.0	3.5
Rodents	Bank Vole	Forest	275	23	0.7	1.7	199	87	110
	Field vole	Field	25	30	0.1	0.2	22	10	12
	Field vole	Forest	10	30	0.04	0.07	9	3.8	5
	Mouse	Field	340	23	0.9	2.1	246	108	136
	Mouse	Forest	175	23	0.5	1.1	127	56	70
	Water vole	Around water[1]	525	74	4.5	9.2	1,090	478	603
Insectivores	Common shrew	Forest+Field	145	8.5	0.14	0.25	35	5.9	29

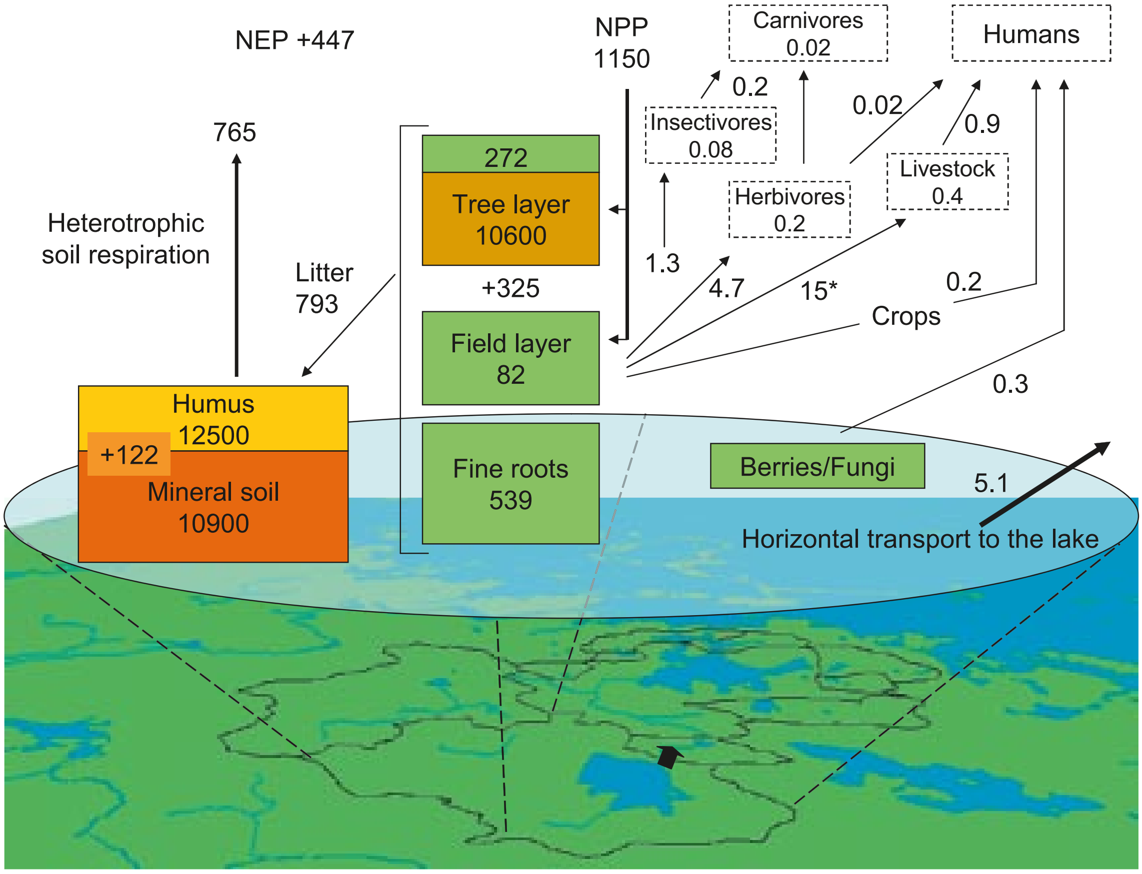

*Figure 4-36. A description of the carbon balance for the catchment of Lake Eckarfjärden, where modelled pools and fluxes for all vegetation types have been summed across the catchment. The production of berries/fungi is the potential harvest available to biota. The black arrows on the map denotes the discharge into the next catchment. All figures within boxes are in 1×10^6 g C and fluxes are in 1×10^6 g $C \cdot y^{-1}$. Changes in the soil organic carbon pool and the vegetation pool are denoted with a ± before the figure. *Livestock consumption is generally divided between locally produced fodder and imported, and this figure includes both.*

Regional carbon balances for catchments

An ecosystem model describing pools and fluxes of carbon for the catchment area of lake Eckarfjärden is illustrated in Figure 4-36. The production by vegetation represents the largest flux closely followed by the litter production transporting carbon from the vegetation pool to the soil carbon pool. The largest part of the carbon entering the soil will be respired by soil fauna and microbes. The net ecosystem production, which is the accumulation of carbon in vegetation and soil organic carbon pool, is positive and more than 70% of the carbon is accumulated in the vegetation and the rest in the soil organic carbon pool. The largest flux of carbon to animals is to livestock. However, this flux includes fodder imported from outside the catchment.

The flux to herbivores represented by large animals such as rodents, roe deer and moose is the second largest flux in the food web. Current hunting in the area is one order of magnitude lower than the fluxes to carnivores. The largest potential human intake of carbon comes from livestock through meat and milk. The small agricultural area compared to the forested land is shown as a larger potential intake of berries/fungi than of crops. The horizontal transport is relatively small compared with the major internal carbon fluxes.

4.6.3 Mass balances

Mass balances are calculated for a large number of elements, but those for iodine, thorium, uranium and phosphorus are presented and discussed in more detail using the discharge areas as units of study (Chapter 9 in /Löfgren (ed) 2008/). Figure 4-37 illustrates the mass balance of phosphorus for the investigated catchments. The calculation suggests a net accumulation of phosphorus within the area. By using the information from the ecosystem model describing carbon pools and fluxes in the same area, it was estimated that approximately 310 kg P y^{-1} was needed to sustain the NPP. Moreover, by adding accumulation in wetlands, /Sternbeck et al. 2006/ further 25 kg would be accumulated in wetlands (all wetlands included). Most certainly there is an overestimation of the accumulation within wetlands because many of the wetlands close to the coast do not yet accumulate much peat, because of minerogenic conditions. Another source of phosphorus is weathering and decomposition of litter that would make further 118 kg available, which suggest a source of 134 kg P unaccounted for. On the other hand, the atmospheric deposition only included wet deposition, which suggests that the input of phosphorus would be somewhat higher.

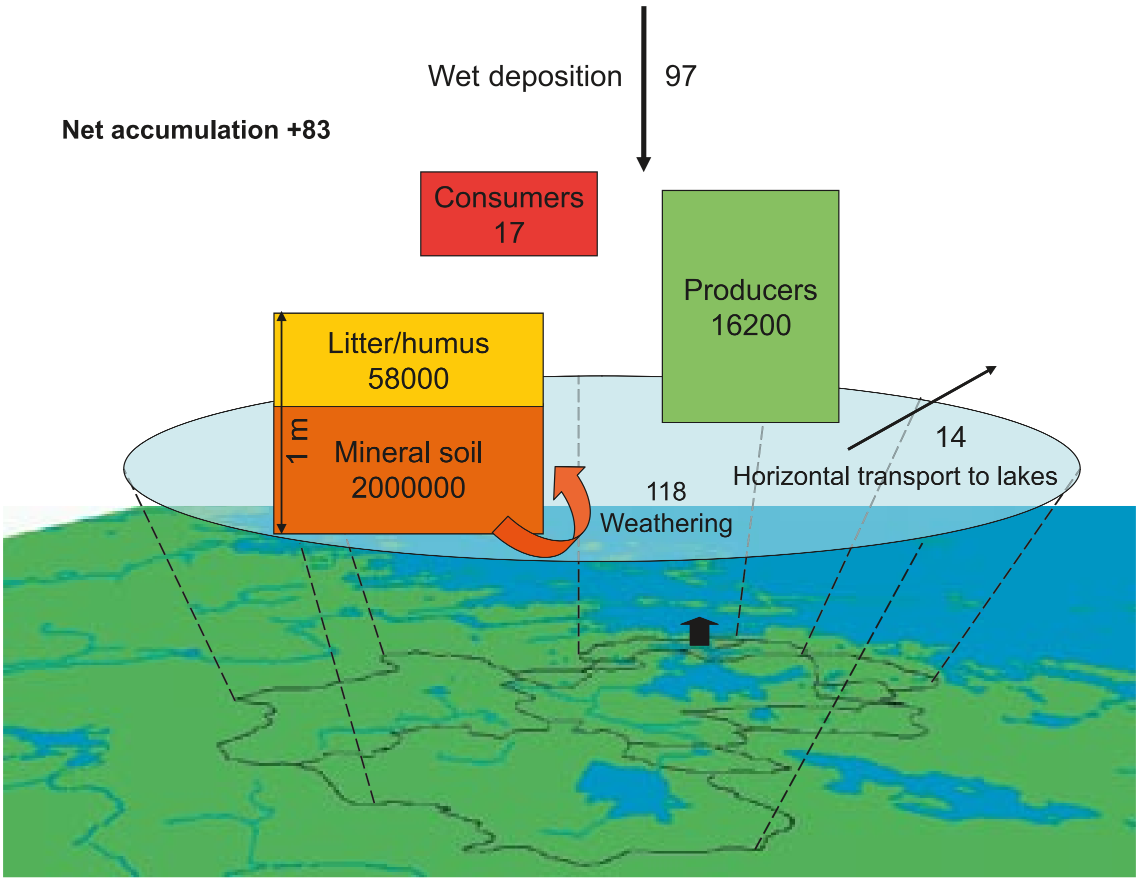

Figure 4-37. *Mass balance of phosphorus for the 11 investigated sub-catchments in Forsmark. The black arrow on the map denotes the discharge into sea. Pools are in kg P and fluxes are in kg P·y^{-1}.*

4.6.4 Conclusions

The detailed site investigations have provided an extensive database that has been combined with dynamic modelling in order to characterize and quantify the distribution of carbon and other elements in the terrestrial landscape. In this section, a subset of the results has been presented and a more detailed description and discussion is found in /Löfgren (ed) 2008/. The terrestrial landscape in Forsmark is characterized by small-scaled and varied vegetation that to a large extent is determined by the land use.

The field- and model-estimated carbon pools and fluxes revealed some general patterns. The largest carbon pool was found in the humus and mineral soil, followed by the vegetation. The accumulation of carbon was, however, dominated by accumulation in vegetation. Export of carbon was low compared to internal fluxes within the terrestrial ecosystems, which was also the case for fluxes to higher trophic levels in the foodweb, considering free-living mammals, livestock, birds, amphibians and reptiles. The largest flux in the food web was found between agricultural land and livestock. Humans were mainly exposed to crops and products from livestock, such as milk, eggs and meat. Some of the studied ecosystems were more or less reluctant to emit or accumulate organic material. For example, a clear-cut initates increased soil respiration and a release of organically bound elements, whereas some wetland types show a long-term accumulation of organic matter. Especially wetlands dominated by reed close to lakes had both high production and high accumulation of organic matter in reed peat. This was also evident for phosphorous that otherwise had its largest content in the soil organic matter pool.

When comparing the distribution of thorium, uranium and iodine, which have an increasing solubility in soil water in that order, iodine showed a different pattern than thorium and uranium. Iodine was found to a higher degree within the vegetation compartments, whereas thorium and uranium were concentrated in the soil compartments. The mass balances of thorium, uranium, iodine and phosphorus illustrate some different behavioural patterns, where the water-soluble highly mobile iodine to a large extent was incorporated into the vegetation and also transported further downstream into the lakes. Phosphorus was to a higher degree found in the vegetation and only a small quantity was transported from the terrestrial areas. Thorium and uranium had their largest pools in the mineral soil and to a lesser extent in the humus layer showing a less mobile pattern with low amounts found in the vegetation or transported downstream.

4.7 Limnic ecosystems

4.7.1 General description

The limnic ecosystem in the Forsmark area includes eight small catchments and contains 25 lakes, see Appendix 1 (map of Forsmark) and /Brunberg et al. 2004/. Most of the lakes are small, only three of the lakes are larger than 0.2 km^2, and most of them are considerably smaller. They are all very shallow (the “median lake” has an average depth of 0.3 m and a maximum depth of 1 m) and have small water volumes and short renewal times. Some of the lakes have not yet become completely separated from the sea, and in these lakes brackish water from the Baltic Sea occasionally intrudes during low pressure weather conditions.

All lakes in the area are classified as oligotrophic hardwater lakes, i.e. they contain high concentrations of calcium, whereas phosphorus concentrations are low. Further, the lakes are characterized by high alkalinity, conductivity, pH values and nitrogen concentrations. The lakes have very high concentrations of dissolved organic carbon which is unusual in combination with the moderate water colour of the lakes. This kind of lakes is common in the region, i.e. along the coast of northern Uppland, but is very uncommon in Sweden and worldwide /Brunberg et al. 2002/.

Due to the shallow depth, all lake bottoms are reached by sunlight and vegetation occurs at all depths. The dominant vegetation is stoneworts (*Chara sp.*). On top of the sediment, a thick layer of algae and cyanobacteria is often found. These two groups of primary producers dominate the biomass and primary production, making phytoplankton biomass and production of less importance. The lakes are surrounded by reed belts which often are extensive, especially around the smaller lakes.

The dense stands of *Chara* house various kinds of benthic fauna and also function as refuges for smaller fish. Common fish species are perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*), as well as tench (*Tinca tinca*) and crucian carp (*Carassius carrasius*). The latter survive low oxygen levels and is the only species present in the smaller lakes where oxygen levels can be very low during winter.

The streams in the Forsmark area are very small and mostly resemble man-made ditches (see Figure 4-38a). Long stretches of the streams are dry during summer (Figure 4-38b). The streams function as passages for migrating spawning fish, especially in the more downstream parts. Fish migration has been observed in the small stream connecting Lake Norra Bassängen with the sea. During one spring investigation, thousands of ruffe (*Gymnocephalus cernua*), roach, perch and pike (*Esox lucius*) were caught on their way from the sea into the lake /Loreth 2005/.

An extensive compilation of all the data concerning limnic ecosystems in the Forsmark area is presented in /Nordén et al. 2008/.

***Figure 4-38**. Left) The largest stream in the Forsmark candidate area, a couple of metres before entering Lake Bolundsfjärden. Photograph taken 21 May 2007. Right) Many streams dry out during summer. Photograph taken 4 July 2003.*

4.7.2 Ecosystem models

Carbon ecosystem model for Lake Eckarfjärden

Eckarfjärden is one of the larger lakes in the Forsmark regional model area. It is the deepest lake in the area (maximum depth 2.1 m) and is situated at the highest altitude of the lakes. Similar to other lakes in the area, Eckarfjärden is a clear-water lake surrounded by reed and with bottoms covered by the macroalgae *Chara* and a thick microbial mat.

The mean annual *biomass* in Eckarfjärden was estimated to 5,900 kg C and was concentrated to the littoral habitat (96% of total). Primary producers make up the major part of the total biomass in the lake and the dominant group is benthic primary producers (making up 83% of the total biomass). Benthic bacteria make up 12% of the total biomass, whereas each of the other functional groups stand for 3% or less of the total biomass.

The annual *primary production* was 30,600 kg C y^{-1} and was similar to biomass clearly concentrated to the littoral habitat, where the benthic primary producers contributed with 88% of total primary production. The annual *respiration* was 21,100 kg C y^{-1} and, accordingly, smaller than primary production. This indicates that the lake is a net autotrophic system with a positive net ecosystem production (NEP) of 9,500 kg y^{-1}. In contrast to biomass and production, a large part of the respiration occurred in the pelagic habitat (58% of total respiration). Benthic bacteria and bacterioplankton dominate respiration, together making up 82% of total respiration. Other important functional groups in terms of respiration were mixotrophic phytoplankton and fish, 9 and 6% of total respiration, respectively. Other functional groups made only small contributions to the total respiration.

***Figure 4-39**. Lake Eckarfjärden, one of the larger lakes in the Forsmark area. It is, like all other lakes in the area, a shallow oligotrophic hardwater lake surrounded by reed. Photograph: Eva Andersson, April 2005*

The benthic primary producers clearly dominate the biomass and production in the lake, whereas bacteria dominate the respiration and consumption. The largest carbon flow to the top predator fish goes from benthic primary producers via benthic fauna to fish (Figure 4-40). Only a small part (7%) of the primary produced carbon is directly consumed by higher organisms. Instead, most of the carbon produced by primary producers is incorporated into the DOC and TOC pools in the system.

The carbon incorporated into primary and secondary producers that was not respired or consumed by higher organisms is called excess. The excess will contribute to the sedimentation in the lake as well as to outflow through the outlet. Using the calculated values in the mass balance for carbon import (inflow from the catchment, carbon deposition and atmospheric gas exchange) and carbon export (outflow through outlet, sediment accumulation, and bird consumption) the ecosystem carbon model for Eckarfjärden still has an excess of c. 3,700 kg carbon. This mismatch is small compared with the flows of carbon in the model, for example it constitutes only 10 and 12% of the total primary production and respiration, respectively.

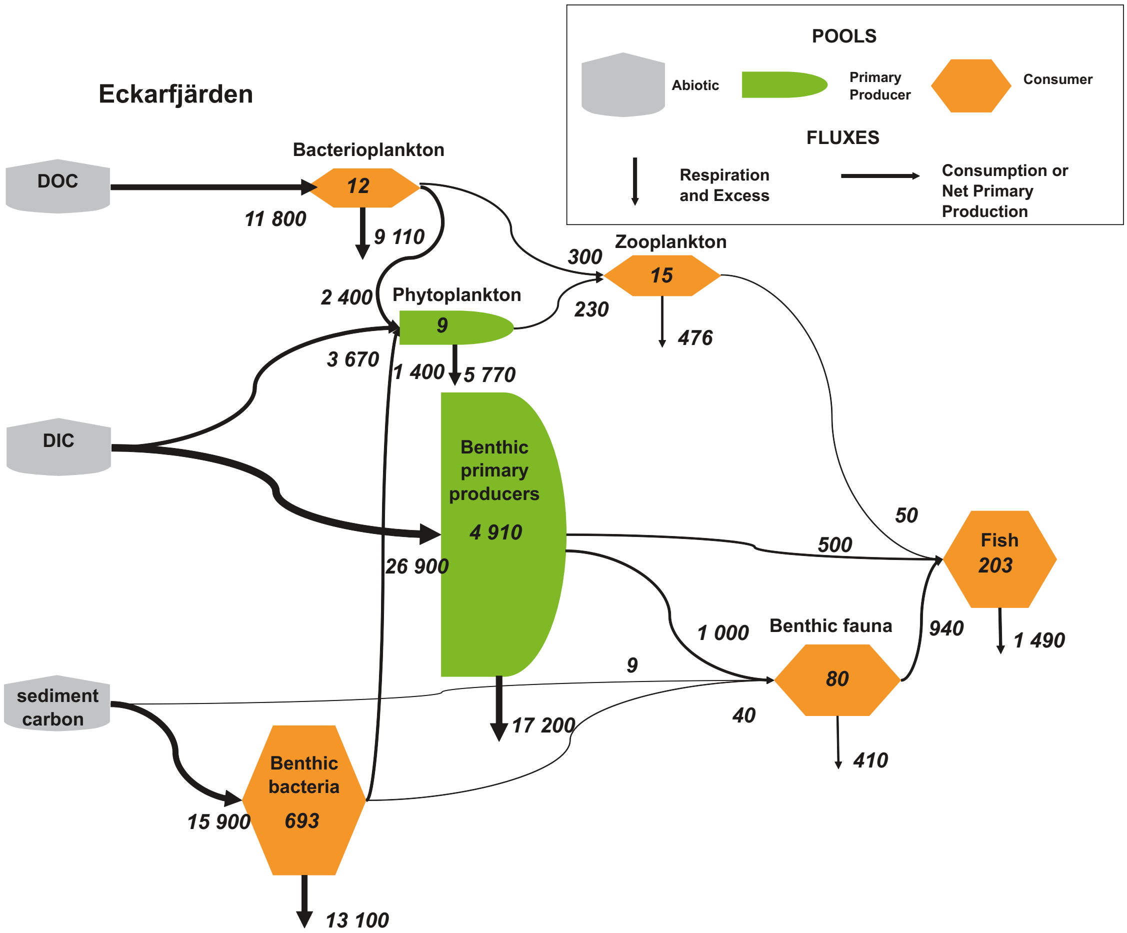

Figure 4-40. Carbon biomass (kg C) of functional groups and carbon flows (kg C y^{-1}) in the ecosystem model for Eckarfjärden. Sizes of boxes and arrows are relative to the sizes of pools and fluxes in the model. The consumption within functional groups is not shown in this figure. The summarised consumption of phyto-, zoo- and bacterioplankton by benthic fauna is shown as consumption of POC in the figure.

4.7.3 Mass balances

Carbon mass balance for Lake Eckarfjärden

The inflow of carbon to Lake Eckarfjärden was dominated by the inflow from the catchment (10,400 kg DIC y^{-1} and 3,500 kg TOC y^{-1}) (Figure 4-41). The atmospheric deposition of organic carbon (200 kg C $year^{-1}$) made only a minor contribution to the carbon input to the lake. The major export of carbon was the downstream flow of DIC and TOC (6,800 and 5,700 kg C y^{-1}, respectively) followed by carbon burial in the sediments (3,600 kg C y^{-1}) whereas carbon export by birds feeding in the lake (300 kg C y^{-1}) was of less magnitude. The flux of carbon dioxide across the lake-air interface indicates an uptake in the lake of about 900 kg C y^{-1} and net autotrophic metabolism (Figure 4-41). The mass balance was somewhat unbalanced and output will exceed the input by c. 1,400 kg C y^{-1}. This corresponds to 8% of the carbon export and 9% of carbon input. The absolute numbers of the different flows in the mass balance are uncertain and flows are also presented as a range. By using other values within this range of the separate flows the mass balance can reach balance and also show result with input exceeding output. Thus, although the absolute numbers in the mass balance may be incorrect the mass balance is robust in magnitudes of the flows.

The net inflows and outflows of carbon in the mass balance are rather small (some order of magnitude) compared with the total amount of carbon involved in the internal ecosystem processes (see primary production and respiration in the ecosystem model above), indicating that the lakes may be more influenced by internal processes than carbon entering the lake from the surroundings.

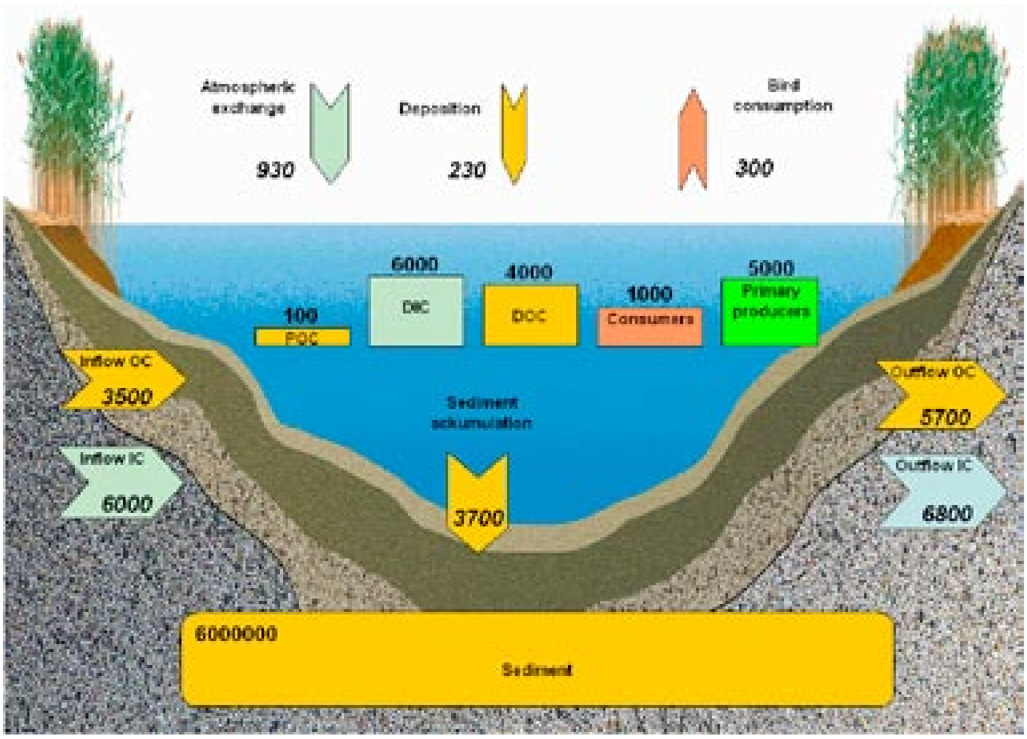

Figure 4-41. *Carbon mass balance for Eckarfjärden (*kgC y^{-1}*).*

Phosphorus mass balance for Lake Bolundsfjärden

Bolundsfjärden is the largest lake in the Forsmark area, with an area about 3 times larger than Eckarfjärden (Figure 4-42). It is somewhat shallower than Eckarfjärden (maximum depth 1.8 m) and is situated close to sea level (0.64 m.a.s.l.). Under extreme weather conditions, brackish water enters the lake from the sea. The water is therefore sometimes more brackish than what is normal for limnic conditions. As with all other lakes in the area, Bolundsfjärden is a clear-water lake surrounded by reed and with bottoms covered by the macroalgae *Chara* and a thick microbial mat.

The inflow of phosphorous via water is in the same order of magnitude as the inflow via atmospheric deposition (c. 10 kg P y^{-1}), and the outflow by accumulation in sediment is in the same order of magnitude as that due to outflow of water (14 and 13 kg P y^{-1}, respectively) (Figure 4-43). Oligotrophic hardwater lakes are expected to function as a phosphorus sink as co-precipitation of phosphorus and calcium from the water phase to the sediment is assumed to take place /Brunberg and Blomqvist 2000/. The large pool of phosphorus in lake sediments, together with the estimated phosphorus accumulation in the sediments also indicates that this is the case. The mass balance is unbalanced and the output exceeds the input by 7 kg y^{-1} (35% of total input, 27% of total output). The most uncertain of the fluxes included in the mass balance is the accumulation in sediment. Calculating the accumulation rate as the difference between the other inputs and outputs in the mass balance indicates an accumulation rate of c. 7 kg P y^{-1}, which is about half of our estimate using phosphorus data from lake sediments. This is a reasonable result as the estimate of sediment accumulation is based on long term accumulation and sediment accumulation most certainly varies over time.

***Figure 4-42**. Lake Bolundsfjärden is the largest lake in the Forsmark area. The smaller lake at the front edge is Lake Graven.*

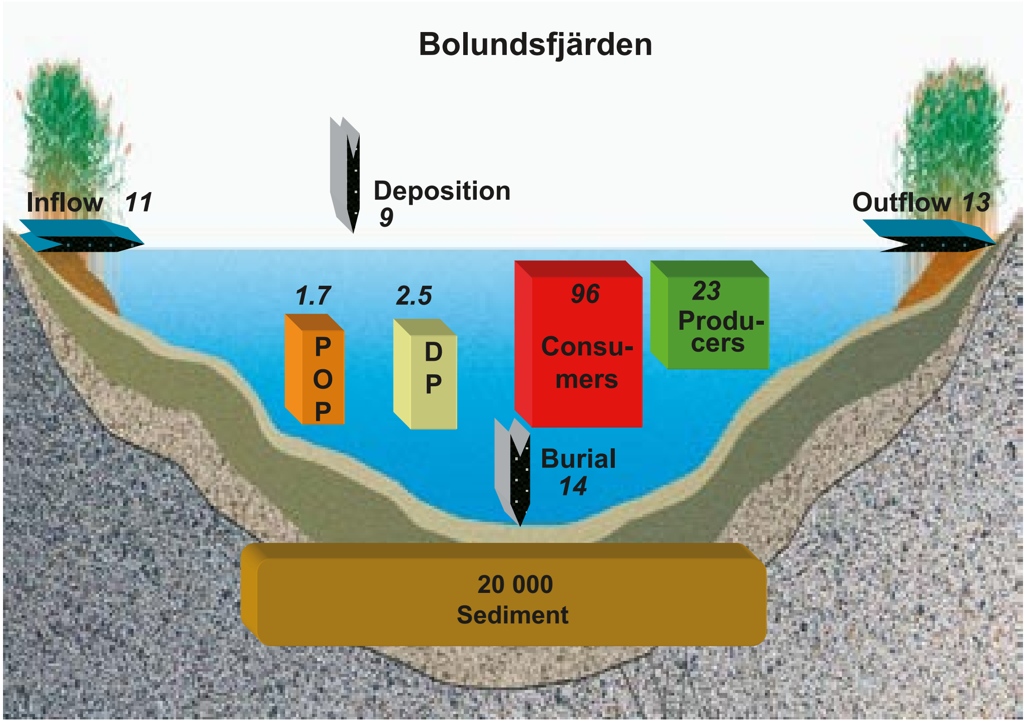

Figure 4-43. *Phosphorus mass balance for Lake Bolundsfjärden. The pools of P are given in the boxes (kg P) and inflows and outflows of P are shown with arrows (kg P year^{-1}). Sizes of boxes and arrows are relative to the sizes of pools and fluxes in the model. Note that the sediment box is scaled differently to fit into the figure. POP = Particulate Organic Phosphorus, DP = Dissolved Phosphorus (from Chapter 7 in /Nordén et al. 2008/).*

The sediment layer is by far the largest phosphorus pool in the lake (20 tonnes, 98% of total P in the lake). The next largest phosphorus pools, consumers and producers, contain much less phosphorus (0.5% and 0.1% of total P in the lake, respectively). The particulate organic (POP) and dissolved (DP) fractions in the water are small and of similar size (c. 2 kg P each correspondingly to 0.01% of total P in the lake).

Mass balances for a number of other elements

The mass balances of elements show that the most important flows differ between elements due to their sorption properties and mobility in the ecosystem. The distribution of fluxes for three selected elements with different sorption properties; iodine (very mobile), uranium (intermediate) and thorium (almost immobile), are shown in Figure 4-44. As expected, the outflow via water is much more important for the mobile iodine than for uranium (intermediate) and thorium (lowest flows). For uranium, outflow via water is the largest outflow but accumulation in sediments is also an important process. Thorium accumulation in sediments is c. 3 times larger than outflow via water. The reasons for the different flows of iodine, uranium and thorium is further discussed in /Nordén et al. 2008/.

Generally, the most important outflux for metalloids, metals and non-metals is the outflow via water, whereas for lanthanides the most important outflow is accumulation in sediments. The mass fluxes for the lanthanides appear to be very unbalanced, with higher outfluxes than influxes. Estimation of atmospheric deposition is missing for the lanthanides and thus, either the sediment accumulation is overestimated or there is a large atmospheric deposition of these substances. A large sediment accumulation of lanthanides is reasonable, since lanthanide phosphates are very insoluble and association of lanthanides to phosphorus should lead to large co-precipitation with apatite (Ca-phosphate). However, as stated above, phosphorus sedimentation is not static over time and the present sediment accumulation seems to be somewhat over-

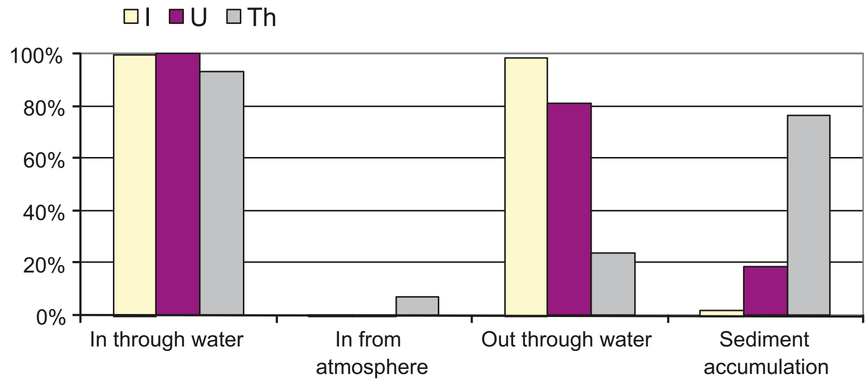

***Figure 4-44**. Fluxes of iodine, uranium and thorium into and out of the average Forsmark lake (% of inflow and % of outflow, respectively).*

estimated in the mass balances, and this may also be the case with the estimates of lanthanide sedimentation. For only half of the elements, the mass fluxes are well balanced (influxes vary between 80 and 110% of outfluxes). Thus, there is a degree of uncertainty in the mass balances, which is further discussed in /Nordén et al. 2008/.

The Forsmark lakes differ in the magnitude of different fluxes. The difference appears to be associated with lake size and position in the catchment. In Lake Bolundsfjärden, Lake Eckarfjärden and Lake Puttan, the inflow of phosphorous via water is in the same order of magnitude as via atmospheric deposition. In two other lakes, Gällsboträsket and Norra Bassängen, inflow via water dominates. Likewise, the atmospheric deposition of iron, iodine and manganese is relatively large in Lake Bolundsfjärden, Lake Eckarfjärden and Lake Puttan, but small in Lake Gällsboträsket and Lake Norra Bassängen. Also, outflows differ between the lakes; in Lake Gällsboträsket and Lake Norra Bassängen, the outflow via water dominates for almost all elements, whereas in Lake Bolundsfjärden, Lake Eckarfjärden and Lake Puttan the accumulation in sediment is the dominating outflux for many elements.

The dominant element in the mass fluxes of elements is carbon. Concerning accumulation in sediments, elements common in biota (carbon, nitrogen, calcium, sulphur and iron) dominate in mass, whereas mercury and lanthanides have the lowest accumulation rates in accordance with their uncommonness in biota and water. Atmospheric deposition has only been investigated for 14 elements, and among those some ions common in marine environments (chlorine, sodium, and sulfur) are dominant. Inflow as well as outflow of elements via water is dominated by the same elements: carbon, chlorine, calcium, sodium and sulphur. Mercury, samarium, europium, thulium and holmium are the least common elements in both inflow and outflow.

Chemical composition of biotic and abiotic pools

The most common element in terms of mass (excluding oxygen and hydrogen) in the lake ecosystem is silicon (40% of total mass) followed by carbon (17%), aluminium (14%) and iron (8%). The components of the water molecule (oxygen and hydrogen) are even more abundant but these are not included in the analyses. The abitotic pool has the same distribution of elements as the total lake ecosystem. The biotic pool, on the other hand, has a different chemical composition and is dominated by carbon (57%) followed by calcium (33%). Nitrogen, zinc and silica make up more than 1% each of the total weight of biota in the average Forsmark lake, whereas all other elements make up smaller parts.

In the abiotic pools, the sediments constitute the dominant pool for the majority of elements. The distribution of elements among biotic pools is shown in Figure 4-45. For almost all elements, the largest biotic pool is the benthic primary producers. This is especially true for the lanthanides, with almost 100% located in the benthic primary producers. This may be a true result but may also be an artifact due to missing data on the chemical composition of bacteria.

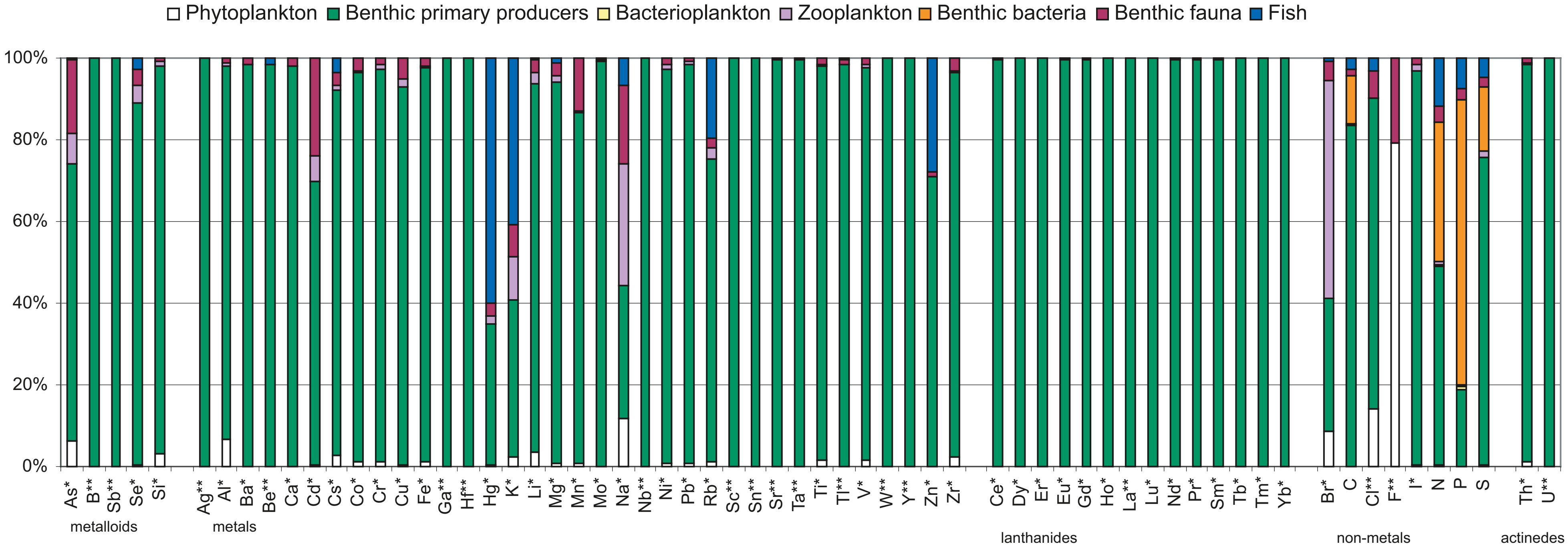

***Figure 4-45**. Elemental distribution, in percent, in biota in the average Forsmark lake. * indicates that data on bacterioplankton and benthic bacteria are missing. ** indicates that data are missing for both bacteria and other types of biota (from Chapter 7 in /Nordén et al. 2008/).*

Data on chemical composition for all functional groups are available only for carbon, phosphorus, nitrogen and sulphur, whereas for all other elements data for bacterioplankton and benthic bacteria are missing. Bacteria have a very high phosphorus content and 70% of all phosphorus in the biotic pool is found in bacteria. Bacteria also contain considerable amounts of nitrogen, sulfur and carbon (34, 16 and 12% at the biotic pool of each element, respectively). Thus, elements are most probably present in consumers to a larger degree than is shown in Figure 4-45 and the distribution of different elements should be viewed with some caution. Some elements, e.g. mercury, potassium, sodium and bromine, show significant levels in consumers despite the lack of data for bacteria. Mercury, which is an element known for biomagnification, has its highest amount in fish. Also potassium, rubidium and zinc show considerable amounts in fish. Bromine is strongly accumulated by zooplankton. The reason for the latter is unknown but the same pattern of bromine accumulation in zooplankton is seen in the marine ecosystem /Wijnblad et al. 2008/.

4.7.4 Conclusions and comparison between small and large lakes

In both larger and smaller lakes in the Forsmark area, biomass is clearly concentrated to the littoral habitat, where between 96 and 97% of total biomass is found. Also primary production is dominated by the littoral habitat in all lakes. In contrast, a substantial part of both respiration and consumption in the lakes take place in the pelagic habitat.

The ecosystem models indicate net autotrophic metabolism and dominance of primary production in the two larger lakes, whereas the primary production and respiration are almost the same in the smaller Lake Labboträsket. The mass balances for the two larger lakes show net autotrophic metabolism (a flux of CO_2 into the lake from the air), whereas Labboträsket shows net heterotrophic metabolism (a flux of CO_2 to the air from the lake water). Many of the smaller lakes in the area have lower chlorophyll *a* concentrations than the larger lakes, indicating a higher degree of respiration in the pelagic habitat and lower net ecosystem production (NEP). However, the largest impact on the NEP seems to be the presence or absence of microphytobenthos in the benthic habitat. Labboträsket lacks a microbial mat, whereas both Eckarfjärden and Bolundsfjärden have a thick microbial mat of microphytobenthos in the benthic habitat. Another factor influencing the NEP is the depth of the water column, since the pelagic habitat is net heterotrophic and the benthic habitat is net autotrophic.

Most of the primary produced carbon in the lakes was incorporated in the DOC and POC pools in the system, and only a small part (7–10%) was directly consumed by higher organisms. Thus, any pollutant incorporated into organic matter during primary production would to a large extent circulate within the microbial loop and not be transported upwards in the food web. However, a large proportion of the total production and consumption takes place in the benthic habitat. Therefore, pollutants settling on the sediments could easily be reincorporated into the lake food web.

The distribution of elements between different pools in the lake ecosystem is almost the same in all five studied lakes. However, the amounts present within the sediments differ between the lakes. This is a direct result of the sediment thickness; Gällsboträsket and Eckarfjärden are among the oldest lakes in the Forsmark area with thick sediment layers and large amounts of elements, whereas Norra Bassängen is one of the youngest lakes with a thin sediment layer and small amounts of elements. The latter has also historically been relatively exposed leading to small sediment accumulation.

The mass balances in all five studied lakes showed that the most important inflow of elements is the inflow in water. However, there are some differences in flows of elements between the studied lakes due to lake size and the position of the lake within the catchment. Bolundsfjärden, Eckarfjärden and Puttan, have relatively large atmospheric deposition of phosphorous, iron, iodine and manganese (9–59% of total inflow of the elements), whereas in the other two lakes, Gällsboträsket and Norra Bassängen, inflow via water totally dominates for all elements.

Overall, the main conclusion from the mass balances for all elements and from the carbon ecosystem model is that the larger lakes may be important sites for biogeochemical processes. In these lakes, primary production and respiration are processes that involve larger carbon fluxes than the inflows and outflows. Therefore, there is a large potential for elements entering the larger lakes to be incorporated into the lake food web. Some of the smaller lakes have large inflows and outflows compared to the internal processes and much of the carbon entering these lakes should, to a large degree, be transported further downstream in the water system, and the lakes should function more as flow through systems. However, there ara also some smaller lakes for which internal processes are of similar size as as that of inflows and outflow. The mass balances showed that in Gällsboträsket and Norra Bassängen, the outflow via water dominates for almost all elements, whereas in Bolundsfjärden, Eckarfjärden and Puttan the accumulation in sediment is the dominant outflux for many elements. Results from Lake Puttan indicates that, in addition to lake size, the position of the lake within the catchment (i.e. size of catchment area) also influences the functioning of the lake.

4.8 Marine ecosystems

4.8.1 General description

The marine ecosystem in Forsmark includes 28 marine basins (see Figure 3-14, section 3.9), which cover a total area of 246 km^2. The mean depth in the area is 9.5 m. The mean water temperature in the area is 7.9°C. The area represents shallows bays of coastal marine water, with salinity values (c. 5‰) somewhat lower than these in the Gulf of Bothnia, due to freshwater influence from land. The mean nitrogen load in the area is considered as medium high, whereas the phosphorous load is low. Nitrogen seems to be the limiting nutrient in the area during the summer months. In comparison with data from the national environmental surveillance, the chlorophyll concentrations from the Forsmark area are considered quite low.

Large parts of the Forsmark marine area consist of open sea and the area is delimited by the steep sloping Gräsö Island in the east and the gentle slope of the mainland to the south-west. Most of the area is characterized by shallow and exposed hard-bottom (boulders or bedrock) communities, interspersed by deeper valleys with soft bottom communities. The photic zone extends roughly down to twice the water transparency depth, and as the average water transparency depth is not more than 3.4 to 3.6 m in the coastal zone, large areas deeper than 7 m are lacking vegetation cover. In the photic zone, the seabed is to a large extent covered with a layer of microalgae, mainly diatoms. The vegetation in the photic zone is dominated by red algae (e.g. *Polysiphonia nigrescens*), brown filamentous algae (e.g. *Spacelaria arctica*) and the larger *Fucus vesiculosus* (Figure 4-46).

A few bays are more or less secluded from wave exposure and host soft bottom communities, e.g. Kallrigafjärden in the south (basins 152, 150 and 146) and Asphällsfjärden (basin 120), adjacent to the Forsmark nuclear power plant. In these areas soft-bottom dwelling phanerogames (e.g. *Potamogeton pectinatus*, see Figure 4-47) are abundant. Charophyceae algae (e.g. *Chara tomentosa*) dominate the macrophytes in the shallow areas. In the deeper areas in Tixelfjärden (basin 134) and Kallrigafjärden, Xanthophyceae algae (*Vaucheria dichotoma)* are found in high densities.

The benthic fauna in the marine area at Forsmark is dominated by *Macoma baltica*. The fish community in the more inner basins is dominated by Perch, and in the more outer basins Herring dominates the fish biomass.

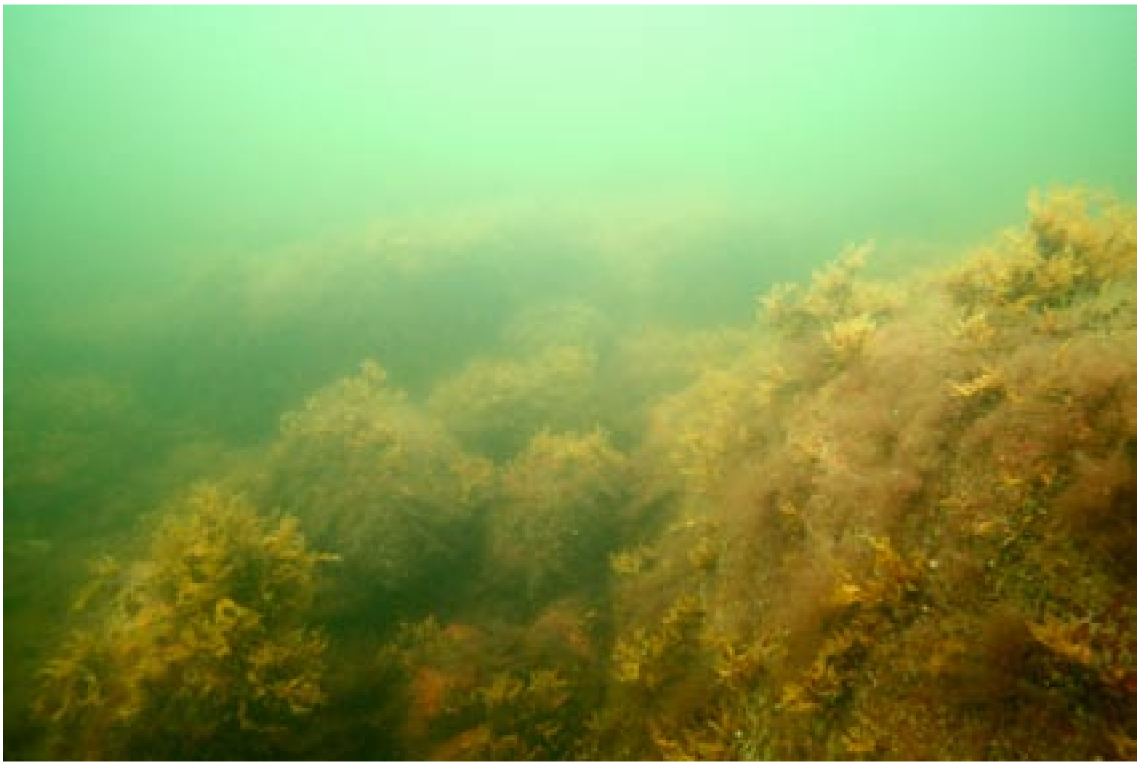

***Figure 4-46**. Fucus vesiculosus and Polysiphonia sp. on bedrock at 1 m depth at the island Marträd, located 6 km east of the Forsmark power plant.*

***Figure 4-47**. Potamogeton pectinatus on a soft bottom at approximately 2 m depth in Asphällsfjärden, Forsmark.*

4.8.2 Ecosystem model

Total biomass varies from just over 5 g C m^{-2} to 160 g C m^{-2} in different basins in the area, and is unevenly distributed, mainly along the coast and in shallow areas. The mean biomass in the whole area is 18 g C m^{-2}, resulting in an estimated total of 4,400 tonnes of carbon fixed in biota in all basins. Biomass in most basins is dominated by macrophytes; macrophyte biomass varies between 4 and 87% of total biomass in the different basins (the larger figure comes from basin 152 in Kallrigafjärden). Macrophytes are especially dominant in basins along the sloping eastern coastline. In the east, the Öregrundsgrepen is steeper and the depths in the basins larger, and therefore not suitable for macrophytes. Here, the consumer part of the biomass is larger and detrivores dominate the total biomass (5–38% of biomass in the various basins). Apart from macrophytes and detrivores, microphytes (2–19% of total biomass in separate basins) and benthic bacteria (also up to 19% of biomass in various basins) are the third and fourth largest organism groups. Other organisms contribute to less than 10% of the total biomass, see Figure 4-48 and Table 4-15.

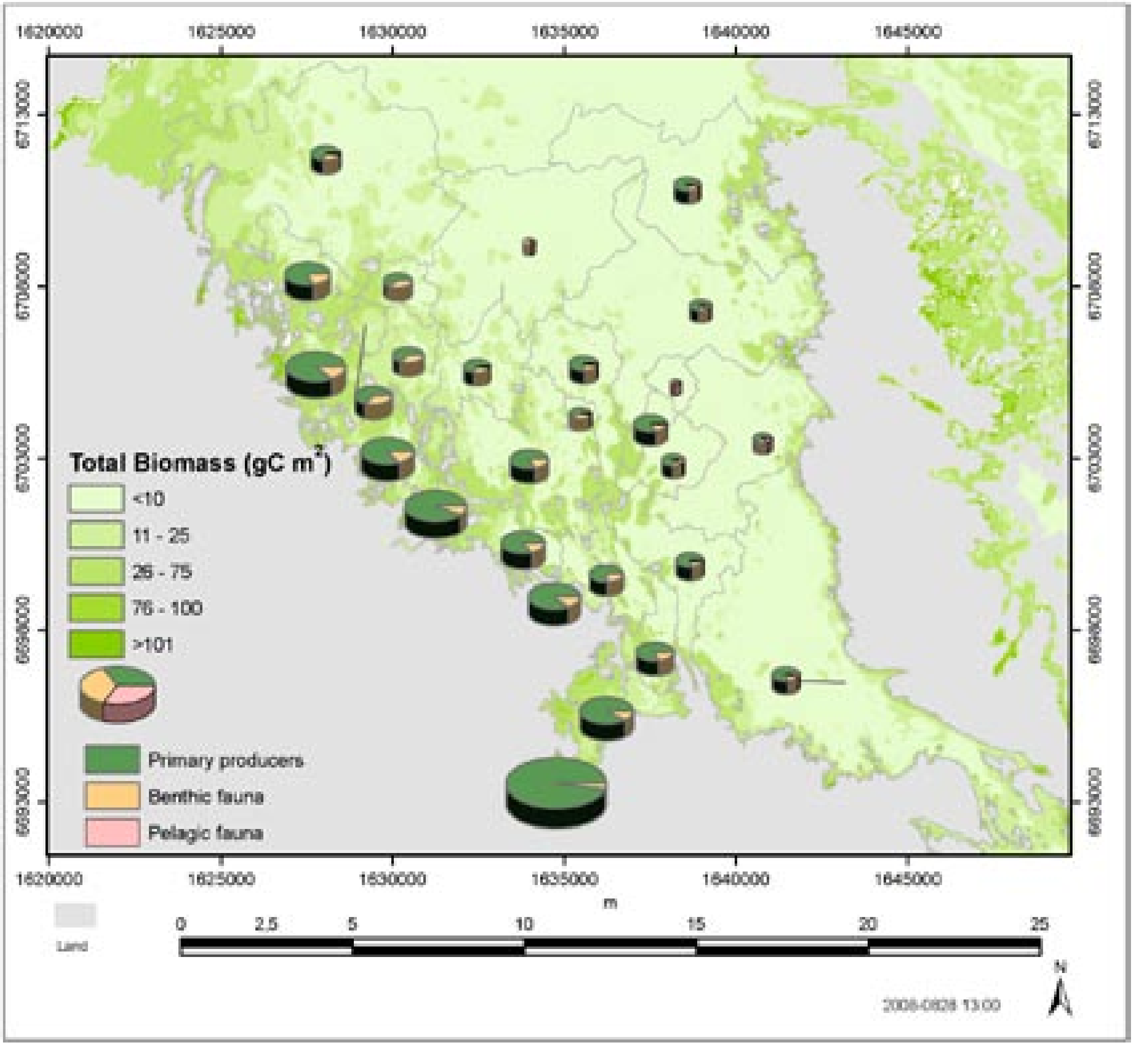

Figure 4-48. *Proportional biomass distribution in the various basins of the functional groups; primary producers, benthic fauna and pelgic fauna, and total biomass (shaded in background) (g C m^{-2}) for all basins in the Forsmark area. For biomasses in figures per basin see also Table 4-16.*

Table 4-16. Annual average biomass of the functional groups in the marine ecosysytem in Forsmark (g C m^{-2} year^{-1}).

Basin	Macro-phytes	Micro-phytes	Phyto-plankton	Bacterio-plankton	Benthic bacteria	Benthic carnivores	Benthic detrivores	Benthic filterfeeders	Benthic herbivores	Benthic feeding fish	Piscivores fish	Zooplankton-feeding fish	Zoo-plankton	Seal	Bird
102	5.8	2.2	0.2	0.3	0.6	0.3	4.6	1.0	1.1	0.1	0.01	0.1	0.1	0.01	0.01
100	5.3	1.1	0.4	0.4	0.9	0.4	3.2	0.8	0.9	0.1	0.02	0.2	0.1	0.01	0.004
101	0.4	0.9	0.3	0.4	0.7	0.4	2.8	0.7	0.7	0.03	0.00	0.1	0.1	0.01	0.001
105	3.3	1.0	0.4	0.4	1.4	0.4	3.2	0.6	0.6	0.05	0.01	0.2	0.1	0.01	0.003
103	16	3.8	0.0	0.1	0.4	0.1	6.1	1.4	1.7	0.2	0.04	0.1	0.01	0.01	0.01
104	4.5	3.1	0.1	0.2	0.7	0.3	5.1	1.0	1.0	0.2	0.04	0.1	0.02	0.01	0.01
108	4.8	1.8	0.2	0.3	0.6	0.3	4.4	1.1	1.0	0.1	0.02	0.1	0.1	0.01	0.01
106	8.8	4.6	0.0	0.1	0.6	0.1	7.2	1.4	1.7	0.3	0.1	0.1	0.01	0.01	0.02
111	29	4.4	0.0	0.1	0.9	0.2	5.7	1.9	1.9	0.5	0.2	0.2	0.01	0.01	0.02
107	5.6	3.3	0.0	0.2	0.6	0.2	5.7	1.4	1.4	0.2	0.1	0.1	0.02	0.01	0.01
110	5.9	1.6	0.2	0.3	0.7	0.3	3.3	1.2	1.1	0.1	0.02	0.1	0.1	0.01	0.003
114	2.1	0.9	0.4	0.4	1.8	0.5	3.3	0.4	0.4	0.1	0.02	0.2	0.1	0.01	0.003
109	0.3	0.5	0.5	0.5	1.4	0.5	2.8	0.4	0.4	0.01	0	0.1	0.2	0.01	0.001
116	11	2.4	0.1	0.2	0.8	0.3	3.8	1.5	1.3	0.2	0.1	0.1	0.04	0.01	0.01
113	8.6	1.6	0.2	0.3	0.9	0.4	2.8	1.3	1.1	0.1	0.01	0.1	0.1	0.01	0.002
117	23	3.8	0.0	0.1	0.8	0.2	5.6	1.6	1.7	0.6	0.2	0.2	0.01	0.01	0.02
112	2.6	1.8	0.1	0.3	0.8	0.3	3.5	1.0	0.9	0.2	0.05	0.1	0.04	0.01	0.002
115	3.8	1.0	0.4	0.4	1.3	0.5	3.0	0.8	0.6	0.04	0.01	0.1	0.1	0.01	0.002
151	5.7	1.2	0.3	0.3	1.7	0.4	3.7	0.9	0.8	0.1	0.02	0.2	0.1	0.01	0.01
118	33	2.7	0.05	0.1	1.7	0.2	5.3	1.3	1.2	0.6	0.2	0.2	0.02	0.01	0.02
123	6.0	1.3	0.3	0.3	1.6	0.5	3.1	0.9	0.6	0.1	0.02	0.1	0.1	0.01	0.003
152	93	2.4	0.1	0.0	2.7	0.2	5.5	0.6	0.5	0.8	0.3	0.3	0.05	0.01	0.03
150	24	2.5	0.2	0.1	4.4	0.2	5.2	1.2	1.1	0.4	0.1	0.2	0.1	0.01	0.02
146	11	2.7	0.1	0.2	1.6	0.4	3.9	1.4	1.2	0.2	0.1	0.1	0.03	0.01	0.01
126	8.2	2.6	0.1	0.2	1.7	0.3	4.3	1.3	1.1	0.2	0.1	0.1	0.03	0.01	0.01
134	22	3.3	0.03	0.05	3.7	0.2	6.9	0.7	0.8	0.1	0.03	0.1	0.01	0.01	0.02
121	15	2.9	0.1	0.1	2.4	0.3	4.4	1.2	1.0	0.3	0.1	0.2	0.02	0.01	0.01
120	23	2.5	0.05	0.1	2.1	0.2	5.9	1.0	1.1	0.5	0.1	0.1	0.02	0.01	0.02

The net primary production (NPP) is, like the biomass, concentrated at the shoreline, where the highest values are found, but is also high in the offshore areas where depth and enhanced water transparency enable high phytoplankton production. The maximum values, over 250 g C m^{-2} in various basins are found along the shoreline in densely vegetated areas, e.g. in Kallrigafjärden (basin 150 and 152), but also on exposed coastal shores (see Figure 4-49).

The benthic and pelagic components of the NPP, display roughly the opposite patterns; pelagic increases and benthic decreases with depth. This is not surprising as light penetration decreases with depth and the benthic primary producers are restricted to the sea floor while increasing depth increases the volume over which phytoplankton can photosynthesize.

The total benthic plus pelagic respiration is shown in Figure 4-50. The respiration includes only respiration by heterotrophes (consumers) as respiration by the autotrohps (primary producers) is included in the NPP presented above. The respiration is, generally, higher where biomass in the vertically integrated water volume is higher per unit area (g Cm^{-2}). The maximum values, over 150 g C $m^{-2}y^{-1}$ are found in areas within basin 152, where high bacterial and benthic fauna biomass is found. Generally, however, at a basin level, respiration increases with depth. The values range from 31 to 162 g C m^{-2}, and the average is 76 g C m^{-2}over the various basins in the area.

Calculations of the total net ecosystem production (NEP) in the Forsmark marine area show that even if the major part of the area is heterotrophic, mean NEP of the area is autotrophic, i. e. more carbon is fixed in the ecosystem by primary producers than is released by respiration by all organisms. The annual mean NEP in basins is 43 g C $m^{-2}y^{-1}$ and ranges from –38 to 224 g C $m^{-2}y^{-1}$ in different basins. As Figure 4-51 suggests, the coastal shallow basins generally tend to be autotrophic while the outer basins are heterotrophic.

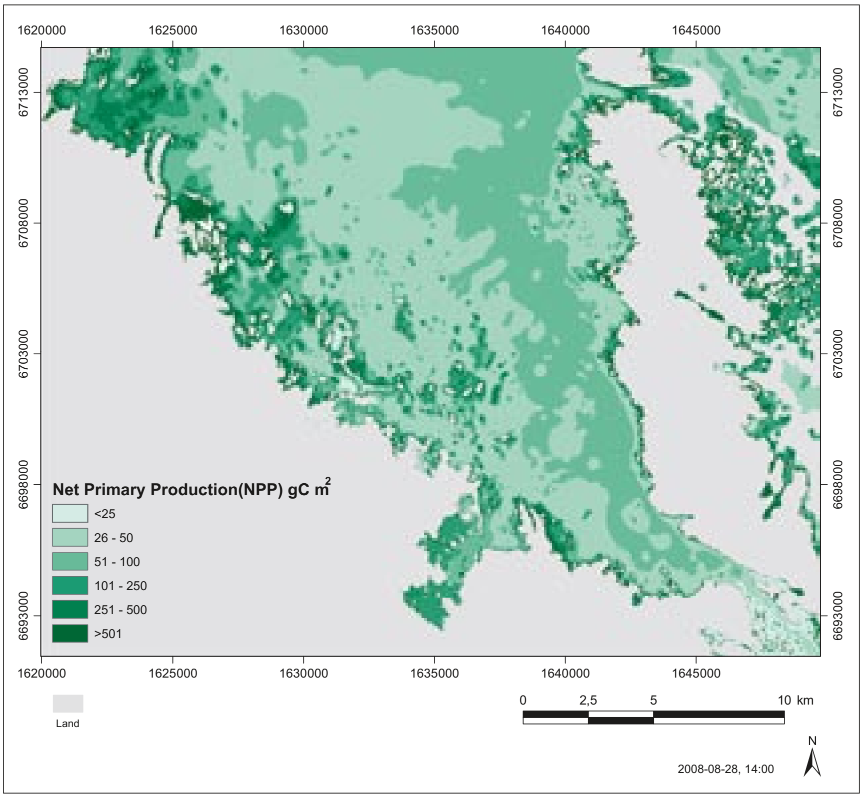

Figure 4-49. *Net Primary Production (g C $m^{-2}y^{-1}$) in the Forsmark area. Higher NPP is indicated by increasingly dark green colour.*

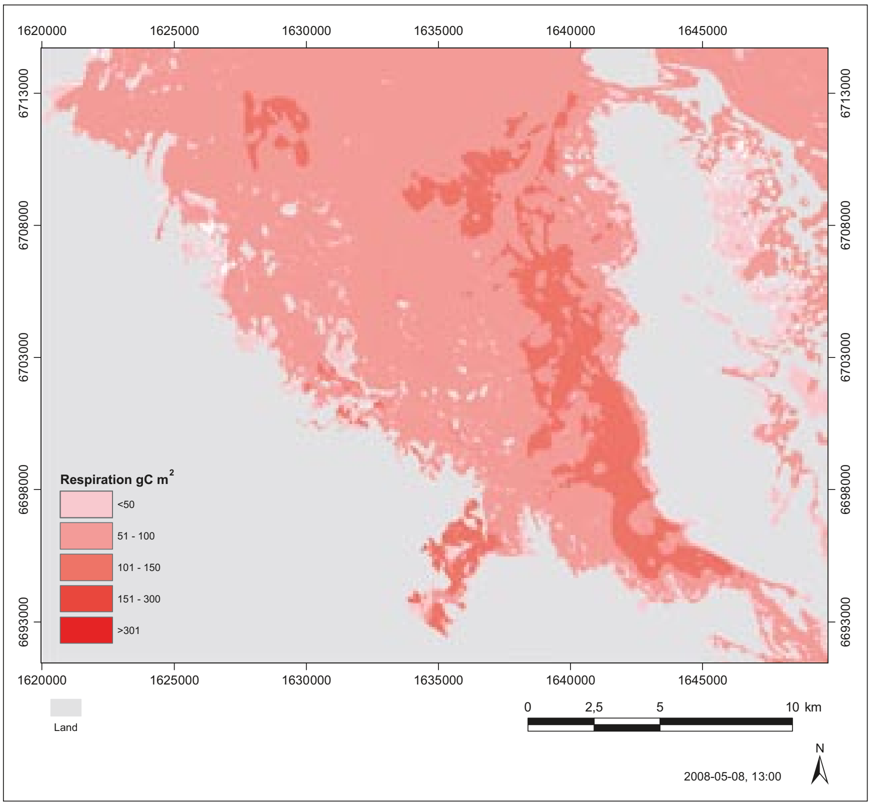

Figure 4-50. *The sum of consumer respiration (g C m^{-2}y^{-1}) in the Forsmark area. Higher respiration is indicated by increasingly dark red colour.*

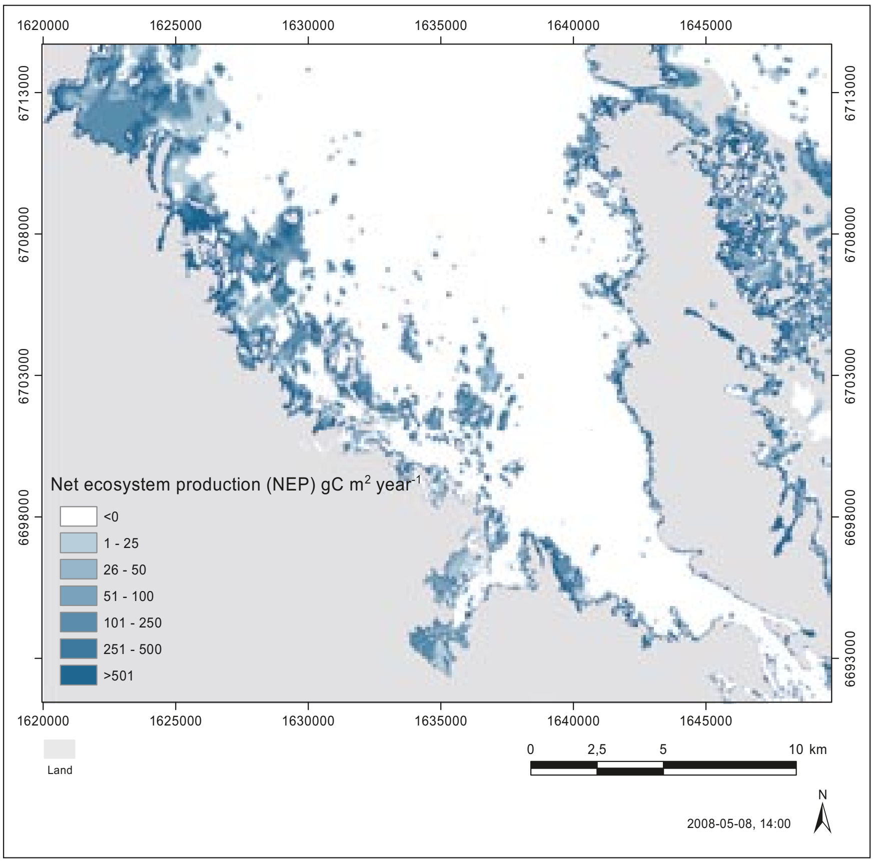

***Figure 4-51**. The net ecosystem production (NEP) (g C m^{-2}y^{-1}) in marine parts of the Forsmark area. Higher respiration is indicated with increasing dark bluegreen colour.*

4.8.3 Mass balances

Pools and fluxes of carbon were calculated for separate basins within the area and not for the whole marine area. Pools and fluxes in Basin 121 are presented as an example in Figure 4-52. Basin 121 is one of the five basins of special interest, since it fulfils two criteria; (i) it has a high density of site-specific data and (ii) it is considered as exit point for any future release of radionuclides according to earlier safety assessments /SKB 2006a/. Generally (and in Basin 121) the overall dominant process in the sea, for flux of carbon, is advective flow. NPP and runoff constitute only minor components of the total carbon input. The dominant carbon pool is the sediment, which is several orders of magnitude larger than the other pools. The main sink for carbon is sediment burial. In some basins, the rate of loss through sediment burial can be as large as 24 g C $m^{-2}y^{-1}$.

The elemental composition of all pools (biota, dissolved in water, particulate and sediment top 10 cm), are presented in Figure 4-53, in weight percent for the model area. Cl is the most abundant element of the analysed elements, (note that oxygen and hydrogen are not included); on average the Cl content in all pools in the model area constitutes 31 kg m^{-2}. The most abundant elements, such as Cl, Na, Mg, S etc. are present to a large extent in the dissolved phase. Carbon appears in the 7[th] place with 0.3 kg m^{-2}.

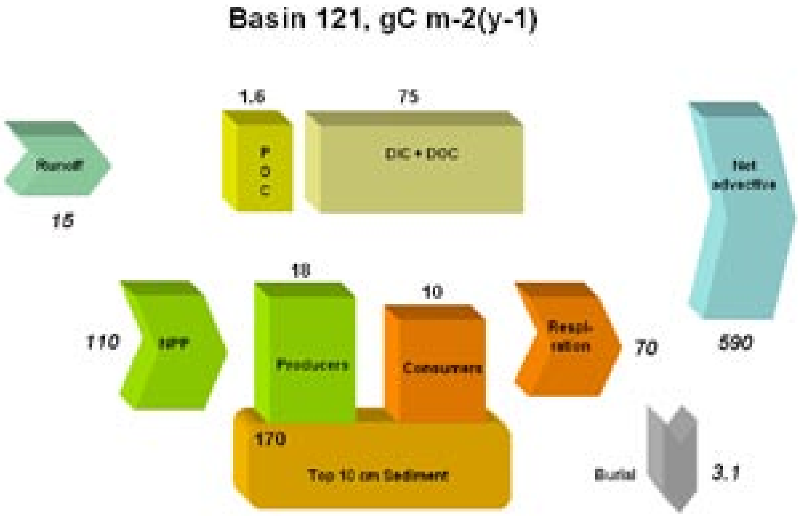

Figure 4-52. *Major pools and fluxes of carbon into and out of basin 121 in g C $m^{-2}y^{-1}$. Boxes and arrows denote relative (square root transformed) sizes of pools and fluxes respectively.*

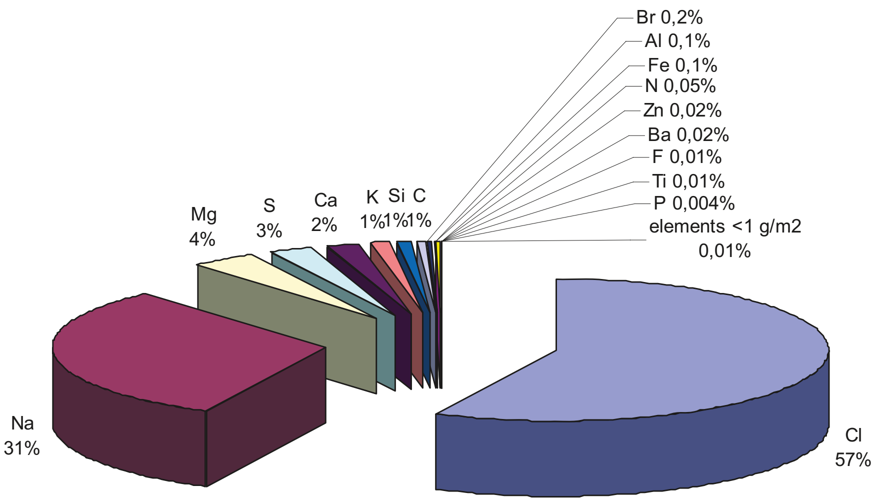

Figure 4-53. *Elemental abundance in all pools in the marine model area in Forsmark, presented in weight percent and in order of magnitude.*

In Figure 4-54 the distribution pattern of all elements in the biotic pool, the sediment, the dissolved phase and in particulate matter is presented. For most elements, the biotic pool contains only a minor part of the total amount in the ecosystem. The only elements with a higher allocation to the biotic pool than 1% are carbon (5%), nitrogen (6%), phosphorous (6%), silicon (3%), manganese (2%) and iodine (1%).

The distribution in Basin 121 of three selected elements (iodine, uranium and thorium) of special interest for the safety assessment, and with very different biogeochemical characteristics (for example considering their K_d-values), are presented in Figure 4-55. These elements are all most abundant in the sediment pool, followed by the dissolved pool, the producer pool, the particulate pool and the consumer pool. This observation indicates that sediments are a major sink for elements with different biogeochemical characteristics, and that the transport of dissolved elements with water is always of great importance.

4.8.4 Conclusions

Below follows the main conclusions drawn from the marine ecosystem modelling.

- Biomass in marine areas is dominated by macrophytes, and most biomass is found in shallower areas and along the shoreline.
- The NPP shows, not surprisingly, the same pattern as the biomass with the highest production in the shallower areas and along the shoreline.
- When the pelagic and benthic NPP are distinguished they show opposite trends, with increasing pelagic NPP and decreasing benthic NPP, with depth.
- Respiration generally increases with depth.
- The coastal basins tend to be autotrophic, whereas the outer basins are heterotrophic. However, as a mean the whole area is autotrophic.
- The major pool of carbon in the ecosystem is the sediment, followed by carbon dissolved in water, producers and consumers. The sediment pool is around 20 times larger than the other pools.
- The advective flow of carbon is the dominant flux and advective flow is several orders of magnitude larger than other fluxes, such as photosynthesis by primary producers.
- In biotic and abiotic pools of the marine ecosystem at Forsmark, Cl (31 kg m^{-2}) is the most abundant element followed by Na, Mg and S, which are elements mainly present in sea water. Carbon appears in the 7th place with 0.3 kg m^{-2}.
- Only carbon, nitrogen, phosphorous, silicon, manganese and iodine have more then 1% of their total inventory in biotic pools.
- The sediments are for most of the elements the major pool. However, the dissolved phase does also play an important role for the distribution of elements.
- The elements reviewed in most detail and representing different ranges of K_d values (iodine, thorium and uranium) are all most abundant in the sediment pool, followed by the dissolved pool, the producers, the particulate pool, and lastly the consumers. However, the dissolved phase of uranium has not been analysed.

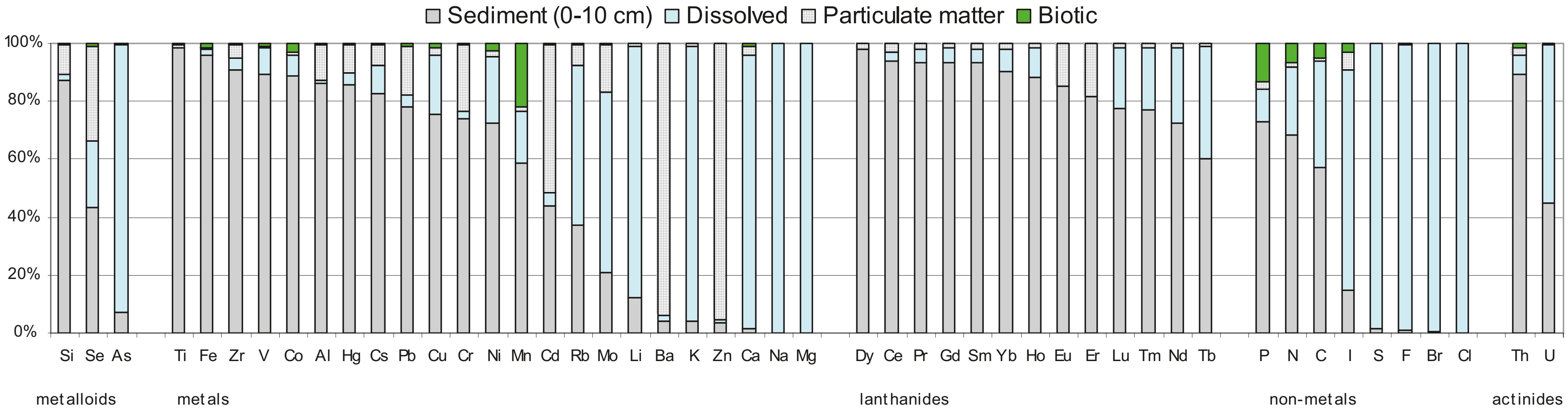

Figure 4-54. *Elemental distribution in percent, in biotic and abiotic ecosystem pools in Forsmark model area, see also Table 4-17.*

Table 4-17. Percental distribution of elements in different biotic and abiotic pools in the Forsmark area.

Element	Sediment (%)	Particulate (%)	Dissolved (%)	Biotic (%)
Si	87	10	2	0.4
Se	44	33	23	1
As	7	0.3	93	0.5
Ti	99	1	0	0.4
Fe	97	1	2	1
Zr	91	4	4	1
V	90	1	9	1
Co	91	1	8	3
Al	87	12	1	1
Hg	86	10	4	1
Cs	83	7	10	0.5
Pb	79	17	4	1
Cu	77	3	20	1
Cr	74	23	3	0
Ni	75	2	24	3
Mn	75	2	23	22
Cd	44	51	5	1
Rb	38	7	55	0.3
Mo	21	17	62	0.3
Li	12	1	87	0.1
Ba	4	94	2	0.1
K	4	1	95	0.1
Zn	4	95	1	0.1
Ca	1	3	95	1
Na	0	0.1	100	0.01
Mg	0	0.04	100	0.02
Dy	98	2	0	0.02
Ce	94	3	3	0.02
Pr	94	2	5	0.02
Gd	94	1	5	0.02
Sm	93	2	5	0.02
Yb	90	2	8	0.01
Ho	88	2	10	0.02
Eu	85	15	0	0.01
Er	81	19	0	0.01
Lu	78	2	21	0.01
Tm	77	2	21	0.01
Nd	72	1	26	0.02
Tb	60	1	39	0.01
P	84	3	13	13
N	73	1	25	7
C	60	1	39	5
I	15	6	79	3
S	2	0.03	98	0.03
F	1	0.2	99	0.1
Br	0.3	0.02	100	0.02
Cl	0.02	0.0004	100	0.003
Th	90	2	7	1
U	45	0.4	55	0.1

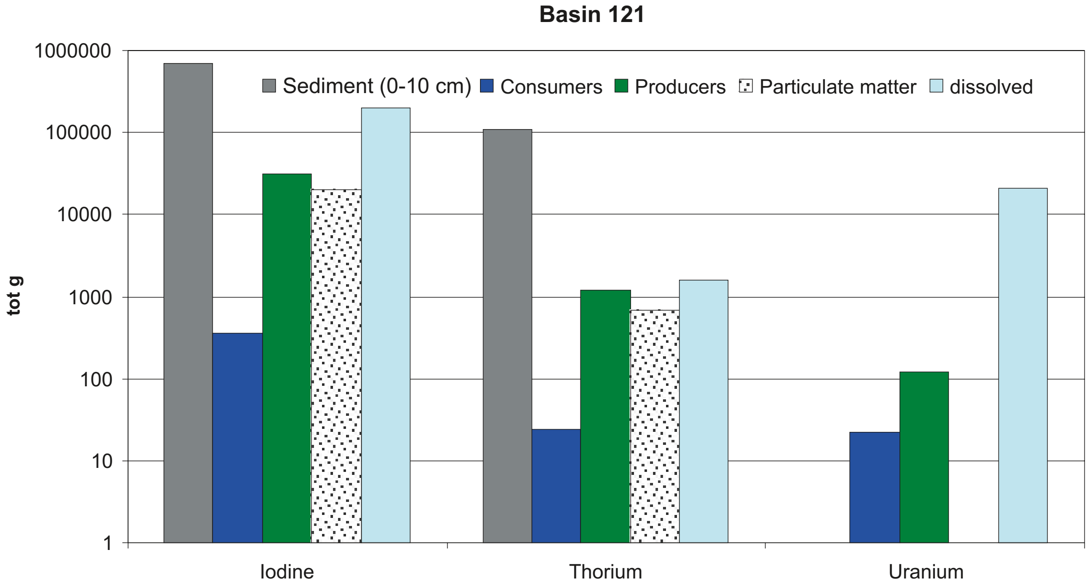

Figure 4-55*. Distribution of iodine, thorium and uranium in biotic and abiotic ecosystem pools in Basin 121, presented as total amount in gram (g). For uranium, data from the sediment and particulate pools are missing.*

4.9 Human population and land use

The following description of the human population and land use at Forsmark is based on /Miliander et al. 2004/. The resulting carbon flows to humans from several drainage areas at Forsmark presented in section 4.9.3, are input data to the terrestrial ecosystem carbon budget described in /Löfgren (ed) 2008/.

4.9.1 Human population in Forsmark

The population density in the Forsmark parish has been very low, but fairly stable, during the period 1993–2002. In total, 168 people lived in the Forsmark parish in 2002. The density was, on average, 1.8 inhabitants per square kilometre. That is 24 times lower than in Uppsala County. 52% of the inhabitants were over 45 years, compared with 40% in Uppsala County.

The inhabitants live in one- or two-family houses (29.9% of the properties) or in farmhouses (28.2%). There are no multi-dwelling houses. In 2002 there were 65 holiday houses in the parish and they are the most frequent type (37.4%). There are in total 1.8 buildings per square kilometre in the parish, compared with 12.7 in Uppsala County. No one- or two-family dwellings were constructed in the parish between 1993 and 2002. However, three building permits for dwellings were granted two years in a row, 1997 and 1998.

The degree of ill health (number of days with sickness benefit or early retirement pension per year and person between 16 and 64) increased remarkably in the parish between 1998 and 2002, from 17.4 in 1998 to 70.8 in 2002. The increase is 300%. Meanwhile, ill health has increased by 30% in Uppsala County. When calculating the ill health figure for a small population, such as the Forsmark parish, one must be aware of the fact that individual ill health has a significant impact on the statistics.

The dominant employment sector in the Forsmark parish is within the electricity supply, and it relates to 79% of the employed day-time population (working in the area). Within the employed night-time population (living in the area) on the other hand, only 19.7% are working in that sector. Thus, there is major inward commuting due to the Forsmark nuclear power plant. The net commuting is positive in the Forsmark parish, meaning that the ingoing commuting is larger than the outgoing. Net commuting is, on the other hand, negative in the Östhammar municipality and Uppsala County. Financial intermediary and business activities is the second largest type of business in the day population and the largest in the night population. Excluding the nuclear power plant, there were in total 17 work places within the parish in 2002. The majority, nine sites, are associated with financial intermediary and business activities.

In the Forsmark parish, 15.3% of the total population was non-employed, which is more than in both the Östhammar municipality and Uppsala County. The early retired and unemployed are proportionately more numerous in the parish than in Uppsala County. This is also true for the category "Other". Students, on the other hand, are proportionately fewer in the parish. The proportion of non-employed inhabitants was approximately the same in 2001 as in 1997. It should be noted that the statistics presented here and in /Miliander et al. 2004/ only cover information available in the year 2003.

4.9.2 Human land use in Forsmark

The land use within the Forsmark area (Forsmark area is in this section defined as the catchment areas northeast of river Forsmarksån water divide (cf. Figure 1-2 in /Miliander et al. 2004/) differs markedly from the average land use in Uppsala County (see Table 4-18). Agricultural land in the Forsmark area is only 4% of the total area, considerably lower than in Uppsala County, where it represents 25%. Furthermore, only 0.04% of the land area is constituted of urban areas (developed areas) compared with 4.9% in Uppsala County. On the other hand, there are far more forests, wetlands and lakes in the Forsmark area. The forest area represents 72.5% of the land area.

Forestry

The forests are heavily influenced by forestry, where large areas are clearcuts of different age and the mean age of the trees in the forests is approximately 65 year (section 4.1.3, /Löfgren (ed) 2008/). About half of the logging products are used for pulp production, and half for timber.

Agriculture

In the Forsmark area, the total agricultural area is 0.84 km^2, where 0.34 km^2 is arable area and 0.50 km^2 is classified as semi-natural grasslands or pastures. There is only one single farm within the Forsmark area and it is not possible to get crop statistics from Statistics Sweden for individual farms. Therefore, data for the parish of Forsmark were used to describe the area and accordingly only 16% of the arable land area is used for cereal and vegetable production, whereas the rest is used for fodder and silage production (see Table 4-19). That corresponds to 6.7% of the total agricultural (field) area in the Forsmark parish. The rest of the agricultural area is assumed to be used for fodder production and grazing. A similar relationship between these land use classes in the Forsmark area would suggest that 0.78 km^2 are used for fodder production and grazing.

The farm density in Forsmark parish is on average only 0.05 farm × km^{-2}, which is considerably less than in the county (0.43 farms per km^{-2}). There were, in total, four farms (> 2 ha) in Forsmark parish in 1999.

The total amount of arable land has in general decreased slightly in Uppsala County between 1990 and 1999, whereas the amount of land classified as grazing has increased, most significantly in Forsmark parish. The total number of farms has decreased as well, but large farms have increased in number, hence farms have become fewer but larger.

Table 4-18. Land use in Uppsala County and the Forsmark area /Miliander et al. 2004/.

Type of land use	Uppsala County		Forsmark area	
	Area (hectares)	Percentage distribution	Area (hectares)	Percentage distribution
Agricultural land	179,940	25.1%		
Arable land			34.0	1.7%
Grazing land			50.0	2.6%
Forest	401,500	55.9%	1,410.5	72.5%
Developed	34,900	4.9%	0.7	0.04%
Pites, mines etc	250	0.0%	0.0	0.00%
Wetlands-mire	17,000	2.4%	206.4	10.6%
Bare rocks, high mountaines, other	65,320	9.1%	66.6	3.4%
Water	19,380	2.7%	163.2	8.4%
Unknown			14.3	0.7%
Total	**718,290**	**100.0%**	**1,945.8**	**100.00%**

Source: Land area for Uppsala län from the report Markanvändning i Sverige, Table 5 /SCB 1998/.
The agricultural area is not divided into arable and grazing area.

Calculated: Land area for Forsmark area from Vegetation Classification /Boresjö Bronge and Wester 2003/.

Table 4-19. Arable land use in the Forsmark parish /Miliander et al. 2004/.

Cultivated crops in the parish of Forsmark (ha)	Percentage of the arable area in average (1995 and 1999)
Seeds, vegetables:	
Rye	0.3%
Barley	15.6%
Oats	0.3%
Potatoes	0.2%
Total seeds and vegetables:	**16.4%**
Fodder, grass:	
Grass, hay or silage, green fodder	71.8%
Pasture/arable land not utilized	0.0%
Pasture, grassland for seed production	9.8%
Bare fallow, untilled arable land	2.0%
Total fodder, grass:	**83.6%**

Crop production

Barley is the dominant seed in Forsmark parish /Miliander et al. 2004/ and the average standard yield of barley in yield survey district 0322 (SKO-area 0322) in which Forsmark is situated is reported in Table 4-20. The standard yield is grain that is gathered at harvest (straw yield and treshing loss are excluded).

Table 4-20. Crop production in Forsmark

Standard yield in SKO-0322, 2000–2007[1]	kg/ha Mean	SD	$gC \cdot m^{-2}$ Mean	SD
Barley	2,874	64	114	3

[1](SCB, 2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007)

Animal production

Production from domestic animals in the Forsmark parish has been obtained from Statistics Sweden and is compiled in /Miliander et al. 2004 / together with calculated values of meat and milk production. The production values have been divided by the total area for grazing and fodder production in the Forsmark parish (see Table 4-21). There are 66 cows and 31 sheep per km^2 in the Forsmark parish. The number of livestock decreases with time in the parish with one exception, beef cattle. The production of beef per unit area is nevertheless 4.5 times lower than in Uppsala County.

According to /Arnesson 2001/, 1.8–3.0 hectares is required to produce the fodder for one cow. That corresponds to a density of approximately 42 cows per km^2. The cattle density in Forsmark parish is higher, which can be explained by the fact that only 63% of the cattle fodder is self-produced by the farms and the rest is purchased /Swedish Dairy Association 2007/.

Horticulture, aquaculture, mineral extraction

There is neither any horticulture nor aquaculture in Forsmark parish. There are no active leases for mineral extraction.

Water supply

The water use at Forsmark nuclear power plant represents most of the total water use within Forsmark parish (93.2%). As the power plant uses water from the river Forsmarksån, most of the withdrawal in the parish is surface water.

The number of work places in the parish is very low, only 0.5% of the work places in Östhammar municipality. The water use within the industry sector, excluding the nuclear industry is, therefore, estimated to be very low (0.2%). In Sweden, industry generally contributes approximately 65% of the water use. The total withdrawal of water in the parish is calculated to be 276,000 m^3 per year.

Table 4-21. Production of animalia (live biomass and utilized meat), milk and eggs in the Forsmark parish (average figures for the specific years 1995 and 1999) presented as carbon per area and year.

Domestic animal	Production (live biomass $mgC \cdot m^{-2} \cdot y^{-1}$)	Meat production ($mgC \cdot m^{-2} \cdot y^{-1}$)	Milk production ($mgC \cdot m^{-2} \cdot y^{-1}$)	Egg production ($mgC \cdot m^{-2} \cdot y^{-1}$)
Beef	1,160	366	7,343	
Sheep	79	18		
Pigs	0	0		
Chicken	93	50		90
Total		**434**	**7,343**	**90**

Coastal fishing

There are approximately 20 licensed fishermen in Östhammar municipality and they undertake coastal small-scale fishing for local consumption, selling their catch to local grocery stores. None of them seem to live in Forsmark parish.

The catch per unit area is considerably lower in the EU-grid for fisheries off the coast of Uppsala County compared with the squares off the southeast of Sweden. The fisheries are most productive in EU-square 47G9, approximately 115 km southeast of the Forsmark area, with a mean catch of 781 kg km^{-2} (1995–2002), according to data from National Board of Fisheries. In EU-square 49G8, which includes Forsmark parish, the catch has on average been 224 kg km^{-2}. For comparison, the catch in EU-square 43G6, in which the Laxemar-Simpevarp area is located, has on average been 1,730 kg km^{-2}. The two dominant species in the grid off-shore of the coast of Uppsala County are Baltic herring and sprat.

Only two commercial receivers of fish are located in Uppsala County, one in Öregrund and one in Östhammar. In 2002, these two received only 8.3% of the weight of fish that the fishermen in Östhammar caught that year. This figure is in consistence with the information that the fishermen mainly sell their fish to local stores. However, it is also possible that they sell their fish to a commercial receiver outside the county border. The fish received by the commercial reciever were used for consumption.

Outdoor life

Wildlife hunting

According to the figures from the County Administrative Board of Uppsala, moose hunting is more intensive in Forsmark parish than in the municipality and the county as a whole (0.53 individuals × km^{-2}, compared with 0.37 and 0.35, respectively, in 2003). No obvious trend can be seen in the data between 1999 and 2003. The number of harvested moose per km^2 reached a peak in 2000–2001. During 2002–2003 the number per km^2 decreased. The harvest was almost equal in Forsmark parish, Östhammar municipality and Uppsala County in 1999, but since then the harvest has been more intensive in Forsmark parish.

The estimated figures concerning the harvest of roe deer and hares in Forsmark parish are based on the figures for the hunting zone of Östhammar hunting association (*Sw: Östhammars jaktvårdskrets*), obtained from the Swedish Association for Hunting and Wildlife Management.

According to these figures, the harvest of roe deer has on average been 1.9 individuals km^{-2} in the parish during the period 1997–2001. The harvest of European hare (*Sw: fälthare*) has on average been 0.28 individuals per square kilometre in the parish during the period 1997–2001. The harvest of Mountain hare (*Sw: skogshare*) has on average been 0.13 individuals per square kilometre in the parish during the period 1997–2001.

Picking of wild berries and mushrooms

Consumption of berries and fungi are two of several potential pathways for human exposure to radionuclides, in case of a radionuclide release. By estimating the yield of berries and fungi, the potential radionuclide transfer to humans by consumption can be estimated.

Neither berry nor fungus yields have been estimated by direct field surveys. An attempt to estimate the yield by using a model that includes other site-specific information to infer the production of berries is presented in /Löfgren (ed) 2008/. Edible fungi were defined as those species that are edible with or without parboiling before consumption. The mean annual yield of edible fungi was estimated from /Kardell and Eriksson 1987/. The results are presented in /Löfgren (ed) 2008/.

Fishing

The coast of Uppsala County attracts an increasing amount of recreational fishermen, even though the river Dalälven is the most attractive fishing water in the county. Two attractive fishing-waters have been identified in Forsmark parish. The first is Södra Åsjön, a fishing-ground that requires a fishing licence, and the second is the waters around the Forsmark power plant. There is a fishing license area called Forsmarks fishing license area, which includes Lake Fiskarfjärden. There is no sport fishing club registered in Forsmark parish.

Other activities

Other out door activities practiced in Forsmark parish are bird watching and hiking. There are two attractive spots for bird watching within the parish. These are Biotestsjön at Forsmark nuclear power plant and Kallrigafjärden. There are three nature reserves in Forsmark parish and they are most likely used for hiking. Furthermore, there are two smaller campsites within Forsmark parish and three boat renters /Miliander et al. 2004/.

4.9.3 Human consumption

The human consumption of animal products and vegetables originating from different drainage areas in Forsmark has been calculated based on the land use allocation in each drainage area. The figures provide input data to the terrestrial carbon ecosystem budget in /Löfgren (ed) 2008/. The figures are presented in Table 4-22.

Human consumption of crops

The human consumption of crops is assumed to be equal to the standard yield of barley in the yield survey district (SKO-area 0322), see Table 4-20. The production in each drainage area has been estimated by multiplying the standard yield by the estimated area for production. According to Table 4-15, only 16.4% of the arable area in the Forsmark parish is used for production of cereals and vegetables for human consumption. This figure has been applied to the drainage areas. Only one drainage area (Eckarfjärden) includes some arable area.

Human consumption of beef

Cattle – a regional generic case

The consumption of beef has been estimated for each drainage area based on the meat production for Forsmark parish (see Table 4-22) and the area for fodder production and grazing in each drainage area.

Human consumption of game-meat

The species that are mainly hunted for consumption are moose, roe deer and hare. The average harvest of moose in Forsmark parish and the average harvest of roe deer and hare in Östhammar hunting association that are reported in /Miliander et al. 2004/ are applied to the drainage areas of Forsmark. The human consumption (utilized carcass weights) are calculated according to the presentation given in /Miliander et al. 2004/.

Table 4-22. The human harvest and consumption according to the "Regional generic case" of Forsmark.

Harvest and human consumption per year (gC/år)		Vambors-fjärden		Subarea: Fräkengropen		Subarea: Stocksjön		Subarea: Bolundsfjärden		Gällsboträsket		Eckarfjärden		Lake 2:2		Kungsträsket		Subarea: Norra Bassängen		Subarea: Graven		Puttan	
"Regional generic case"		mean	± SD	mean	± SD	mean	± SD	mean	± SD	mean	± SD	mean	± SD	mean	± SD	mean	± SD	mean	± SD	mean	± SD	mean	± SD
Hunting of moose	Harvest[1]	6,271	917	1,849	270	2,762	404	24,811	3,628	28,809	4,212	28,233	4,128	897	131	1,646	241	4,276	625	5,111	747	2,953	432
	Consumption[2]	2,759	403	814	119	1,215	178	10,917	1,596	12,676	1,853	12,423	1,816	395	58	724	106	1,881	275	2,249	329	1,299	190
Hunting of roe deer	Harvest[1]	2,589	714	764	210	1,140	314	10,243	2,824	11,893	3,278	11,656	3,213	370	102	679	187	1,765	487	2,110	582	1,219	336
	Consumption[2]	1,139	314	336	93	502	138	4,507	1,242	5,233	1,443	5,129	1 414	163	45	299	82	777	214	928	256	536	148
Hunting of European hare	Harvest[1]	11	4.8	3.2	1.5	5.4	2.4	41.8	18.7	31.2	14.0	33.7	15.1	1	0	0.8	0.4	11.1	5.0	12.8	5.8	10.1	4.5
	Consumption[2]	4.7	2.1	1.4	0.6	2.4	1.1	18.4	8.2	13.7	6.2	14.8	6.6	0	0	0.4	0.2	4.9	2.2	5.7	2.5	4.4	2.0
Hunting of Mountaine hare	Harvest[1]	17	20	5.0	6.0	7.3	8.7	68	81	85	102	82	98	2.8	3.3	5.2	6.2	10	12	12	15	6.3	7
	Consumption[2]	7.5	9	2.2	2.6	3.2	3.8	30	36	38	45	36	43	1.2	1.5	2.3	2.7	4.5	5.4	5.5	6.6	2.8	3.3
Domestic animals	Harvest[1]	0		0		3,753		0		15,855		137,508		0		0		0		0		0	
(cattle + sheep)	Consumption[2]	0		0		1,163		0		4,915		42,627		0		0		0		0		0	
Milk	Production and consumption	0		0		22,252		0		94,017		815,387		0		0		0		0		0	
Crop	Production and consumption	0		0		0		0		0		243,961	6,420	0		0		0		0		0	

[1] Live biomass

[2] Utilized carcass weight

5 Near-surface transport conditions and integration with the bedrock system

5.1 Integration needs and data exchanges

5.1.1 Bedrock-surface systems integration

The integration and linking of the bedrock and surface systems is a multidisciplinary task involving all modelling disciplines dealing with water flow and transport of particles and dissolved species. The aim of the integrated system descriptions is to describe the conceptual understanding and properties of the deep rock volumes and the upper parts of the rock, the transition between the rock and the regolith, and finally the regolith itself. The ultimate goal of this integration is to provide a context and specific input data for descriptions of solute transport in rock and regolith. Solute transport scenarios of interest include descriptions of transport from the deep rock to the surface system, primarily radionuclide transport associated with hypothetical releases from the planned repository, but also transport from the surface system to the rock. The analyses of transport from surface to rock are mainly focused on substances with potential negative influence on the conditions in the repository.

One aim of the present chapter is to describe the various aspects of the surface system that are of importance for the bedrock modelling. Specifically, these aspects include the following parameters, models and observations.

- Parameters describing the properties of the upper part of the integrated rock-regolith model domains. In the site descriptive modelling, integrated model domains are considered primarily within the hydrogeological and hydrogeochemical modelling.
- Models produced and presented within the surface system modelling that are used as direct inputs to hydrogeological and hydrogeochemical models. In particular, these inputs include geometric descriptions such as the topographic and shoreline displacement models.
- Other inputs used as a basis for setting (top) boundary conditions, i.e. groundwater pressure and flux data for use in hydrogeological models and chemical compositions of infiltrating groundwater in hydrogeochemical models.
- Measured and modelled data in surface system descriptions that are used for data interpretation and/or otherwise as supporting evidence in the development of bedrock models. For example, hydrogeological and chemical data providing information on discharge of deep groundwater are important for the bedrock modelling.

The Digital Elevation Model (DEM) describing the topography and bathymetry in the Forsmark area (see section 4.2.1) constitutes a basic input to several modelling activities. A DEM with a horizontal resolution of 10 m was presented in /Brydsten and Strömgren 2004/. This DEM is classified due to national security reasons, which implies restrictions on its use. Recently, a non-classified DEM with a resolution of 20 m was presented /Strömgren and Brydsten 2008/. This non-classified DEM is used as a basis for all hydrological and hydrogeological modelling in SDM-Site Forsmark.

In addition to describing data and model exchanges of the types listed above, this chapter also seeks to convey a broader picture of the bedrock-surface systems integration work performed as a part of the site descriptive modelling. Specifically, the aim is to present the available site data and modelling results of particular importance for this integration. This means that the following material is covered in the remainder of this chapter.

- Summaries of the geological, hydrogeological and hydrogeochemical descriptions of the bedrock, with particular emphasis on the upper parts of the rock. These are to large extent based on the corresponding discipline-specific chapters in the Forsmark SDM-Site report /SKB 2008/, i.e. Chapters 5, 8 and 9 for geology, hydrogeology and hydrogeochemistry, respectively.
- Available site-specific data on transport properties and other parameters that can be used to support the assessment of site-specific transport conditions. This part of the description is focused on the Quaternary deposits.
- Results of conceptual and mathematical modelling of solute transport in the integrated bedrock-surface system. Transport modelling has been performed both in direct connection with the SDM work, using the SDM flow models, and as separate activities investigating specific aspects of transport at the site.

Whereas the material taken from the Forsmark SDM-Site report, as well as the surface system description presented in this report, represent the final site description delivered to the SR-Site safety assessment and other users, the transport modelling described below should be regarded as a work in progress. Numerical modelling and analysis of data on transport parameters are still ongoing, and final reporting of these activities will be done in connection with the safety assessment SR-Site.

5.1.2 Conceptual models for solute transport

The conceptual model for solute transport from a repository in the deep rock to the surface system and further in and between the surface ecosystems is described in section 3.1.1 (see Figure 3-2). Figure 5-1 and Figure 5-2 show two types of conceptual models developed within the site descriptive modelling, i.e. a flowpath-based model similar to that in Figure 3-2 and a compartment model based on the different types of systems considered in the ecosystems modelling.

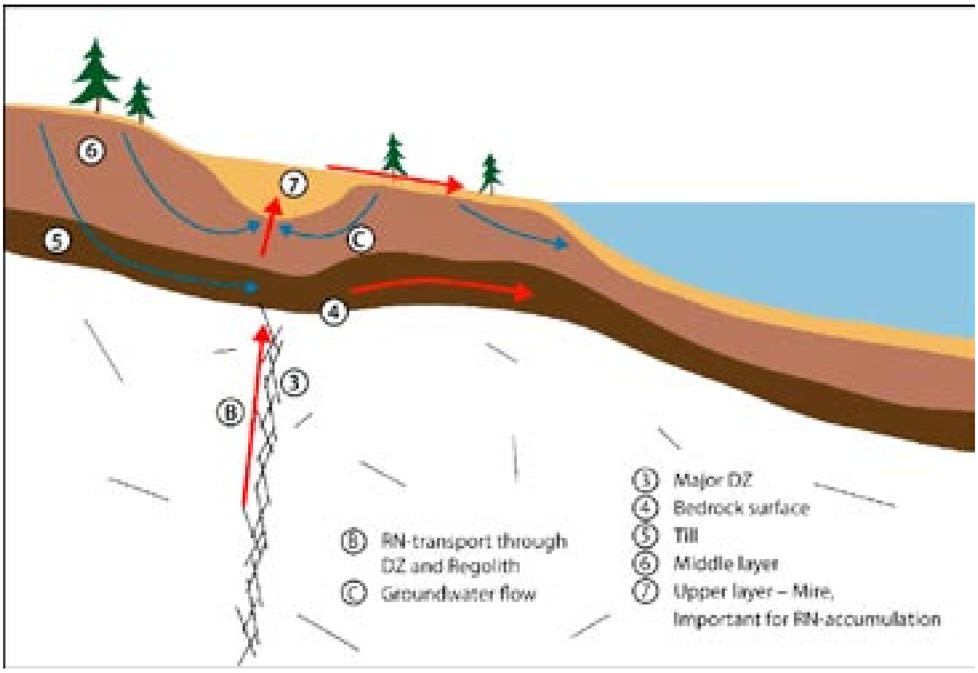

Figure 5-1. *Example illustration of possible solute transport paths to a recipient from a source in the bedrock.*

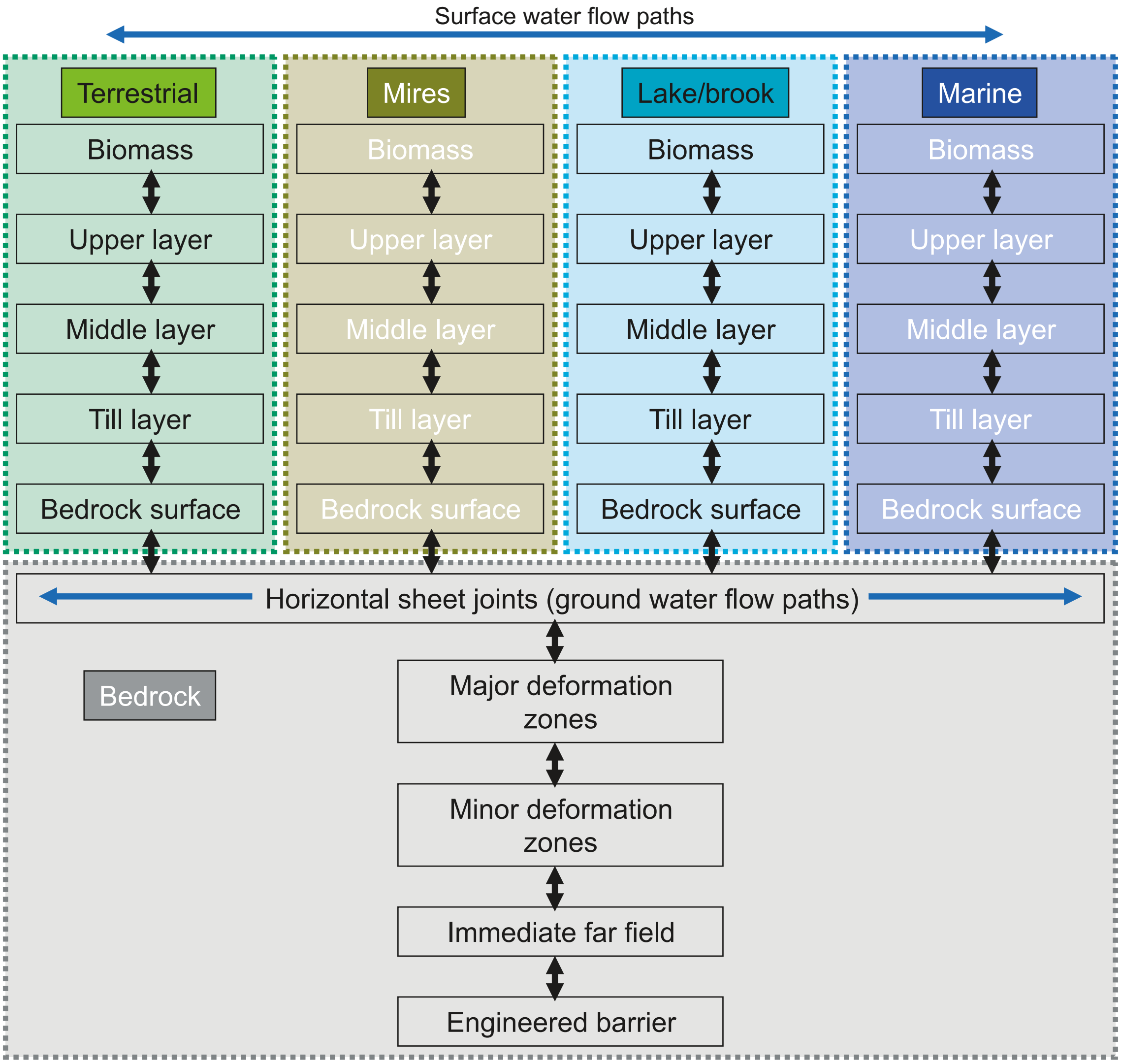

Figure 5-2. *Conceptual illustration of transport domains at the Forsmark site.*

Figure 5-1 illustrates alternative flow and transport paths in the uppermost part of the system, i.e. that solutes coming from the rock could be transported vertically in the regolith up to the ground surface (in this case in a mire), or horizontally in the bedrock-regolith interface zone towards the sea. In Figure 5-2, the various domains a solute could go through along its way from the rock to the surface are represented by a set of compartments. This type of conceptualisation is often useful for organising and parameterising a model. Essentially, the subdivision of the transport model in Figure 5-2 into compartments is based on geological distinctions. This is practical because characterization is usually organised in the same way, i.e. based on different types of Quaternary deposits, rock types and structures in the rock (different types/sizes of fractures and deformation zones).

The conceptual models discussed above consider the upward transport of solutes from a hypothetical repository in the deep rock, whereas transport scenarios associated with, for example, the composition of the groundwater flowing downwards to the rock are not described. Similar flowpath-based or compartment models for downward transport through the regolith and further into the rock should describe groundwater recharge areas instead of the discharge areas where upward flow and transport take place. For the regolith, this would imply a simpler stratigraphy, i.e. till on bedrock or just exposed bedrock, than in the discharge case, whereas transport in the rock to larger extent would take place in smaller structures than the ones often associated with discharge areas.

Figure 5-2 also illustrates the key role of the horizontal fractures/sheet joints in the bedrock at Forsmark, which, as indicated in Figure 4-10 and explained in some detail in section 5.2 below, may short-circuit flow paths from the deep rock and divert them towards the sea. This effect is illustrated by the red arrows in Figure 5-3. The main implication of this would be that there are no discharge areas within the present land area for flow paths from the deep rock in the target area (to be defined below), and, consequently, that the terrestrial, mire and lake/brook compartments would be by-passed in a model for the present conditions. The horizontal fractures/sheet joints have a similar effect on the downward transport from the surface to the rock, see Figure 5-4.

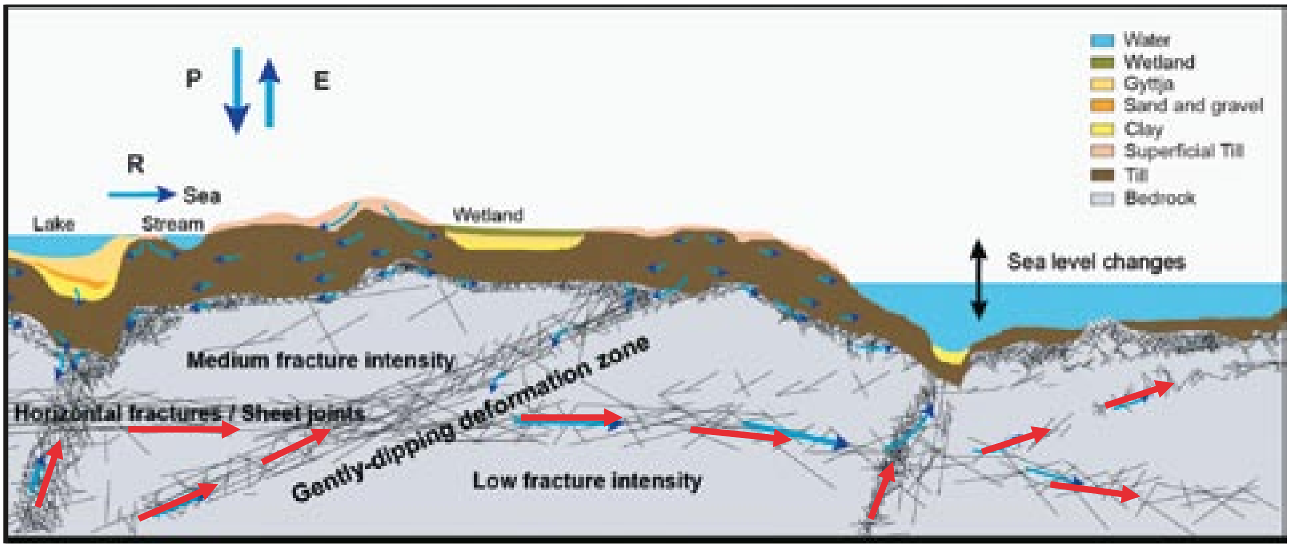

Figure 5-3. Possible influence of horizontal fractures/sheet joints on solute transport from the deep rock. Red arrows indicate solute transport directions (only directions, not magnitudes).

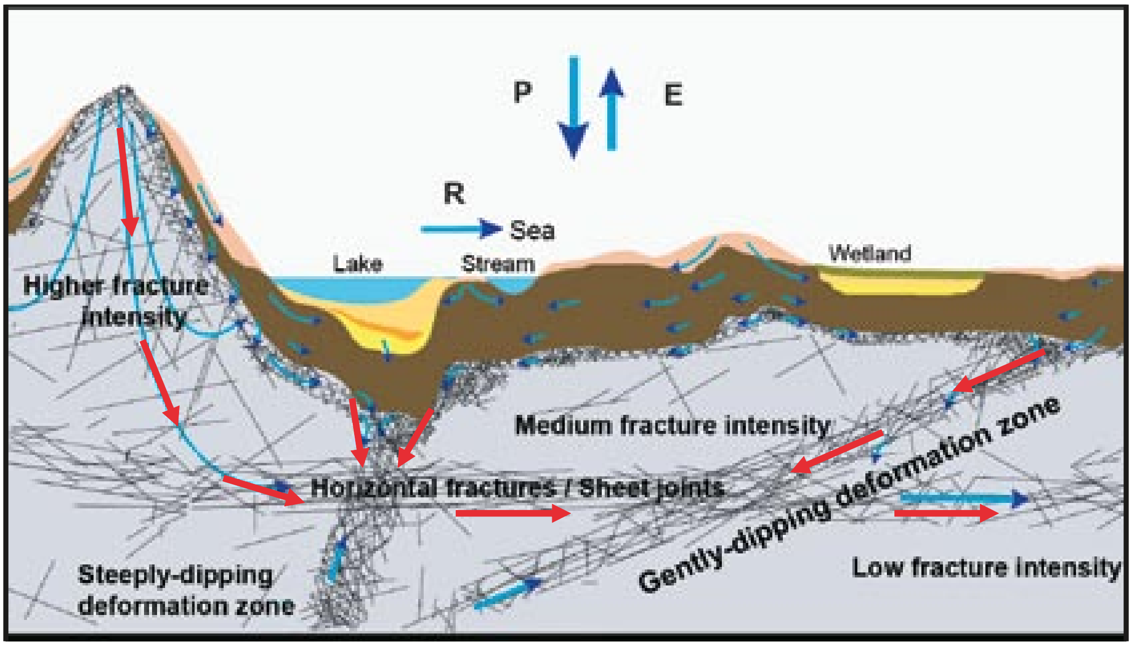

Figure 5-4. Possible influence of horizontal fractures/sheet joints on solute transport from the surface. Red arrows indicate solute transport directions (only directions, not magnitudes).

5.1.3 Interfaces between bedrock and surface systems

For several of the disciplines involved in the SDM work, e.g. geology, hydrogeology and hydrogeochemistry, a distinction is made between the surface system and the bedrock system. The reasons for this distinction are 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. The delimitation between the surface and bedrock systems is, of course, artificial and somewhat arbitrary /SKB 2008, Follin et al. 2007/.

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

The handling of the interfaces in the hydrogeological models are described in the bedrock hydrogeology modelling reports /Follin et al. 2007, 2008/ and in the reports describing the modelling of the near-surface hydrogeology /Johansson 2008, Bosson et al. 2008/. As indicated in Figure 5-5, the numerical modelling of groundwater flow in the bedrock and in the surface system were performed with the ConnectFlow and MIKE SHE tools, respectively. The ConnectFlow model had its bottom boundary at a depth of 1,200 m. Different depths of the bottom boundary in the MIKE SHE model, i.e. from 150 m to 600 m below the ground surface, were tested in the modelling. The model selected for use in the detailed modelling, including the transport simulations discussed in section 5.4, had a no-flow boundary at a depth of 600 m. Thus, a relatively large depth interval in the rock was included in both models.

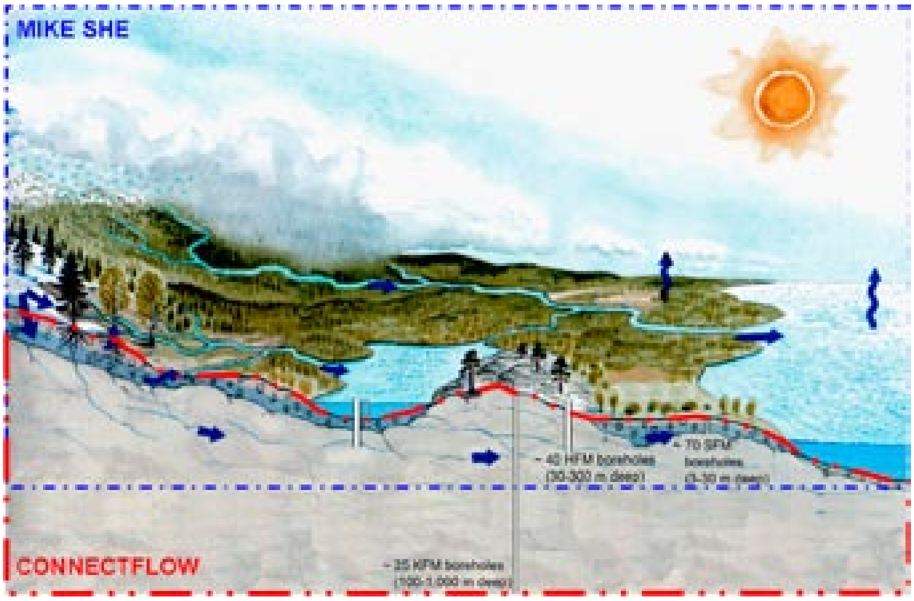

__Figure 5-5.__ Illustration showing how the modelling of the hydrologic cycle is divided into a surface-based system and a bedrock-based system. The former is modelled with the MIKE SHE numerical modelling tool and the latter with the ConnectFlow modelling tool. Reproduced from /Follin et al. 2007/.

5.2 Geology, hydrogeology and hydrology

5.2.1 References and terminology

Central to the description of the bedrock is the geological model which provides the geometrical context in terms of the characteristics of deformation zones and the rock mass between the zones. Using the geometric component in the bedrock geological models as a basis, descriptive models for other geoscientific disciplines (e.g. hydrogeology, hydrogeochemistry and bedrock transport properties) have been developed.

In this section, results of the bedrock modelling are summarised together with some aspects of the bedrock-surface systems integration. For convenience, the main bedrock and surface system modelling reports used as input here are listed in Table 5-1. The SDM report /SKB 2008/ chapters summarising the modelling within each discipline are also indicated in the table together with the relevant discipline-specific sections of the present report.

The term "target area" is used frequently in the bedrock descriptions, and therefore needs to be explained. As shown in Figure 5-6, the target area is the north-western part of the Forsmark candidate area. It was selected as the target area for the complete site investigation work (i.e. the later stage of the site investigation), which implies that it has a higher density of rock boreholes than the rest of the candidate area. This also means that the repository engineering work is focused on this area; if SKB selects Forsmark as repository site, the continued planning and analyses, and the resulting application for building and operating a repository will be for a location within the target area. Sometimes, e.g. in the geological description below, also the term "target volume" is used, see /SKB 2008/.

Also the investigations of the surface system are to some extent concentrated to the target area, especially the more recent investigations and monitoring installations (e.g. groundwater monitoring wells installed during the complete site investigations stage). It is noted that Lake Bolundsfjärden is located within the target area, whereas the other large lakes, Lake Eckarfjärden and Lake Fiskarfjärden, are situated outside this area. However, from a surface hydrology point of view, Lake Eckarfjärden and Lake Gällsboträsket and their terrestrial catchment areas are located upstream Lake Bolundsfjärden, which implies that they affect the conditions within the target area and hence must be (and are) included in the ongoing hydrological and hydrochemical monitoring.

Table 5-1. Main references used as a basis for the geological, hydrogeological and hydrogeochemical descriptions in the present chapter.

	SDM-Site/Surface system report ref.	Background reports
Geology		
Bedrock	Chapter 5 *	R-07-15 /Olofsson et al. 2007/ R-07-45 /Stephens et al. 2007/
Surface	Sections 3.5, 4.4 **	R-08-04 /Hedenström and Sohlenius 2008/
Hydrogeology		
Bedrock	Chapter 8 *	R-07-49 /Follin et al. 2007/ R-08-23 /Follin et al. 2008/
Surface	Sections 3.4, 4.3 **	R-08-08 /Johansson 2008/ R-08-09 /Bosson et al. 2008/
Hydrogeochemistry		
Bedrock	Chapter 9 *	R-08-47 /Laaksoharju et al. 2008/
Surface	Sections 3.6, 4.5 **	R-07-55 /Tröjbom et al. 2007/

* SDM-Site report /SKB 2008/

** Sections of this report

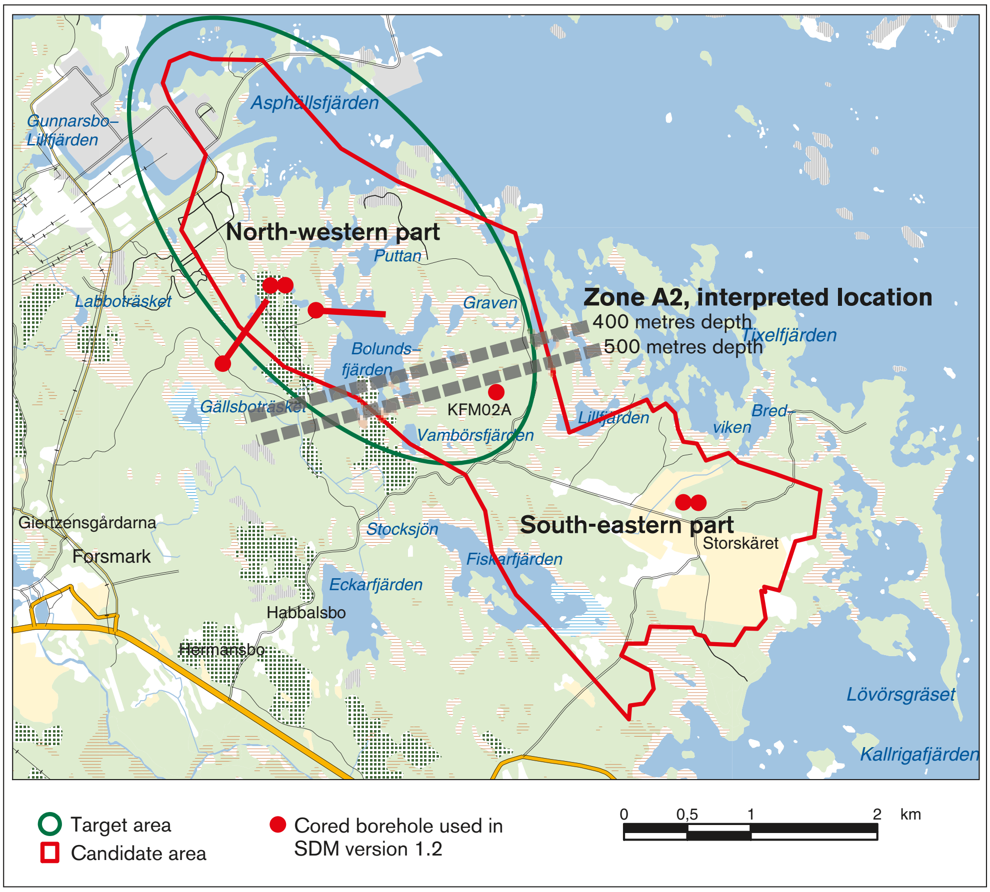

Figure 5-6. The north-western part of the candidate area is referred to as the "target area", since it was selected as the target area for the complete site investigation work /SKB 2008/.

The bedrock investigations at the site and the presentations of investigation and modelling results are in many cases organised in terms of the different drill sites in the investigated area. Some of the drill sites are also mentioned in the following. Therefore, the drill sites, labelled DS1 to DS12 as given by the numbering of the core-drilled borehole(s) at each site, are shown in Figure 5-7. A comparison with Figure 5-6 shows that most of the drill sites indeed are located within the target area. Not only cored boreholes are located at the drill sites; both percussion-drilled boreholes in rock and groundwater monitoring wells in the regolith have been installed at most drill sites. As shown in Figure 5-7 there are also several percussion-drilled boreholes outside the drill sites. This is also the case with the groundwater monitoring wells (not shown in the figure).

5.2.2 Geological description

The geological descriptions of the regolith and the bedrock are presented in /Hedenström and Sohlenius 2008/ and /Stephens et al. 2007/, respectively, and associated background and higher-level reports (see Table 5-1). The general description of Quaternary deposits that make up the regolith at Forsmark is summarised in sections 3.5 and 4.4 of the present report and needs not be repeated here. However, for the flow and solute transport from rock to surface and vice versa it is interesting to note that the rock is overlain by till in most of the area, and that till is also the dominant Quaternary deposit at the ground surface.

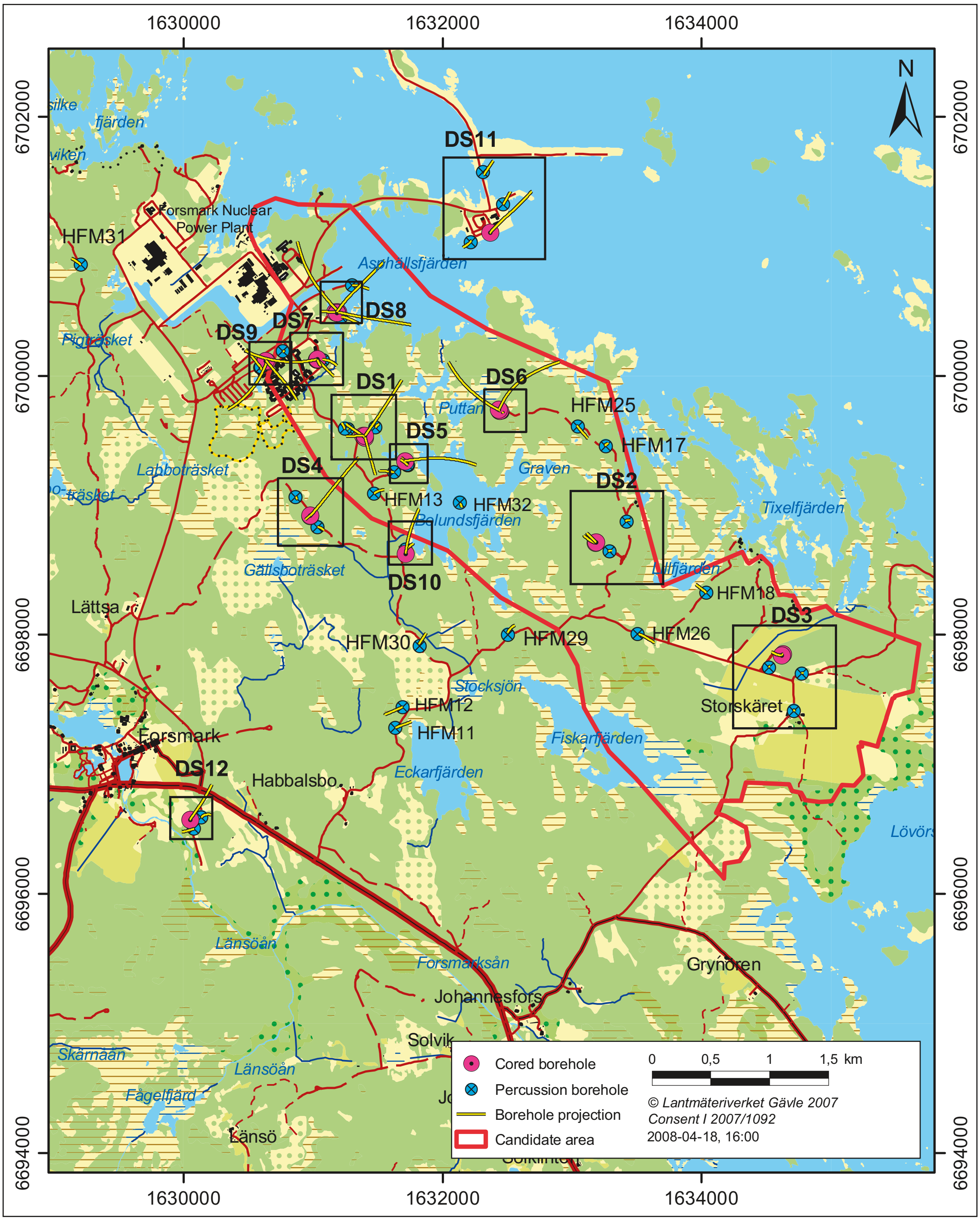

Figure 5-7. *Drill sites in the Forsmark site investigation area /SKB 2008/. The drill sites are labelled DS1 to DS12, where the numbering is the same as that of the core-drilled borehol(s) at each site (for example, KFM01 is located at DS1). The projection of each cored borehole on the ground surface (due to their inclination) and the percussion-drilled boreholes within and outside the drill sites are also shown.*

Thus, the properties of the till are important for the groundwater recharge and discharge of the bedrock, and likely also for other processes governing solute transport (e.g. retention processes such as sorption). Some key investigations and results related to the till properties are illustrated below. However, as described in section 4.4 (see Table 4-5), other, mostly fine-grained Quaternary deposits such as clay and clay gyttja are found below lakes and wetlands, which means that the properties of these materials affect flow and solute transport in these areas.

The bedrock geology of the Forsmark site is described in /Stephens et al. 2007/; only a brief summary is provided here to frame the topic of this section, namely the properties governing water and solute transfer between the deep rock and the surface. The Forsmark area is situated within an ancient Precambrian crystalline terrain, referred to as the Fennoscandian Shield. Forsmark lies within the southernmost part of a complex structural domain with predominantly high-grade metamorphic rocks. In the regional structural context, the target area is located within a tectonic lens that developed more than 1,850 million years ago when the rock units were situated at mid-crustal depths and were affected by penetrative but variable degrees of ductile deformation. The bedrock inside the lens at the depths of a potential repository is relatively homogeneous, whereas the lithology and deformation is more variable outside the lens.

The deterministic geological modelling of the bedrock addressed three aspects that serve the needs of different users: rock domains, deformation zones and fracture domains. The identification and description of fracture domains also provided a basis for the statistical modelling of fractures and minor deformation zones, so-called geological discrete fracture network modelling (DFN). The identification of rock domains was initiated at the surface and made use of the division of the bedrock during the bedrock mapping work into two different types of rock units defined on the basis of the composition (and to some extent the grain size) of the dominant rock type and the degree of bedrock homogeneity in combination with the style and degree of ductile deformation.

Fourteen rock domains have been recognised inside the local model volume. Most of these domains are situated outside the tectonic lens and target volume. Key domains RFM029 and RFM045 occur inside the tectonic lens and target volume; the geological properties of the rock domains have been presented in Appendix 14 in /Stephens et al. 2007/. Rock domain RFM029 is the volumetrically most significant domain inside that part of the Forsmark tectonic lens that is situated inside the target volume for a potential repository. It is estimated that medium-grained metagranite comprises 74% of the RFM029 domain, pegmatite and pegmatitic granite 13%, Group C fine- to medium-grained metagranitoid 5%, and amphibolite and other minor mafic to intermediate rocks 5% /Stephens et al. 2007/.

Early in the borehole data interpretation work, it was recognised that the upper part of the bedrock inside the tectonic lens at Forsmark contains an increased frequency of sub-horizontal and gently dipping fractures with apertures. A systematic assessment of the variation in the frequency of particularly open and partly open fractures with depth along each borehole contributed significantly to the division of the bedrock between deformation zones into fracture domains /Olofsson et al. 2007/. On the basis of the borehole data, a 3D geometric model for four of the six fracture domains inside the target volume (FFM01, FFM02, FFM03 and FFM06) was constructed (Figure 5-8). Since few data are available outside this volume and the character of fracture domains FFM04 and FFM05 are poorly constrained, no model for these two fracture domains could be constructed /Olofsson et al. 2007/.

In addition to providing a 3D representation of the modelled fracture domains and deformation zones, Figure 5-8 also contains information on the fracture mineralogy characterizing the different fracture domains. Data on fracture mineralogy are central to the development of solute transport models for the fractured rock; for more information on the fracture mineralogy, see /Sandström et al. 2008/. Sections through the fracture domain model are shown in Figure 5-9. It can be noted that the thickness of fracture domain FFM02, which, as explained in more detail below, contains the more fractured upper rock within the target area, decreases in the direction of the cooling water intake canal and drill site 8 (Figure 5-7).

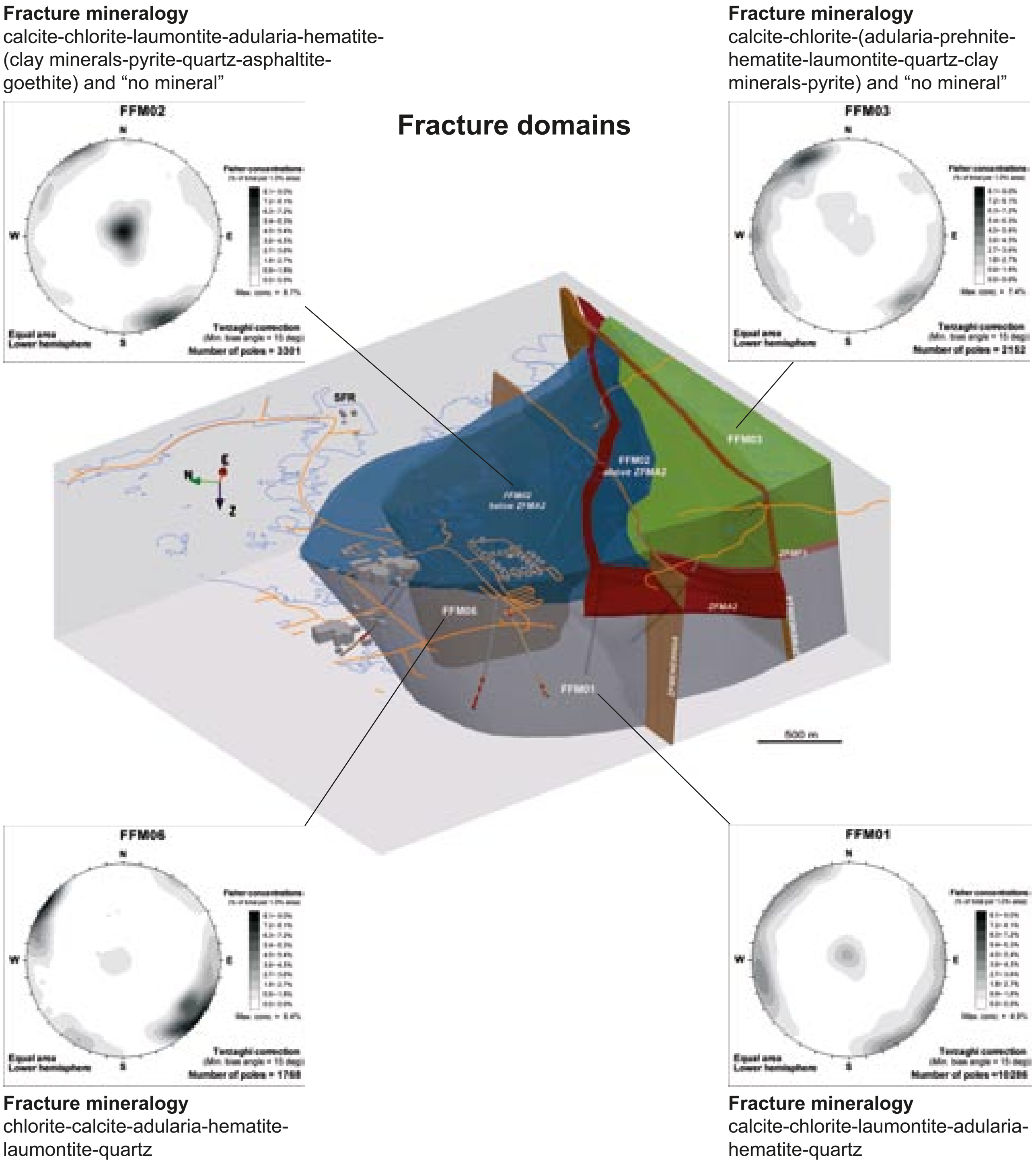

Figure 5-8. Three-dimensional model for fracture domains FFM01, FFM02, FFM03 and FFM06 in the north-western part of the Forsmark tectonic lens, viewed towards the ENE. The local model block is shown in pale grey. The gently dipping and sub-horizontal zones A2 and F1 as well as the steeply dipping deformation zones ENE0060A and ENE0062A are also shown. The fracture mineralogy in each domain is also shown and the order of mineral presentation reflects the order of abundance. The figure is reproduced from /SKB 2008/.

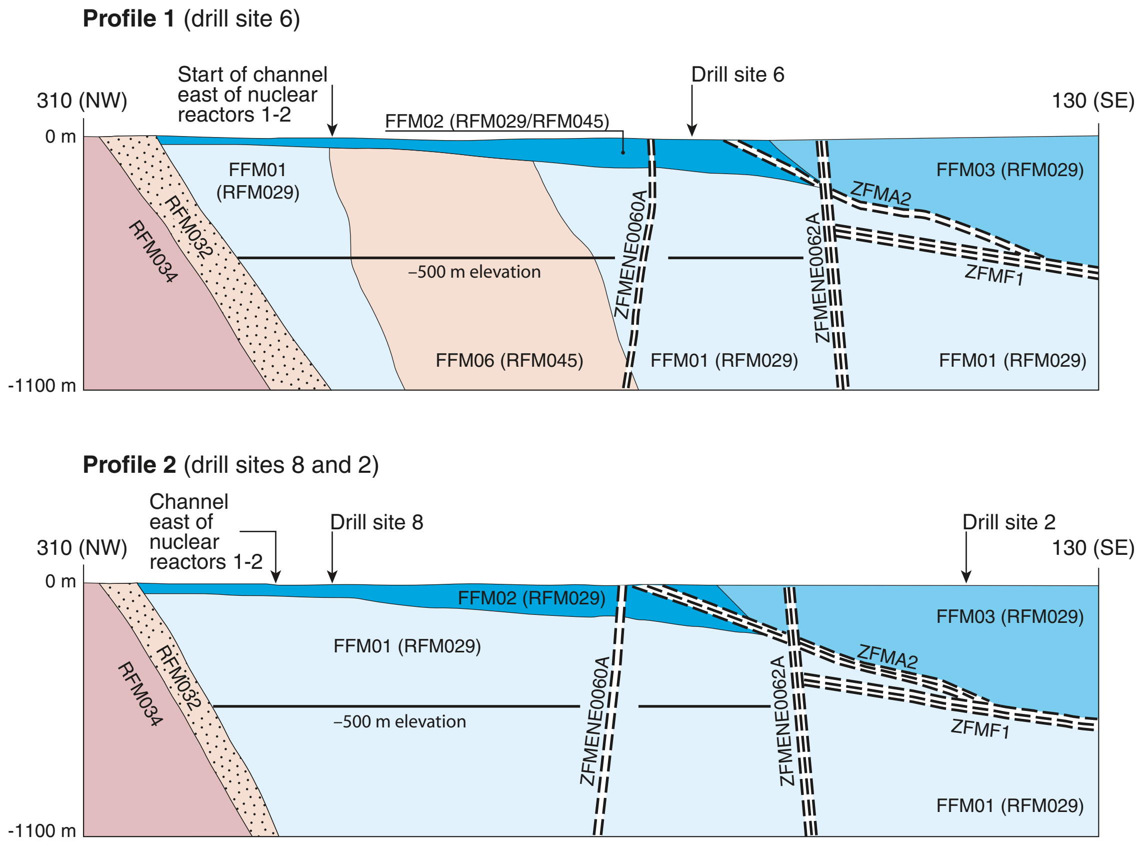

Figure 5-9. *Simplified profiles in a NW-SE direction that pass through drill sites 2 and 8 (lower profile) and drill site 6 (upper profile). The labelled fracture domains occur inside rock domains RFM029 and RFM045. Only deformation zones referred to as high confidence zones are included in the profiles (figure taken from /Olofsson et al. 2007/).*

As mentioned above, the upper part of the bedrock volume in the target area for a potential repository is distinguished from the deeper parts of the bedrock in terms of fracture frequency (Chapter 5 in /Olofsson et al. 2007/). Therefore, a separate fracture domain, FFM02, has been identified to describe this part of the model volume. The FFM02 domain is situated close to the surface inside the target volume, directly above fracture domains FFM01 and FFM06 (Figures 5-8 and 5-9). The domain is characterized by a complex network of gently dipping and sub-horizontal, open and partly open fractures, which are known to merge into at least one deformation zone in the central area of interest. The transition from more fractured bedrock close to the surface to less fractured bedrock at depth (domain FFM01) takes place deeper down as the distance from zone ZFMA2 decreases. Thus, the special character of the proposed surface fracture domain FFM02 is not solely determined by elevation.

The occurrence of this domain at greater depths beneath ZFMA2 is related to an inferred higher frequency of such older fractures in the vicinity of this zone, to higher rock stresses beneath zone ZFMA2 or to a combination of these two possibilities. The gently dipping and sub-horizontal fractures are oriented at a large angle to the present-day minimum principal stress in the bedrock. This relationship favours their reactivation as extensional joints in the present stress regime, the development of conspicuous apertures along several fractures, and the release of high stress. Thus, the uppermost part of the bedrock is characterized by a high frequency of gently dipping and subhorizontal fractures; as shown in Figure 5-10, this fracturing has been observed in connection with construction work. This fracture domain contains the open and hydraulically connected fractures and stress release fractures, and the vertical extension of this upper domain appears to increase towards SE.

Figure 5-10. Observed near-horizontal and subvertical fracturing in near-surface rock along the Forsmark cooling water inlet canal. Pictures reprodued from /Martin 2007/.

Concerning the fracture mineralogy of the FFM02 domain, it is noted that calcite, chlorite, laumontite, adularia, hematite and quartz are present along the different sets of fractures (Figure 5-8). Clay minerals, pyrite, asphaltite and goethite, which all belong to the younger generations of minerals, are more conspicuous in fracture domain FFM02 relative to all the other domains. Furthermore, fractures without any mineral coating or filling ("no mineral") are also prominent in FFM02. However, there remain some uncertainties concerning the mapping of these fractures (see /Stephens et al. 2007/), and a complementary investigation has been initiated to shed more light on these structures. The older minerals epidote and laumontite, which formed at different times in the geological evolution, occur along the three different sets of fractures in FFM02, while clay minerals, pyrite and goethite in the younger generations and "no mineral" are most conspicuous along the gently dipping to sub-horizontal fractures /Stephens et al. 2007/.

Fracture domain FFM01 (Figures 5-8 and 5-9) is situated within rock domain RFM029 inside the target volume. It lies north-west of the steeply dipping zone NE0065, beneath the gently dipping or sub-horizontal zones A2, A3 and F1, and beneath a depth that varies from c. 40 m (large distance from zone A2) to c. 200 m (close to zone A2). Relative to the overlying fracture domain FFM02, the bedrock in this domain shows a lower frequency of fractures with apertures. Furthermore, gently dipping or sub-horizontal fracture zones are also uncommon inside this part of rock domain RFM029.

Excavation of the Quaternary deposits during preparation of drill site 5 revealed freshly fractured bedrock with displacement of bedrock blocks and the occurrence of several fractures filled by glacial sediment /Hedenström and Sohlenius 2008, Leijon (ed.) 2005/. These features strongly resemble those identified in the superficial rock mass close to the Forsmark nuclear power plant. Detailed mapping of the bedrock surface verified the occurrence of a high frequency of open fractures compared to other areas at Forsmark.

The most prominent features documented in the investigations at drill site 5 (Figure 5-7) had apertures ranging up to about 20 cm and were typically filled with unconsolidated sediment. Investigations of the filling material revealed a composition resembling that observed in the covering till. It was inferred that sediment-loaded water flowed into the fractures and was followed by calm sedimentation of the material. The presence of wide and sediment-filled fractures was verified down to a maximum depth of 10 m. Below this depth, there were no signs of conditions that deviate from those typically encountered within the tectonic lens at Forsmark. Additional sites with open fractures and dislocated bedrock blocks, similar to what was observed at drill site 5, were observed after excavating the Quaternary deposits in the central part of the candidate area /Albrecht 2005/.

The geological conditions in the regolith are of great significance for the transfer of water and solutes from the bedrock to the surface ecosystems and vice versa. Information on the spatial variations in the horizontal plane as well as with depth of relevant properties contributes to the modelling of flow paths and the retention and transformation processes along them; this modelling is discussed in section 5.4. Specifically, geological properties of particular importance for the flow and transport modelling include the spatial distribution of Quaternary deposits, which is expressed through the RDM (section 4.2.2), mineralogy (primary minerals and clay minerals), and physical properties such as density and porosity.

An investigation of particular interest for the description of the bedrock-regolith interface is the excavation of two adjacent trenches down to the bedrock surface that was performed east of Lake Bolundsfjärden /Lundin et al. 2005, Albrecht 2005/. The cleared trenches provided a two-dimensional vertical view of the regolith, which was documented and where sampling was performed (Figure 5-11), providing data on spatially distributed soil physical and chemical parameters describing the conditions for transport between bedrock and ground surface. Prevailing soil thicknesses in the trenches varied considerably as the almost flat ground surface was shown to be combined with a strong small-scale topographical contour of the bedrock relief; the regolith thickness differed much already within short distances /Albrecht 2005/.

Regolith physical conditions at the trench sites coincided fairly well with properties found elsewhere in till above the highest coastline /Lundin et al. 2005/. Such conditions have also been observed in not wave washed tills below the highest coastline. A considerable stone and boulder content together with high bulk densities provided low porosities, especially in the deeper regolith layers. In the top soil layers, higher porosities and lower densities were observed (Figure 5-12). The example results presented in Figure 5-12 indicate relatively large variations with depth, providing support for a layered model of the till.

A high $CaCO_3$ content influenced the chemical conditions in almost the entire profiles investigated. These conditions implied high pH values, often exceeding 6. Only in the top soil of two profiles and in the humus layer, low pH values were found. These conditions were also reflected in the calcium content of the soil. Magnesium and potassium showed normal or even somewhat low concentrations when compared to statistics describing Swedish forest soil conditions. The carbon and nitrogen contents found in the trenches were similar to those in the soil type inventory of the Forsmark area, and agreed reasonably well with data from other parts of Sweden /Lundin et al. 2005/.

Figure 5-11. The bedrock-regolith contact in the excavated trench LFM000810 (figure from /Albrecht 2005/).

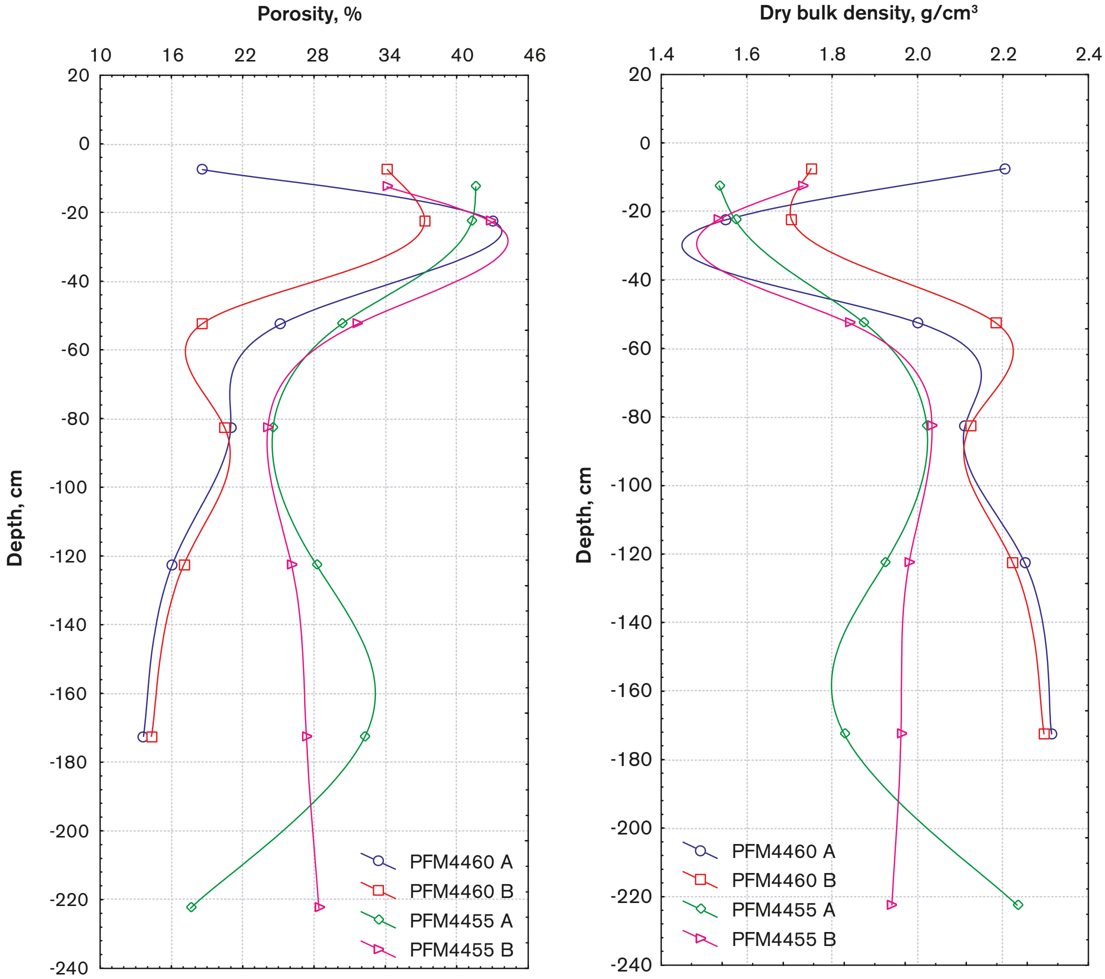

Figure 5-12. Porosity (left) and dry bulk density (right) from regolith investigations in excavated trenches in Forsmark (figure from /Lundin et al. 2005/); depth zero (0 on the vertical axes) corresponds to the mineral soil surface.

5.2.3 Hydrogeological description

The hydrogeological modelling of the bedrock is described in /Follin et al. 2007, 2008/ and summarised in Chapter 8 of the Forsmark SDM-Site report /SKB 2008/. The modelling of surface hydrology and what is referred to as near-surface hydrogeology is presented in /Johansson 2008/ and /Bosson et al. 2008/; a summary of this modelling is provided in sections 3.4 and 4.3 of the present report. Essentially, the subdivision of the hydrogeology into bedrock and surface/near-surface parts implies that hydrogeological data obtained from boreholes in rock are analysed within the bedrock modelling and data from drillings and monitoring wells in the regolith within the surface system modelling, whereas there is an overlap in the conceptual and mathematical models for groundwater flow developed by the two disciplines (cf. section 5.1.3).

Since the bedrock and the surface modelling activities partly deal with the same model domain, there is an obvious need for interactions and integration in the modelling process. In the Forsmark site descriptive modelling, this integration has been achieved by data exchanges as well as a series of joint meetings. The data exchanges included hydrogeological parameters, i.e. deliveries of parameterised regolith and bedrock models, and other data used as a basis for calibration and identification of boundary conditions (e.g. calculated groundwater fluxes and time series data on groundwater levels). This section gives a short description of the integrated bedrock-regolith conceptual model and its data support, with emphasis of the upper part of the rock. In the next section, some surface system data and modelling results of particular interest for the bedrock modelling are summarised.

The following description is based on text and figures from Chapter 8 of the SDM-Site report /SKB 2008/. Figure 5-13 shows a perspective view of the candidate area towards the south including the main geological-hydrogeological objects of the Forsmark area. The regionally significant, ductile and brittle deformation zones with WNW-NW strike, i.e. the Forsmark (FDZ), Eckarfjärden (EDZ) and Singö (SDZ) deformation zones, border the candidate area and run more or less perpendicular to the regional hydraulic gradient. Zones A2 and ENE0060 are local major deformation zones. Zone A2 dips gently to the south and splits the bedrock within the candidate area into two parts. In the modelling, the south-eastern part is referred to as the hanging wall bedrock and the north-western part as the footwall bedrock to zone A2. Zone ENE0060 dips steeply and strikes parallel to the regional hydraulic gradient. It divides the target volume in the footwall bedrock into two parts.

The hydraulic investigations carried out in the fracture domains suggest that the frequency of water-conductive fractures varies significantly in space. Data suggest that there is less than one flowing fracture per hundred metres below c. 400 m depth within the target volume, which is located in the footwall bedrock. In contrast, the uppermost c. 150 m of bedrock inside the target volume is considerably more fractured, with more than 30 flowing fractures per hundred metres. In addition, the near-surface bedrock between the deterministically modelled deformation zones within the target volume contains discrete sub-horizontal fractures/sheet joints, many of which have high in-plane transmissivities and extend tens to hundreds of metres (Figure 5-10). Here, the hydraulic gradient is low due to the flat topography and the pronounced structural-hydraulic anisotropy.

The highly transmissive sub-horizontal fractures/sheet joints encountered in the north-western part of the candidate area suggested that there may be a well-connected network of structures with very anisotropic hydraulic properties in the uppermost c. 150 m of the bedrock. Thus, the strong contrast in the structural-hydraulic properties with depth within the target volume creates a hydraulic phenomenon that short-circuits the near-surface flow system, which may contribute to a slow transient evolution of fracture water and porewater hydrochemistry at depth. The groundwater levels monitored in the Quaternary deposits and in the bedrock at depth suggest that the network short-circuits the recharge from above as well as the anticipated discharge from below.

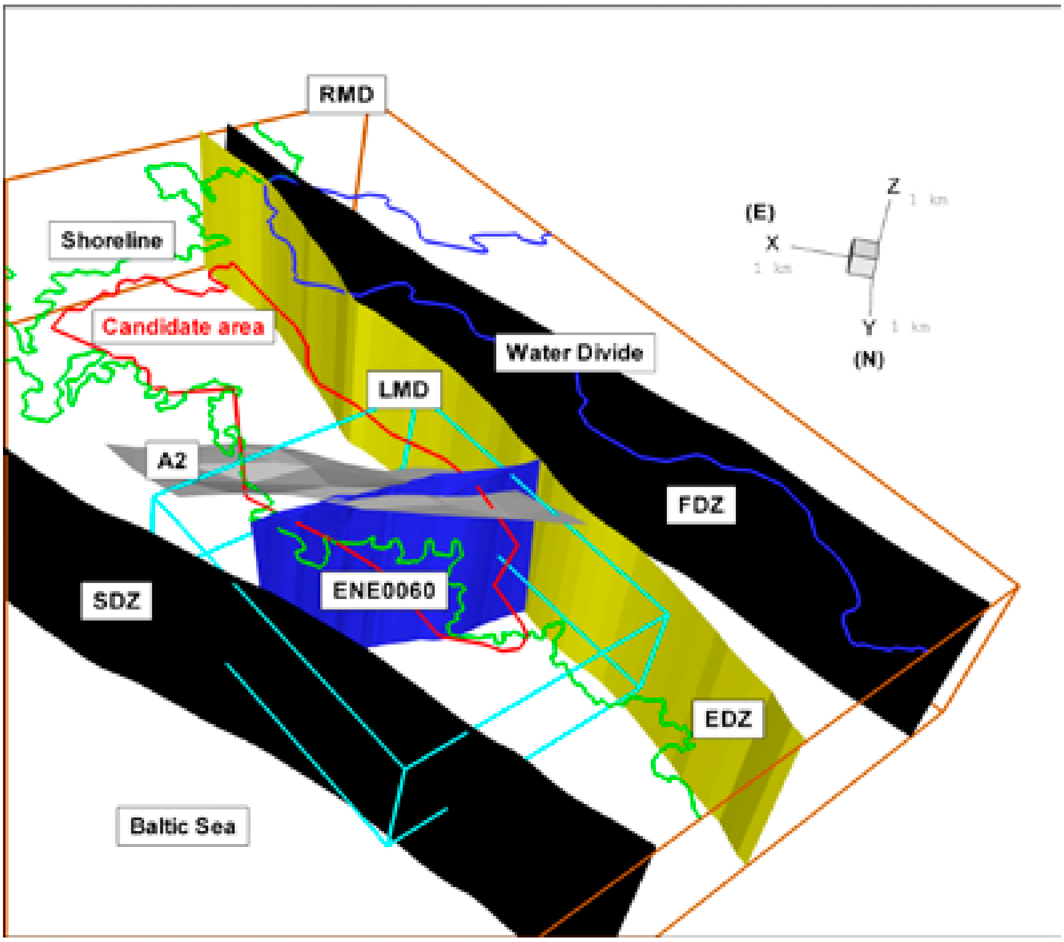

__Figure 5-13.__ A perspective view towards south showing the candidate area, the local model domain (LMD), the south-western part of the regional model domain (RMD); the figure is taken from /SKB 2008/. The regionally significant deformation zones Forsmark (FDZ), Eckarfjärden (EDZ) and Singö (SDZ) border the candidate area. The remaining zones, A2 and ENE0060, are local major deformation zones. The solid blue line indicates the nearest regional topographical water divide.

In /SKB 2008/ it is recognised that the "hydraulic cage" analogue tentatively suggested in earlier works is misleading as there is no hydraulic cage at Forsmark *sensu strictu*. A more appropriate hydrogeological description of the hydraulic short-circuit phenomenon observed in the uppermost part of the bedrock is a shallow, anisotropic, bedrock aquifer on top of a thicker segment of bedrock with aquitard (flow restricting) type properties. The bedrock aquifer has little or no storage, hence it has a high hydraulic diffusivity. The cartoon shown in Figure 4-10 illustrates the overall conceptual model including the shallow bedrock aquifer concept.

As described above, the uppermost part of the bedrock in the Forsmark area is recognised for its large horizontal fractures/sheet joints (see Figure 5-10). Besides this structural evidence, there are three pieces of hydrogeological evidence that support the hydraulic importance of these horizontal fractures/sheet joints /Follin et al. 2007, SKB 2008/.

1. Exceptionally high water yields. The median yield of the first 22 percussion-drilled boreholes is c. 12,000 L/h. This is c. 20 times higher than the median yield of the domestic water wells drilled outside the candidate area, which is no different from the median yield of all bedrock wells (c. 200,000) registered at the Geological Survey of Sweden.
2. The near uniform groundwater level in the uppermost c. 150 m of bedrock observed among the percussion-drilled boreholes within the target area. This level is on the average c. 0.5 m above the datum plane (RHB 70). In contrast, the average groundwater level among the percussion-drilled boreholes outside the candidate area is c. +2.8 m above the datum plane. The mean gradient between the Quaternary deposits and the uppermost part of the bedrock is downwards (cf. section 5.2.4).
3. The extensive and rapid transmission of fluid pressure changes (drawdown) during the large-scale interference test that was run over three weeks in the summer of year 2006 in borehole HFM14, which is located at drill site 5 in the centre of the target area (just west of Lake Bolundsfjärden, see Figure 5-7).

In conclusion, geological and hydrogeological observations indicate a well-connected network of structures of high transmissivity in the uppermost c. 150 m of the bedrock in the target area. The network is thought to consist of extensive horizontal fractures/sheet joints, outcropping deformation zones and increased, though structurally anisotropic, fracture intensity in the bedrock in between the outcropping deformation zones.

Based on the results obtained from the interference test that was run in HFM14 for three weeks in the summer of 2006, the envisaged lateral extent of the horizontal fractures/sheet joints was hypothesised to correspond approximately to fracture domain FFM02, but stretching north all the way to the Singö deformation zone (WNW001) as shown in Figure 5-14. The other hypothesised physical boundaries are deformation zone ENE0062A to the south-east and the border of fracture domain FFM02 to the south-west and west, with the modification that the boundary passes between boreholes HFM20 and HFM28. The crosses in Figure 5-14 mark the positions of the percussion-drilled and core-drilled boreholes for which transmissivity measurements were available for parameterisation of the discrete features implemented in the numerical modelling of the sheet joints in the shallow bedrock aquifer.

In 2007, two vital, confirmatory, large-scale, interference tests were conducted, one during the summer over three months in HFM14 (at drill site 5) and the other during the fall over two weeks in HFM33 (at drill site 11 on the SFR peninsula, see Figure 5-7). Neither of the two tests falsified the hypothesised lateral extent of the discrete features inferred to characterize the shallow bedrock aquifer; on the contrary, they reinforced the hypothesis /SKB 2008/. Besides confirming the hypothesis of a shallow bedrock aquifer, the two large-scale interference tests provided two additional important results.

- The interference test that was run over three months in HFM14 resulted in almost identical final drawdowns at many observation points compared with the previous interference test that was run in this borehole over three weeks in the summer of 2006, in spite of the significant difference in test time. This observation indicates a positive hydraulic boundary nearby and/or leakage from groundwater storage in the Quaternary deposits above. (In the context of interference tests, a positive hydraulic boundary means an infinite source of water, e.g. the Baltic Sea).
- The interference test that was run over two weeks in HFM33 at drill site 11 was conducted in a horizontal fracture located at about 100 m depth. The pressure changes during the pumping propagated rapidly under the Baltic Sea, and clear hydraulic responses were observed in many boreholes within the target area including HFM14. Interestingly, no responses were observed in the nearby boreholes HFM34 and HFM35, which are located on the other (north-eastern) side of the Singö deformation zone.

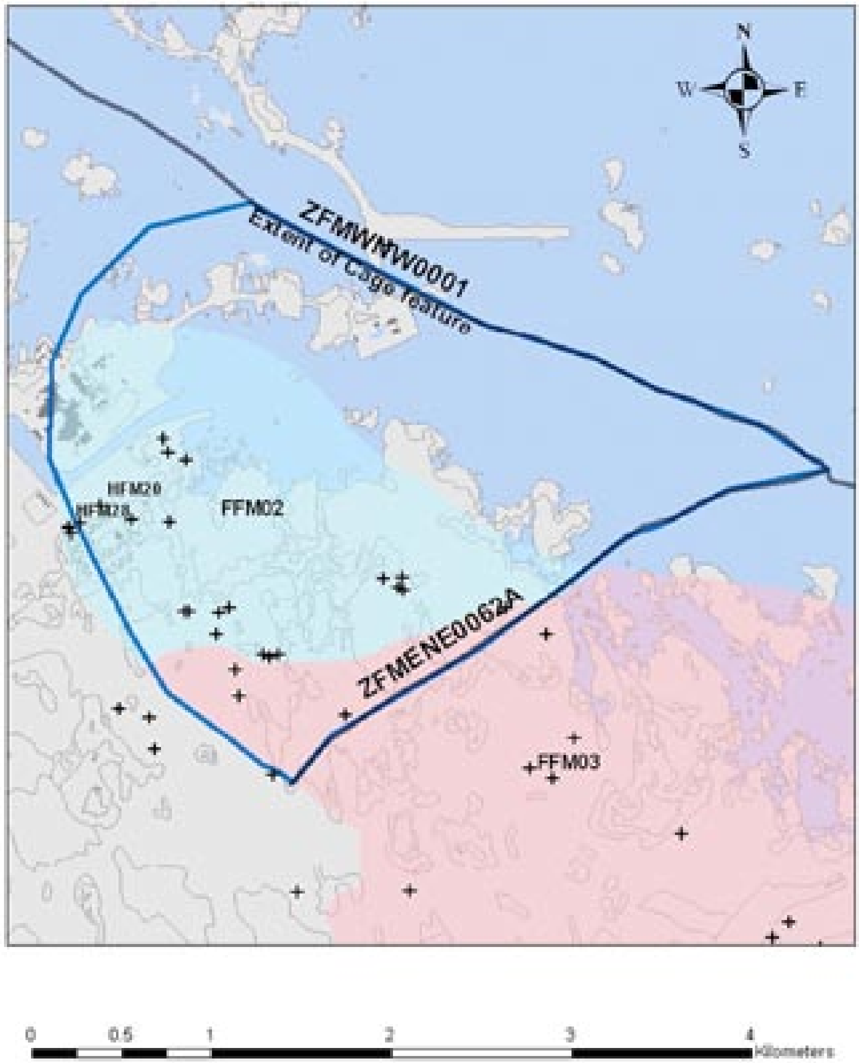

Figure 5-14. The hypothesised lateral extent of the discrete features implemented in the ConnectFlow and MIKE SHE codes to model the sheet joints in the shallow bedrock aquifer figure (reproduced from /Follin et al. 2007/). The crosses mark the positions of percussion- and core-drilled boreholes for which transmissivity measurements were available. The bluish area represents fracture domain FFM02 and the pinkish area fracture domain FFM03.

In summary, the bedrock in the Forsmark area has been thoroughly characterized with both single-hole and cross-hole (interference) tests. Constant-head injection tests and difference flow logging pumping tests have been used in parallel to characterize the fracture properties close to the boreholes, and interference tests have been used for larger-scale studies. The overall experience from these investigations is that the anisotropy in the structural geological model effectively governs the pathways for flow at all depths. In addition, there is a considerable depth trend in transmissivity, where the uppermost part of the bedrock is found to be significantly more conductive than the deeper parts.

5.2.4 Surface system data used in bedrock modelling

The conceptualisation of the hydrological-hydrogeological system at Forsmark is summarised in the preceding section and in section 4.3 (see Figure 4-10); more detailed descriptions are given in the reports referred to above. The present section summarises results from surface system modelling activities and joint interpretations considered important for the bedrock modelling. In particular, hydrogeological properties and time-series data on groundwater levels are discussed.

As described in some detail above, the uppermost rock is a key component in the overall groundwater flow system at Forsmark. The transmissivities measured in this part of the rock are, in many cases, exceptionally high, in particular in the north-western part of the candidate area (the target area). This relatively shallow and anisotropic bedrock aquifer, consisting of a lattice of high-transmissive structures including extensive horizontal fractures/sheet joints, intercepts the recharge from above as well as the discharge from below. This means that it has important implications for the groundwater exchange between the regolith and the bedrock within the target area.

The geology of the regolith in the Forsmark area is described in /Hedenström and Sohlenius 2008/ and summarised in sections 3.5 and 4.4 of this report. Till is the dominant Quaternary deposit in the area, whereas fine-grained materials such as gyttja and glacial and post-glacial clay are found below lakes and wetlands. Based on a simplified conceptual model in which the regolith was subdivided into a limited number of layers, available data on surface distribution, total depth and stratigraphy were used to construct a three-dimensional geometric model of the distribution of Quaternary deposits (section 4.2). This model, in turn, was used as a basis for the development of the hydrogeological model of the regolith. Specifically, the various layers in the geometric model were assigned hydrogeological parameters, see /Johansson 2008/ and /Bosson et al. 2008/ for details.

Regarding the hydrogeological properties of the regolith, the following should be noted /Johansson 2008/.

- The hydraulic conductivity (K) values for till in the Quaternary deposits model are horizontal conductivities obtained from slug tests. The only vertical K-values from till are from the laboratory permeameter tests, which indicate a K_h/K_v ratio of about 30 (K_h is the horizontal and K_v the vertical hydraulic conductivity). Note that this result should be used with caution since the scales of the tests are not the same.
- The hydraulic conductivities are considerably higher in the uppermost c. one metre of the soil profile. The difference, due to impact of soil forming processes, is 2 to 3 orders of magnitude. In the model, this was considered by including a differentiation of the hydraulic properties between the upper 0.6 m of the profile and the deeper part of the profile for some of the Quaternary deposits.
- A pumping test in till with observation wells near and below Lake Bolundsfjärden showed that there is a limited hydraulic contact, potentially determined by low-permeability lake sediments, between Lake Bolundsfjärden and the pumped aquifer. The evaluation of the vertical leakage through the sediments (gyttja, clay gyttja) indicated a vertical K of the sediments of 10^{-9} to 10^{-8} m/s.

Groundwater levels in the regolith are of potential interest as a basis for setting the upper boundary conditions in hydrogeological models. Measured groundwater elevations in the regolith at Forsmark range from about –1 m to +13 m. However, the range in groundwater levels is only about 5.5 m when represented as depths below the ground surface. The majority of wells form a tight cluster with reported groundwater levels in the range of approximately +0.25 to –1.5 m relative to the surface /Johansson 2008/. These wells typically show a strong uniformity in response to drier summer conditions in July and August. Similarly, these wells also display uniformity in their response to recharge events following major precipitation and snow melt events.

Figure 5-15 summarises the strong correlation that was observed between mean observed groundwater and ground surface elevations in the regolith. It can be stated that the average position of the groundwater in the regolith with few exceptions appears to be largely determined by the local ground surface elevation. In other words, the shape of the groundwater surface in the regolith generally follows that of the ground surface. The most pronounced outliers are located below the ridge of the glaciofluvial deposit Börstilåsen, or in typical recharge areas (see /Johansson 2008/ for a detailed discussion on the outliers).

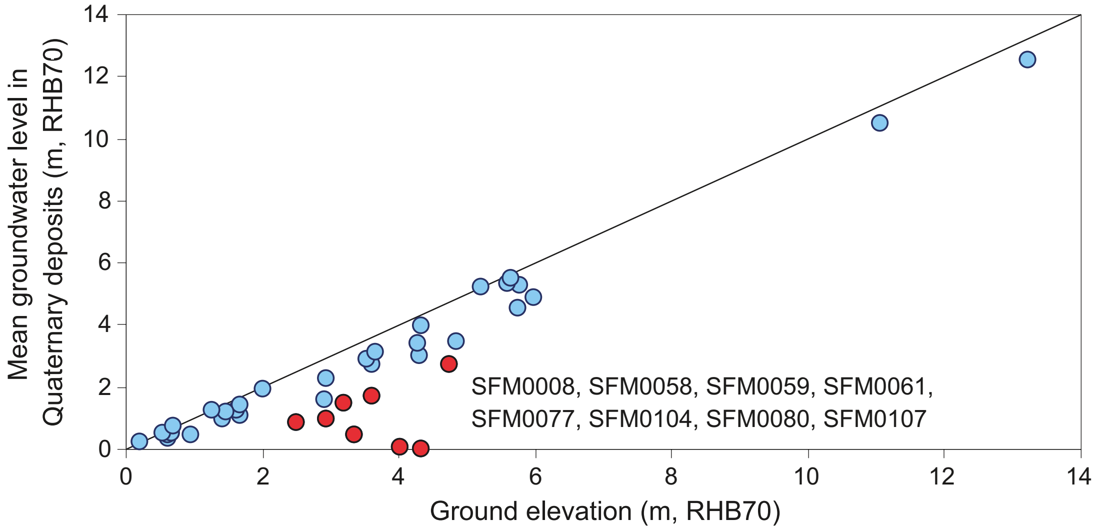

Figure 5-15. *Cross-plot of average groundwater level elevations in the Quaternary deposits versus ground elevations at the well locations /Johansson 2008/. The red dots represent outliers; the ID numbers of these wells are listed in the figure.*

Modelling of groundwater flow in the bedrock at Forsmark has also been performed using flux boundary conditions at the top boundary; in fact, this has been the most common option in the later stages of the site descriptive modelling. Water balances provide a basic input when assigning flux boundary conditions, and for Forsmark both measured and calculated water balances are available. In particular, the water balance of the saturated zone is needed, so that the groundwater recharge can be estimated. However, at Forsmark overland flow is small, implying that the groundwater recharge is approximately the same as total discharge.

According to /Johansson 2008/, the long-term average specific discharge in the Forsmark area is estimated to 150–160 mm y^{-1}. However, it should be noted that this is a spatial average for the whole model area, including both the recharge areas, where recharge actually takes place, and the discharge areas. In some cases, spatial distributions or values representing recharge areas only are more relevant. As shown in section 4.3, this information can be obtained from the available modelling results.

/Johansson 2008/ used a systems approach to describe the hydrological and near-surface hydrogeological flow system of the central parts of the regional model area. The description is to a large extent based on a joint evaluation and interpretation of time-series data from regolith and bedrock, see also /Johansson and Öhman 2008, Juston et al. 2006/. Some results of particular interest for the bedrock modelling and the interactions between regolith and bedrock are summarised in the following.

- Correlations between seawater levels and groundwater levels in rock and in regolith were investigated by several methods. The regression coefficients for the groundwater levels in the regolith with sea levels were very low with the exception of two wells located in glaciofluvial material within 100 m distance from the sea.
- The regression coefficients were also quite low for groundwater levels in the rock and sea levels, with the exception of boreholes located at the SFR peninsula. The analysis indicated that seasonal variations in precipitation and evapotranspiration determined the main part of the variations in groundwater levels.
- During events of very high seawater levels, seawater flows into several of the lakes. In connection with these events, the sea obviously has an impact on both surface water and groundwater flow systems in these lakes and their surroundings.

- Direct recharge from precipitation is the dominant source of groundwater recharge. However, the groundwater level measurements in the vicinity of Lake Bolundsfjärden and Lake Eckarfjärden show that also the lakes may act as recharge sources to the till aquifers in the immediate vicinity of the lakes during summer. In addition, the Baltic Sea can potentially act as a source of groundwater recharge during periods of high seawater levels.
- The strong correlation between the mean groundwater elevations observed in the till and ground elevation data means that the average vertical hydraulic flux at some point below the surface is considerably smaller than the net infiltration into the saturated zone of the till. This could partly result from a contrast in vertical hydraulic conductivity between the till and the bedrock, with the uppermost bedrock having a lower K_v.
- The groundwater level in the till seems to be considerably higher than that in the rock within the target area. At drill site 1, for example, absolute groundwater levels in the Quaternary deposits are well above the point water heads in bedrock except during dry summer conditions.
- The groundwater levels in the bedrock boreholes are above the interface between regolith and rock under undisturbed conditions, indicating that no unsaturated zone exists below this interface.
- In general, there is no discernable response in the groundwater levels in the regolith to disturbances in the groundwater levels in the bedrock. On the other hand, groundwater levels in both regolith and bedrock are correlated to precipitation and evapotranspiration.
- Variations in groundwater levels in the till and in the bedrock are correlated. The natural groundwater level fluctuations are, however, smaller in the bedrock, but still to a great extent controlled by the annual precipitation and evapotranspiration cycles. The conditions prevailing within the target area, with a lower groundwater level in the bedrock than in the regolith, mean that the groundwater flow has a downward component at the sites studied, implying an inflow from the till to the bedrock. The difference between the levels in till and in bedrock indicates a limited hydraulic contact between regolith and rock.
- Outside the tectonic lens and the target area, for example at drill site 4 (Figure 5-7) and in the area around Lake Eckarfjärden, 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.
- The lake water level-groundwater level relationships indicate that the lake sediments and the underlying till have low vertical hydraulic conductivities. If the hydraulic contact had been good, the situation with groundwater level drawdown from evapotranspiration extending below the lakes, and the quick and extensive propagation of drawdowns from the pumping tests, would not have appeared.

Figure 5-16 shows the groundwater levels in wells in regolith and bedrock at drill site 1 located within the target area. The groundwater levels in the regolith are above those in the rock except during the summers of 2003 and 2006. Figure 5-17 shows the groundwater levels in a monitoring well in till below the middle of Lake Bolundsfjärden (in monitoring well SFM0023) and in a nearby percussion-drilled borehole (HFM32) located on a small island in the lake. Water levels in the sea and in the lake are also shown in the figure. The lake level and the groundwater level in till are considerably higher than the levels in the four sections in borehole HFM32. The heads are lowest in the two deepest sections. The results indicate a downward flow gradient from the lake and the regolith below it to the bedrock.

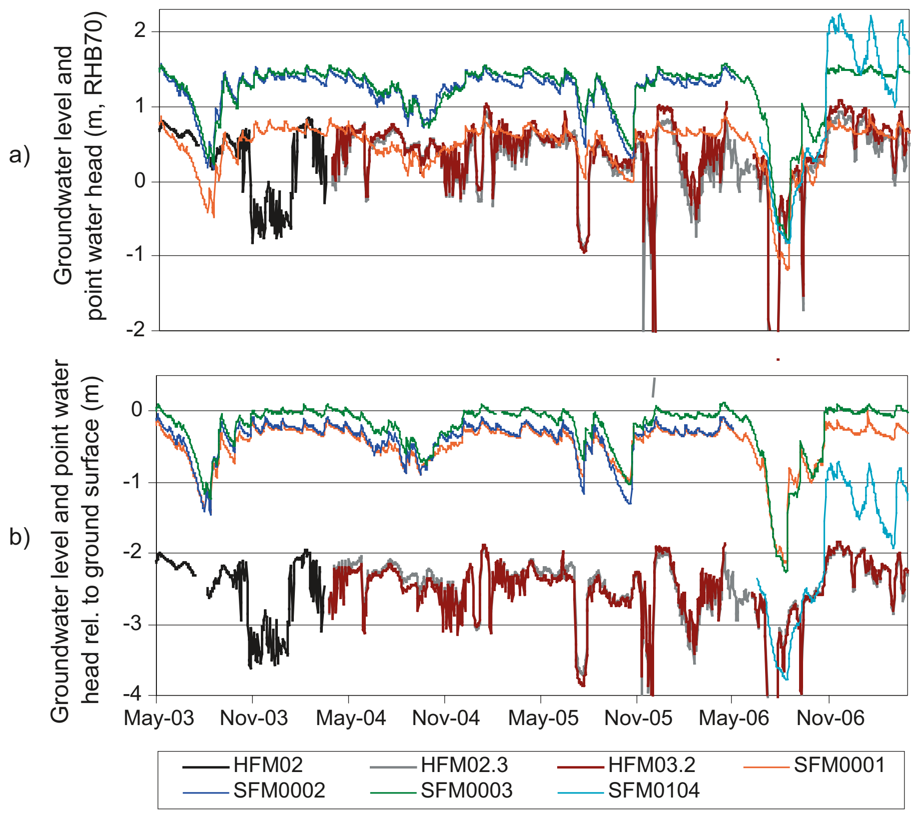

Figure 5-16. *Comparison of groundwater levels in wells in Quaternary deposits (SFM) and in bedrock (HFM) at drill site 1 in terms of a) metres above sea level and b) depth below ground surface; data from the shallowest HFM-sections are shown /Johansson 2008/.*

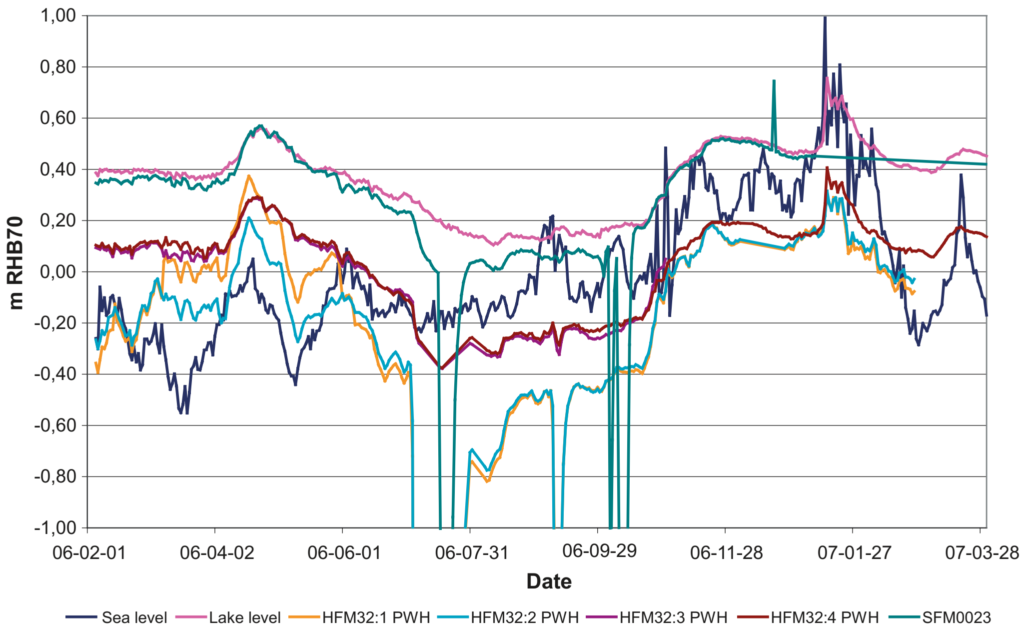

Figure 5-17. *Water levels in the Baltic Sea and Lake Bolundsfjärden plotted together with groundwater levels in till below the lake (SFM0023) and in sections in the bedrock borehole HFM32 (elevations in m RHB 70: HFM32:1: –198.75 to –96.27; HFM32:2: –95.27 to –30.95; HFM32:3: –29.95 to –24.97; HFM32:4: –23.97 to +0.97) /Johansson 2008/.*

5.3 Hydrogeochemistry and retention parameters

5.3.1 Hydrogeochemical overview

The modelling of the surface system hydrogeochemistry is presented in /Tröjbom et al. 2007/; this description is summarised in sections 3.6 and 4.5 of the present report. In addition, a recent analysis involving a chloride mass balance of a part of the model area is reported in /Johansson 2008/, cf. below. The hydrogeochemical description of the bedrock is given in /Laaksoharju et al. 2008/ and associated background reports, and is summarised in Chapter 9 of the Forsmark SDM-Site report /SKB 2008/.

Similar to the hydrogeological descriptions discussed in the preceding section, there is an overlap between the bedrock and surface system descriptions. However, although the two modelling activities partly deal with the same model volume (in particular, the regolith and the upper bedrock) and hence both present models including both regolith and bedrock, it should be noted that their main purposes are different. The bedrock modelling should primarily provide a basis for describing the hydrogeochemical conditions at repository depth, whereas the surface system modelling primarily seeks to provide input to descriptions of various material fluxes in the surface system. As a somewhat rough distinction, it could be stated that the bedrock modelling is mainly focused on changes in hydrogeochemical conditions in the vertical direction, whereas the surface system modelling mainly describes variations in the horizontal directions (and on or very close to the ground surface).

In /SKB 2008, Chapter 9/, the hydrogeochemical description of the integrated regolith-bedrock system is summarised as follows.

Near-surface waters (0–20 m): Within this 0–20 m depth interval, including the regolith, *Fresh groundwaters* (< 200 mg/L Cl) comprise the most recent recharge compositions. Therefore, their hydrogeochemical evolution is mainly determined by weathering reactions, in particular reactions influenced by limestone. The extensive presence of limestone blocks in the Quaternary overburden, a feature very uncommon in soils in other parts of Sweden, promotes an overall distinctive character to the near-surface groundwaters with respect to that observed in other areas.

Properties include variable but higher pH values (usually higher than 7) and variable but higher calcium concentrations (mostly between 50 and 200 mg/L) depending on the biogenic carbon dioxide input. This fact, together with weathering of the aluminosilicates (kinetically much slower) and the localised presence of especially intense biogenic input, contribute to the higher bicarbonate values observed (between 200 and 900 mg/L). Groundwater redox conditions at these shallow levels are oxidising/reducing in character. No rock matrix porewater data are available from these very shallow levels.

Shallow groundwaters (20–200 m): This depth interval in the upper part of the footwall bedrock (i.e. rock below zone A2, see section 5.2.3, in fracture domain FFM02) includes the shallow bedrock aquifer, which rapidly transports recharging meteoric groundwaters laterally towards the north-east and effectively limits further recharge to deeper levels. These shallow groundwaters therefore consist of a large percentage of *Fresh groundwater* that has persisted to the depths of the shallow bedrock aquifer. However, not surprisingly, they do not share the same variability and high bicarbonate or calcium contents as the near-surface fresh groundwaters. Only waters which have short residence times in the regolith (i.e. travel along fast paths), and therefore are more dilute, are effectively recharging these shallow hydrological systems.

This uppermost 20–200 m of the bedrock is also characterized by groundwaters displaying a wide chemical variability. This may be due to: a) natural mixing of fresh recharging waters and discharging (or flushed out) saline groundwaters (i.e. recent Baltic or old Littorina Sea relicts), and/or b) mixing resulting from anthropogenic effects related to drilling and sampling activities. Collectively, these two types are referred to as Mixed Brackish groundwaters with chloride contents in the range 200–2,000 mg/L. These shallow mixing processes occur throughout the Forsmark area, but are much more prevalent in the hanging wall segment (i.e. above zone A2) where the shallow bedrock aquifer is virtually absent and variable discharge and recharge is occurring along the gently dipping deformation zones.

These hydrogeochemical and hydrogeological observations are supported by environmental isotope studies which show that recent to young fresh groundwaters, some showing signs of mixing, characterize the upper approximately 100–200 m of bedrock. This is shown by tritium and ^{14}C which indicate that near-surface groundwaters have short residence times mainly in the order of only a few decades to a few hundred years. This is in agreement with palaeohydrogeological evidence which indicates that the regional area at Forsmark started to emerge from the sea c. 2,500 years ago with subsequent land uplift establishing meteoric water recharge some 900 years ago.

Few data exist for the redox characterization of this shallow groundwater system. Nevertheless, tentative calculations suggest the existence of a generalised anoxic state with possible episodic inputs of oxidising waters. However, these oxidising episodes have not been intense enough to exhaust the reducing capacity of fracture filling minerals which are still present in the shallow system (e.g. Fe(II) chlorite or pyrite). Goethite is found in some fractures mainly associated with deformation zones, and Mössbauer analyses of fracture fillings from hydraulically conductive fractures in the upper 50 m show Fe^{3+}/Fe(tot) ratios between 0.35 and 0.75.

These observations support the fact that redox conditions have varied both in time and space within the uppermost part of the bedrock. At present, the contents of dissolved Fe^{2+} are high and represent post-oxic environments in which iron-reducing bacteria (IRB) activity seems to be dominant. Locally, sulphidic environments with high contents of dissolved sulphide, probably active precipitation of amorphous monosulphide and, therefore, important sulphate-reducing bacteria (SRB) activity are also found.

The results of U-decay series analyses of fracture filling materials indicate mobilisation as well as deposition of uranium in the upper 150 m of the bedrock. This is ascribed to the transition from near-surface oxidising conditions to more reducing conditions at depth within the last 1 Ma.

Intermediate depth groundwaters (200–600 m): During the Littorina Sea transgression, the Forsmark bedrock was under water and therefore no active hydraulic gradient existed. This resulted in the seawater penetrating downwards into the bedrock by density intrusion flow. The bulk of the Littorina Sea waters, i.e. *Brackish Marine groundwaters* (2,000–6,000 mg/L Cl), preferentially entered the bedrock in the hanging wall segment along the gently dipping, highly transmissive deformation zones where the shallow bedrock aquifer does not exist. These waters mixed with more dilute post-glacial waters resident in the bedrock, and eventually came to rest when older *Brackish Non-marine groundwaters* of similar to higher salinity (4,000–10,000 mg/L Cl) were increasingly encountered. The average depth of penetration at the present time along the gently dipping deformation zones is approximately 600–700 m. Penetration depth may also have been influenced by a decrease in transmissivity along these deformation zones.

In the footwall bedrock dominated by fracture domains FFM01 and FFM02, the situation was somewhat different. The shallow bedrock aquifer subsequently became saturated by Littorina Sea water which persisted until recent uplift stimulated an increase in the hydraulic gradient. The bulk of the Littorina waters then were flushed out by recharging meteoric waters, a process which is still on-going. However, Littorina Sea water components are still present down to 250–300 m depth in the footwall bedrock (fracture domain FFM01).

This is illustrated by data from borehole KFM01D, where sub-horizontal to very gently dipping transmissive discrete single fractures within the upper 300 m bedrock (i.e. the defined fracture domain) have been sampled. Here, the Littorina Sea component is weak to intermediate, probably due to mixing with fresh groundwaters during the on-going flushing out process. In addition, the gently dipping single fractures sampled may connect with the shallow bedrock aquifer and act as conduits bringing some brackish marine (Littorina) groundwaters down to around 300 m depth.

5.3.2 Hydrochemical interactions

Data evaluations and modelling related to the hydrochemistry of the surface system are reported in /Tröjbom et al. 2007/, where, among other things, indications of deep groundwater discharge are discussed. This section summarises a recent set of analyses in which hydrochemical data have been used for interpretation of flow systems. The emphasis is on the conditions within potential discharge areas for groundwater below the lakes, especially focusing on evidence for deep groundwater discharge. This analysis is based on and extends the description in /Tröjbom et al. 2007/ (see section 4.5), in terms of the integration between hydrology and hydrogeochemistry. The work summarised below is reported in /Johansson 2008/.

In /Tröjbom et al. 2007/, the method of principal component analysis (PCA) was applied to establish an ion-source model for the Forsmark data. In a first step, only data from percussion-drilled and core-drilled boreholes were used to optimise a model for distinguishing the groundwater types found in the bedrock. This model was then applied to observations of surface water and groundwater in Quaternary deposits, revealing similarities in hydrochemical composition between these observations and the main patterns found in the groundwater in the bedrock.

Figure 5-18 is a slightly modified version of Figure 4-28 showing the ion-source model developed in /Tröjbom et al. 2007/ for labelled monitoring wells in the regolith with different possible ion sources and possible groundwater types. As described in section 4.5, five major water types were identified in the above-mentioned PCA, i.e. *modern sea water*, *water influenced by relict marine water* (Littorina), *deep saline water* (water significantly influenced by shield brine), *altered meteoric water* (water of meteoric origin, but significantly altered by processes in the regolith), and *freshwater* (including both surface water and shallow groundwater showing "immature" ion signatures).

Most of the samples were classified as belonging to the *freshwater* and *altered meteoric groundwater* groups. The wells placed in till below lakes and the sea show quite different chemical compositions. In general, the waters from these wells have a high salinity, including a high chloride content. The well below Lake Gällsboträsket (SFM0012) and the wells located in the Gällsboträsket depression (SFM0011 and SFM0013) were classified as belonging to the *influenced by relict marine water* group; they have chloride contents of approximately 2,000 mg/L.

Interestingly, SFM0057 located at the edge of the Gällsboträsket depression has a signature indicating an influence from deep saline water and shows similarities with the signatures of percussion-drilled boreholes HFM11 and HFM12 in the bedrock. These boreholes are located near Lake Eckarfjärden and in the major Eckarfjärden deformation zone (cf. above), which also passes below Lake Gällsboträsket. The water in SFM0057 is, however, quite diluted with an average chloride content of c. 250 mg/L.

The monitoring well in the middle of Lake Bolundsfjärden (SFM0023), where the groundwater has a chloride concentration of c. 3,775 mg/L, was also found to belong to the *influenced by relict marine water* group. The chloride concentration is approximately the same as in the nearby percussion-drilled borehole HFM32 down to a depth of c. 100 m. Also, the well SFM0022 below Lake Fiskarfjärden shows a chemical signature clearly influenced by relict marine water. The water from the well below Lake Eckarfjärden (SFM0015), however, shows a quite different chemical composition and was in the ion-source modelling considered to be closest to the group *altered meteoric water*. The chloride content in the SFM0022 well is c. 300 mg/L.

The occurrence of water belonging to the *influenced by relict marine water* group below Lake Bolundsfjärden, Lake Fiskarfjärden and Lake Gällsboträsket is a strong indication of very low flow rates in the flow systems involving these parts of the regional site investigation area. In the perspective of the total annual water balance of the area, the water can be considered as stagnant. At Lake Bolundsfjärden, no flow from below reaches the till at present, according to the groundwater levels measured in the regolith and the bedrock. Furthermore, the water composition indicates that the leakage from the lake through the sediments must be very small. The hydrogeological and hydrochemical interpretations indicate that shallow groundwater flow systems involving Quaternary deposits only have discharge areas around the lake and in the near-shore parts of the lake, while deeper systems are drained by the highly transmissive shallow bedrock.

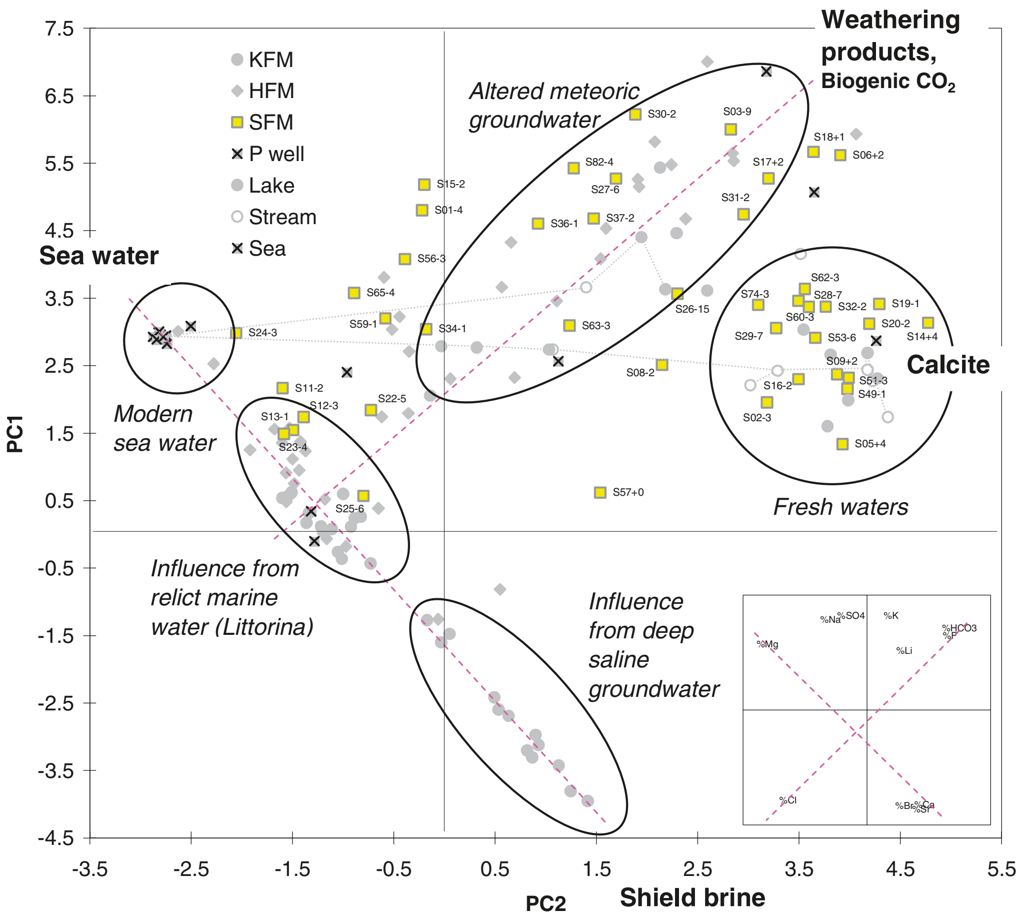

Figure 5-18. *The ion-source model showing labelled monitoring wells in the regolith with different possible ion sources and possible groundwater types (modified from /Tröjbom et al. 2007/ where a detailed description of the underlying modelling is given). Note that FM and two zeros have been deleted from the well numbers, and that the last part of the well number is the mean elevation of the sampling interval (therefore, it is preceded by either "+" or "–").*

The monotoring data on the chemistry of the water flowing out of Lake Eckarfjärden and Lake Gällsboträsket give an opportunity to investigate to what extent relict marine water and deep saline groundwater are present in the flow systems generating surface discharge. Chloride is considered as a good tracer since it follows the water, and due to the large difference in concentrations between water containing chloride from atmospheric deposition only and relict marine and deep saline water. In /Johansson 2008/, an evaluation of the transport of chloride from Lake Eckarfjärden and Lake Gällsboträsket is reported. The quantification of chloride transport is based on the hydrochemical analysis in /Tröjbom et al. 2007/ and the hydrological data presented in /Johansson and Öhman 2008/.

The average Cl concentration measured at the outlet of Lake Eckarfjärden is 5.1 mg/L. This chloride concentration corresponds to what can be assumed to originate from atmospheric deposition. The chloride concentration in the discharge from Lake Gällsboträsket, measured upstream of the conjunction with the brook from Lake Eckarfjärden, is considerably higher (the average is 29 mg/L) and it was concluded in /Johansson 2008/ that an additional source of chloride besides atmospheric deposition has to exist.

By using the continuous discharge and electrical conductivity (EC) measurements, and the correlation between EC and the chloride concentration, daily values of the transport of chloride from Lake Gällsboträsket have been calculated. The average annual chloride transport for the period from December 8, 2004, to March 31, 2007, was approximately 9,900 kg. The annual atmospheric deposition in the catchment area was estimated to 1,800 kg, leaving approximately

8,000 kg originating from other sources. From the regolith depth and stratigraphy model (RDM), the volume of the regolith in the Gällsboträsket depression below a depth of 2.5 m was calculated, and the total water volume in the regolith was estimated from values of the total porosity.

Based on this volume and the mean chloride concentration of c. 2,000 mg/L in the three monitoring wells in the depression, the storage of chloride in the regolith was estimated to c. 500 tonnes. With the current transport rate, this storage will be depleted in approximately 60 years. Further analysis of the relationship between discharge and hydrochemical composition indicated influence of deep saline water. This, together with the current outflow rate compared with the estimated storage in the regolith, raises the question of whether there is an additional source of chloride, i.e. upward flow of deep saline groundwater, in the Gällsboträsket area (see /Johansson 2008/ for a more detailed description of the analysis).

Concentrations of ^{3}H, $\delta^{18}O$ and ^{2}H, as well as the concentration of chloride, may contain information on the origin of the sampled groundwater that is not used in the ion-source model. These parameters are plotted on the ion-source model in Figure 5-19. Specifically, the three wells below Lake Bolundsfjärden (SFM0023), Lake Eckarfjärden (SFM15) and Lake Gällsboträsket (SFM0012) are labelled. In general, the SFM0012 and SFM0023 wells show similarities for the presented parameters. SFM0015, below Lake Eckarfjärden, deviates significantly from SFM0012 and SFM0023, with slightly higher ^{18}O and lower ^{2}H excess values as well as a considerably lower chloride concentration. The combined picture is difficult to interpret, but may be a result of a mixed water with component(s) exposed to evaporation.

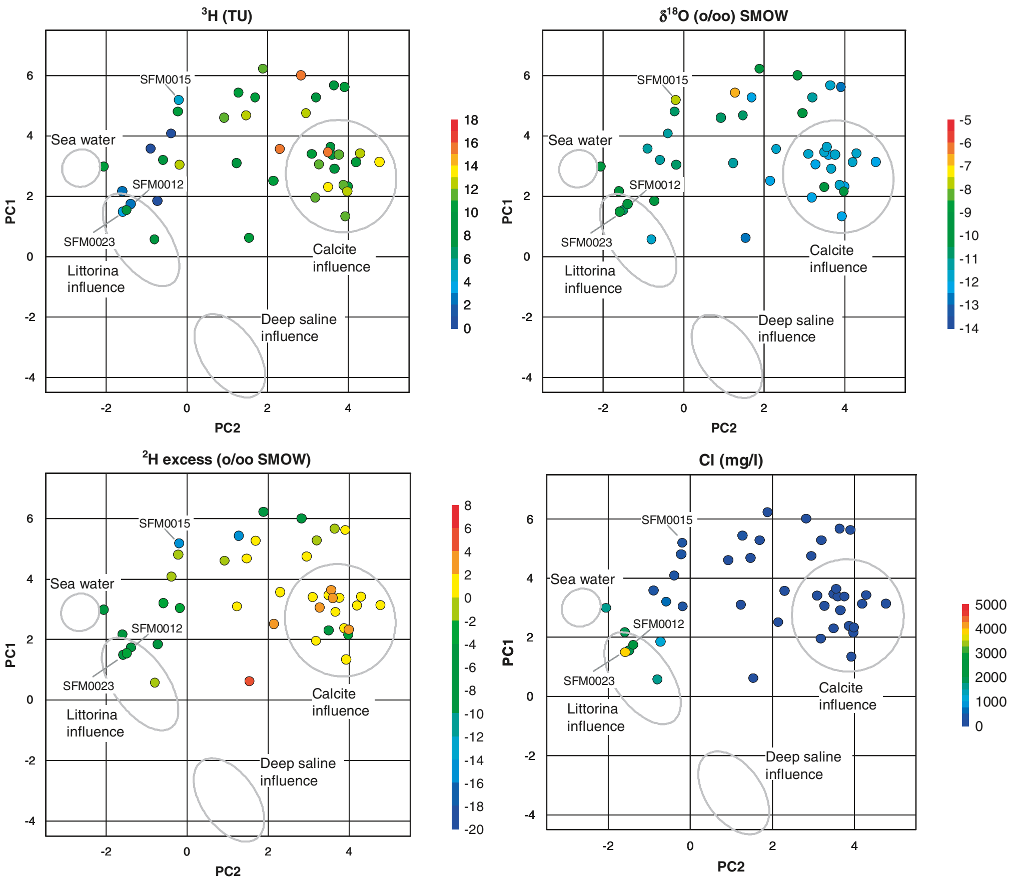

Figure 5-19. *The parameters ^{3}H, $\delta^{18}O$ and ^{2}H and the chloride concentrations in the wells in the regolith, plotted on the ion-source model, with the wells SFM0012, SFM0015 and SFM0023 labelled /Johansson 2008/.*

5.3.3 Hydrochemical indications of microbiological processes

Microbiological investigations and modelling of the deep bedrock have been performed as a part of the bedrock hydrogeochemistry program. The results are reported in /Hallbeck and Pedersen 2008/ and summarised in /Laaksoharju et al. 2008/; the deep rock microbiology will not be further discussed here. For the surface system, a "desktop study" not involving specific microbiological laboratory or field investigations was performed. In this study, reported in /Hallbeck 2008/, hydrochemical data from groundwater monitoring wells in the regolith and percussion-drilled boreholes in the upper rock were evaluated from a microbiological perspective. The results are summarised in the following.

For the evaluation of microbiology in the surface system in /Hallbeck 2008/, hydrochemical data were gathered from regolith monitoring wells with sceens at depths from c. 1 m to c. 10 m below ground and from percussion-drilled boreholes having mid-point depths of measurement sections between c. 30 m and c. 180 m. Only a few of the percussion-drilled boreholes had packers installed. The sampled sections were therefore very long, allowing groundwater from many different depths to mix. This also means that it in many cases could not be established from which depth the sampled groundwater came.

Because of the variable quality of the oxygen analyses and the oxidation-reduction potential data, it was difficult to draw any conclusions as to the presence of oxygen, other than that if oxygen was present in the shallow groundwater it was in low concentrations. However, based on the presence of the reduced species ferrous iron and sulphide, it could be concluded that reduced conditions prevailed at most sampled depths. There was a seasonal variation controlled by the DOC amounts. Monitoring wells placed in similar vegetation types displayed similar chemical signatures regarding DOC. The wells in forested areas generally showed evidence of high DOC.

The monitoring points displayed individual chemical profiles in terms of chemical species related to microbial activity. Furthermore, the microbial activity could not be linked to the hydrological recharge-discharge classification of the monitoring wells /Johansson 2008/. Groundwater from the Lake Bolundsfjärden area displayed more of ongoing iron- and manganese-related biogeochemical reactions (in other words, iron and manganese reduction) than did water from other areas. This could be because there were iron and manganese precipitates left from the relatively recent period when this area was part of the bottom of the Baltic Sea.

Thus, active microbial processes could not be conclusively identified, but the chemistry gave a clear indication that DOC had been consumed by aerobic microorganisms and that various anaerobic processes had taken place. Autotrophic anaerobic processes, such as methanogenesis or acetogenesis, may be ongoing, but the proper microbial data on which to base conclusive statements were not available. Microbial activity and processes seemed mostly to be linked to the specific characteristics of the studied boreholes and to the biotope in which they are situated.

A direct relationship between microbial processes and depth could not be identified. Similarly, a depth limit for oxygen penetration could not be established from the available data, because of the relatively low quality of the oxygen data and because data were missing for the 10–25 m depth interval where, based on experiences from other sites (Olkiluoto, Finland), the transition to oxygen-free conditions was considered most likely to occur.

5.3.4 Properties affecting solute retention

Many radionuclides and other solutes transported by groundwater in bedrock and regolith are subject to processes acting to immobilise (for short or long time periods) or transform the solutes along the flow paths in the subsurface. In the present context, radioactive decay is an obvious example of a transformation process. Sorption and precipitation/dissolution processes are two categories of processes that associate solutes with different types of immobile phases. In line with common nomenclature in radionuclide transport modelling, they are here referred to as retention processes. After a brief description of the bedrock transport properties modelling, this section summarises the site-specific information available for describing the conditions governing solute retention in the regolith.

Radionuclide retention in the bedrock

The modelling of bedrock transport properties is performed as a separate modelling discipline within the site descriptive modelling work. The results of the SDM-Site Forsmark modelling are presented in Chapter 10 in /SKB 2008/ and in more detail in /Crawford 2008/ and underlying reports. The field and laboratory investigations within the bedrock transport programme are focused on determining a set of parameters used in the safety assessment radionuclide transport modelling, i.e. the porosity, formation factor (a diffusion parameter) and sorption coefficients (K_d values) for each geological material included in the model; the Kd-values are also radionuclide- and water-specific and are therefore presented for selected combinations of radionuclides and "type waters".

Rock samples and experimental conditions in the laboratory (e.g. the "type waters") are selected based on the site information on, primarily, the general geology (rock types and structures), fracture mineralogy, and hydrogeochemistry. In addition to the transport parameters listed above, supporting parameters describing the surface properties of the geological materials, i.e. their specific surface areas and cation exchange capacities (CEC), are collected and described. A central part of the bedrock transport modelling is the development of a "retardation model", where site-specific sets of rock types, fracture types and deformation zone materials are identified and parameterised.

Recalling that the main focus of the present description is on the properties of the upper part of the rock and the regolith, it is noted that the bedrock transport modelling provides a more detailed description of the conditions at repository depth and that the level of detail decreases with increasing transport distance along hypothetical transport paths from the repository towards the surface system (see section 5.1.2). This is mainly because transport would take place in successively larger fractures and deformation zones, with the smaller structures encountered close to the repository offering most of the retention capacity available along the transport paths (see /Crawford 2008/) and thus also deserving the most detailed evaluation.

Regarding transport data from the upper part of the bedrock, it could in any case be noted that one of the fracture types in the retardation model (fracture type G with clay fracture coating) is based on data from a relatively shallow sampling point (at c. 118 m in KFM02A). Furthermore, one of the deformation zone materials, "fault rock", uses data from a shallow sample from zone A2 (c. 48 m in KFM01B). However, no modelling specifically dealing with the retention properties of the near-surface horizontal fractures/sheet joint discussed above has been performed.

Transport conditions in the regolith

In the transport scenario discussed above, retention processes in the regolith could also contribute to the overall retention effect on radionuclides released in the deep rock. As with retention in the bedrock, the effect of retention in the regolith depends on a variety of physical and chemical properties of the solid materials, the groundwater and the radionuclides. The properties of the various Quaternary deposits and the near-surface groundwater are also central to the assessment of other transport scenarios, primarily those associated with downward transport through the regolith, where the groundwater composition could be altered before it enters the bedrock.

Many of the site investigations providing data relevant for describing retention conditions were performed within the framework of the geological investigations, i.e. the investigations of soils and Quaternary deposits (see Table 3-3), and the hydrochemical monitoring (Table 3-4). The physical and chemical properties of Quaternary deposits and the groundwater are described in /Hedenström and Sohlenius 2008/, see also Tables 4-7 to 4-11 in the present report, and /Tröjbom et al. 2007/.

In particular, data on the following properties and parameters of importance for the assessment of solute retention data are available from the Forsmark site:

- Chemical compositions, i.e. elemental compositions (major and minor constituents and trace elements), of Quaternary deposits /Hedenström and Sohlenius 2008/ and groundwater /Tröjbom and Söderbäck 2006/.
- Organic content, pH values and redox conditions in the groundwater /Tröjbom and Söderbäck 2006, Tröjbom et al. 2008/.
- Contents of clay, organic material, and calcium carbonate in the Quaternary deposits /Hedenström and Sohlenius 2008/.
- Mineralogical compositions: primary minerals and clay mineralogy /Sohlenius and Rudmark 2003, Hedenström and Sohlenius 2008/.
- Chemical properties of solid surfaces: individual exchangeable cations and total cation exchange capacity (CEC) /Lundin et al. 2005, Hedenström and Sohlenius 2008/.
- Physical properties of Quaternary deposits: grain size distribution, porosity, density and water content /Hedenström and Sohlenius 2008/.

Whereas the general geochemical and hydrochemical descriptions are provided in the references cited above and need not be repeated here, some notes on more specific (and less accessible) parameters are summarised in the following.

- Most Quaternary deposits in the Forsmark area are characterized by high contents of calcite (i.e. calcium carbonate, $CaCO_3$). The average calcite contents in till and clay samples from the terrestrial area are c. 20% (Table 4-7). However, the results also show that the content of this mineral is low in a majority of the gyttja sediments. An exception is the high calcium carbonate contents in the youngest lake sediments formed during the present lake stage, which are due to precipitation caused by the high concentration of dissolved calcium carbonate in the lake water /Hedenström and Sohlenius 2008/.
- Calcite dissolution releases large amounts of Ca^{2+} and HCO_3^- ions into the shallow groundwater system. The rich supply of Ca^{2+} ions is an important prerequisite and driving force for an extensive cation exchange that seems to take place in the Quaternary deposits, where Na^+ and other cations, released by e.g. weathering of rock minerals, exchange with Ca^{2+} and get into the solution /Tröjbom et al. 2007/.
- Groundwater from monitoring wells at topographically higher locations, presumably recharge areas, show clear influences of the calcite rich deposits, resulting in very high levels of calcium, bicarbonate and strontium.The strontium content in till in the Forsmark area is about seven times higher than normal values of Swedish till. A similar elevation is also seen when surface waters in the Forsmark area are compared to most Swedish surface waters /Tröjbom and Söderbäck 2006/.
- Average clay contents in samples from the terrestrial area range from 2–4% in sandy and gravelly till and 11% in clayey till to 15% and 57% in samples classified as silt and clay, respectively (Table 4-7).
- The development of a biologically active soil layer and the accompanying supply of organic carbon to the Quaternary deposits give prerequisites for drastic alterations in the hydrochemical conditions in the shallow groundwater. Present concentrations of total organic carbon, TOC, in surface water and shallow groundwater in the Forsmark area are high in a national perspective /Tröjbom and Söderbäck 2006/.
- Postglacial clay can often be found in the deeper parts of valleys below the highest coastline. It often contains organic material and is then often referred to as gyttja clay (2–6% organic matter), clay gyttja (6-20% organic matter) or gyttja (> 20% organic matter). Thus, the geological classification directly corresponds to ranges of organic contents. A detailed presentation of measured organic contents in specific samples and sampling profiles is given in /Hedenström and Sohlenius 2008/.

- The quantitative mineralogical analyses showed small variations in the contents of most silicate minerals in the till, see /Sohlenius and Rudmark, 2003/. The samples contained almost 40% of quartz, which is similar to most of the bedrock in the investigated area. There was a relatively high content of hornblende in two samples from west of Lake Bolundsfjärden.
- The qualitative analyses of clay mineralogy in samples from the terrestrial area showed that illite is the most common clay mineral in all four samples analysed. The results also showed that the illite/chlorite ratio is higher in the clayey till compared to the silty-sandy till /Sohlenius and Rudmark 2003/.
- Qualitative analyses of the mineralogy in samples from lake sediments showed that illite is the most common clay mineral in the three samples analysed. One obvious discrepancy between the clay samples was that the postglacial clay did not contain any calcite, which was present in the two glacial clay samples. The results showed similar distributions of clay minerals in glacial and postglacial clay /Hedenström and Sohlenius 2008/. Illite is the dominating clay mineral followed by chlorite and small amounts of kaolinite. The results imply that the clays only to a small degree have been affected by chemical weathering.
- Exchangeable cations were measured in samples from a set of vertical profiles in the excavated trenches mentioned in section 5.2.2, see /Lundin et al. 2005, Albrecht 2005/. The results are summarised, including calculated cation exchange capacities (CEC), in /Hedenström and Sohlenius 2008/. Most samples were classified as till (sandy or in some cases gravelly or clayey till). The CEC values of these samples are in the range 2–14 $mmol_c$/100g dw (dry weight). Considerably higher CEC values, 80–150 $mmol_c$/100g dw, were obtained for the uppermost samples in the profiles. These samples were also characterised by much higher organic contents and somewhat lower pH values than those from larger depths.

5.3.5 Retention parameters and process identification

The handling of solute retention in transport models could range in complexity from relatively simple K_d-based modelling concepts to so-called process-based or mechanistic modelling. In K_d-based models, retention is modelled as a linear equilibrium process, which means that the relation between sorbed and aqueous concentrations is given by a constant coefficient, the K_d distribution coefficient. This is the modelling appoach taken in the SKB safety assessment modelling of the surface system, i.e. the biosphere modelling; note that in this modelling the solutes may also be subject to other retention processes (primarily diffusion). In the safety assessment modelling, also other, conceptually similar distribution coefficients are used for describing, for instance, the solute distribution between water and biota; these are often referred to as transfer factors.

Mechanistic modelling of retention processes implies that the processes are described using more basic information about the system, e.g. geochemical and hydrochemical data including speciation and properties of reactive surfaces. Whereas potentially providing a more detailed and therefore (hopefully) also a more correct description of the system, this type of modelling involves parameters that are not always easy to measure or otherwise estimate on a site-specific basis.

In the SDM-Site Forsmark work, data collection and evaluations intended to provide a basis for both K_d-based and mechanistic retention models have been performed. However, these activities, which are summarised in the remainder of the present section, as well as the transport modelling presented in the next section, are to be considered as parts of a work in progress. Further studies will be performed in the SR-Site stage and the final results will be presented in the SR-Site reporting.

Site-specific Kd values

In an on-going project, site-specific data on K_d values are obtained by measuring the aqueous (pore water) and solid phase concentrations in soil samples. Sampling for these measurements has been performed in both Forsmark and Laxemar-Simpevarp; samples were taken at three locations in Forsmark and four locations in Laxemar-Simpevarp. In Forsmark, the following Quaternary deposits and environments were included in the sampling programme:

- Clayey, silty till from a fen in mixed forest.
- Clayey silty till (with mull) from arable land.
- Peat from a fen in *Pinus* forest.

At each sampling location, ten sub-samples were taken at a depth of c. 30 cm. The individual sub-samples were "randomly" collected from an area of around 30 m^2. The ten sub-samples from each site were mixed into one general sample, which was used for further analyses. As a supporting characterization, grain size analyses and measurements of the calcite and organic matter contents were performed on the till samples.

The soil solids and the pore water in the general samples have been analysed for elemental composition; the methods used are described in /Sheppard et al. 2007/. In short, the samples are incubated for at least seven days at field capacity moisture content, followed by extraction of the pore water by centrifugation, analyses of the compositions of the two phases, and calculations of K_d values based on the concentration ratios. This procedure will result in K_d values for approximately 50 elements. As a part of the evaluation of the resulting dataset, the site-specific K_d values will be compared with literature data from other sites.

Site-specific K_d values of suspended material and sediments in lakes and sea bays are also currently under evaluation. The sampling and chemical analyses performed to obtain these K_d data are described in /Engdahl et al. 2008/.

Conceptual model of retention processes

As described in the preceding section, parameters of interest for modelling of retention properties, including mineralogy and geochemistry, are available from the geological investigations of the Quaternary deposits in Forsmark. Based on this information and on the hydrochemical monitoring data available at the time of the study, /Grandia et al. 2007/ evaluated potential retention processes for a set of selected radionuclides. The main objective of the work, which included both conceptual and numerical transport modelling, was to assess the transport behaviour of selected long-lived radionuclides, with special focus on evaluating the capacity of the Quaternary deposits for radionuclide retention. The work was based on data and other information from Forsmark data freeze and SDM version 1.2.

Five radionuclides were selected for conceptualisation and qualitative evaluation of retention processes: uranium (U) as an actinide, selenium (Se) as a redox-sensitive radionuclide, caesium (Cs) as a monovalent cation, strontium (Sr) as a divalent cation, and iodine (I) as an anion radionuclide. In principle, radionuclide retention capacity in the surface system at the Forsmark site can be provided by sorption on charged surfaces of clays and oxyhydroxides, co-precipitation with sulphates, sulphides, oxyhydroxides and carbonates, and sorption on organic matter /Grandia et al. 2007/.

Different processes will dominate under different conditions and for different radionuclides; thus, one major aim of the study was to determine, based on the then available information, which processes would dominate under the conditions prevailing in Forsmark. The conclusions in /Grandia et al. 2007/ regarding retention processes for the selected radionuclides can be summarised as follows.

- The adsorption on ferrihydrite is the most plausible retention mechanism for uranium in till. The elemental analyses of the till in Forsmark support this hypothesis, since uranium concentrations are relatively high showing a rough correlation with the iron content. In more reducing glacial and postglacial clays, ferrihydrite is unstable and uranium is expected to be retained via precipitation of U(IV) solid phases. However, the uranium complexation with organic acids (e.g., humic acids) can reduce the availability of free aqueous uranium preventing a quick saturation with these phases.
- Selenium retention will also be strongly related to redox conditions. Under reducing conditions, microbial activity is able to reduce both selenite and selenate to elemental selenium, which subsequently precipitates as iron selenide or co-precipitates with pyrite or amorphous FeS. In contrast, the retention capacity in more oxidising conditions can be much lower, although some mechanisms such as incorporation into carbonate minerals and adsorption onto organic matter may be effective.
- Caesium competes with other monovalent and divalent cations in the interlayer of the clay minerals. In particular, this element has a strong affinity to so-called "frayed edge sites" (FES) in clay minerals such as illite, which is a major component of some Quaternary deposits at Forsmark. Therefore, cation exchange is expected to be the main retention mechanism for caesium in both glacial clay and till.
- Strontium is also involved in cation exchange reactions in illite, competing with other divalent cations for the so-called "planar" sites. Strontium can also co-precipitate with calcium forming $Sr_xCa_{1-x}CO_3$ solid solutions, although the incorporation of strontium into the calcite lattice is limited to molar fractions below 3.5×10^{-3}. This limitation is caused by the non-ideal behaviour of this solid solution series.
- Iodine is a highly mobile element that can be present in soils as organic and inorganic complexes. The retention processes affecting this element are dependent on the aqueous speciation. Sorption onto hematite and kaolinite is an effective retention mechanism for iodate, whereas iodine can be adsorbed on illite. In organic matter-rich soils, iodine is effectively complexed by humic acids. Microbial activity can drive the methylation of iodide (CH_3I), which is volatile.

The result of the process evaluation for the five radionuclides is shown in Table 5-2. Many processes occurring at low redox potentials (e.g. precipitation of selenium in sulphides) are in grey since reducing conditions were not confirmed to occur in the Forsmark near-surface system. However, it should be noted that in the data evaluation presented in section 5.3.3 (which was performed after the study summarised in Table 5-2) it was concluded that reduced conditions prevailed at most depths from which the hydrochemical data used in the evaluation were obtained.

The conceptual retention process models for different radionuclides were also implemented in numerical models, see /Grandia et al. 2007/. Specifically, two-dimensional coupled hydrogeological and reactive solute transport models were developed to simulate the geochemical behaviour of U, Cs and Sr. In a second step of the numerical modelling reported in /Sena et al. 2008/, the modelling was extended to include also radium (Ra). This coupled transport modelling is discussed in the next section together with the other transport modelling activities performed in connection with the Forsmark SDM-Site modelling.

5.4 Solute transport modelling

According to the general conceptualisation of solute transport outlined above (section 5.3.4) the media where transport takes place, i.e. fractured rock and regolith, can be viewed as consisting of mobile and immobile zones. Water flow and advective transport of solutes (i.e. transport with the flowing water) are restricted to the mobile zone(s), whereas solutes can be retained (retarded or immobilised permanently) through interactions with various immobile zones. The notion of immobile zones should be taken in a wide sense; it includes, for instance, solid surfaces, precipitates and stagnant water.

Table 5-2. Evaluation of retention processes reported in /Grandia et al. 2007/. The mechanisms that are "able to retain" and are likely to occur under the conditions found in the Quaternary deposits at Forsmark are indicated by black cells. Processes judged "able to retain" but of questionable occurrence at Forsmark are grey-shadowed. Processes considered "unable to retain" and/or unlikely are indicated by colourless cells in the table.

Radionuclide / *Retention process*	*U*	*^{79}Se*	*^{129}I*	*^{135}Cs*	*Sr*
Precipitation as pure phases	Favourable but perhaps unlikely	Favourable but perhaps unlikely	Unfavourable and/or unlikely	Unfavourable and/or unlikely	Unfavourable and/or unlikely
Sorption onto phyllosilicates	Favourable but perhaps unlikely	Unfavourable and/or unlikely	Favourable and possible	Favourable and possible	Favourable and possible
Sorption on organic matter	Favourable and possible	Favourable and possible	Favourable and possible	Unfavourable and/or unlikely	Unfavourable and/or unlikely
Sorption onto Fe-Mn-Al oxyhydroxydes	Favourable and possible	Favourable but perhaps unlikely	Favourable and possible	Unfavourable and/or unlikely	Unfavourable and/or unlikely
Association with carbonates	Unfavourable and/or unlikely	Favourable but perhaps unlikely	Unfavourable and/or unlikely	Unfavourable and/or unlikely	Favourable and possible
Association with phosphates	Favourable but perhaps unlikely	Unfavourable and/or unlikely	Unfavourable and/or unlikely	Unfavourable and/or unlikely	Unfavourable and/or unlikely
Association with sulphides	Unfavourable and/or unlikely	Favourable but perhaps unlikely	Unfavourable and/or unlikely	Unfavourable and/or unlikely	Unfavourable and/or unlikely

Favourable and possible (black)

Favourable but perhaps unlikely (grey)

Unfavourable and/or unlikely (white)

In this section, we summarise the modelling of advection and coupled advection and retention that has been performed in support of SDM-Site Forsmark. The following modelling activities are discussed:

- Particle tracking and advective-dispersive modelling with the MIKE SHE tool /Gustafsson et al. 2008, Bosson et al. 2008/. MIKE SHE is the main tool used in the numerical groundwater and surface water flow modelling of the surface system; it also contains a set of transport modules.
- Particle tracking simulations with the ConnectFlow tool /Follin et al. 2007, 2008/. ConnectFlow is the code used in the hydrogeological modelling of the bedrock.
- GIS-based modelling of coupled advection and decay/degradation using the PCRaster-POLFLOW approach /Jarsjö et al. 2005, 2007, 2008/.
- Modelling of coupled advective-dispersive and reactive transport using the PHAST tool /Grandia et al. 2007, Sena et al. 2008/; the starting point of the process-based modelling of solute retention was the conceptual models described above.

5.4.1 Flow paths and discharge areas

Modelling of flow paths and discharge areas for groundwater from the deep rock, particularly groundwater that passses through the intended repository area, is important for understanding the effects of a hypothetical radionuclide release from the deep repository. Specifically, this type of analysis shows where radionuclide-bearing groundwater may discharge, and hence which areas need to be considered in the assessment of the effects of this discharge. However, flow path analysis is also used for improving the general understanding of the site hydrology, e.g. by evaluating discharge areas for deep groundwater from the whole model area (not just the repository area) or the recharge-discharge pattern related to the surface system.

Regarding the flow paths from the repository area. it should be noted that the final analysis of flow paths and associated performance measures (i.e. solute travel times and "transport resistances") is performed in the safety assessment. One important difference between SDM and safety assessment calculations of flow paths is that the details of the repository layout and canister positions are not taken into account in the SDM work. This implies that particles may be started at positions where canisters would never be placed due to too high groundwater flow velocities. Another important difference is that the SDM modelling considers the past and the present only, whereas the safety assessment also deals with future hydrogeological conditions including changes in boundary conditions related to the predicted shoreline displacement.

ConnectFlow particle tracking results

In particle tracking simulations, imagenary “particles” or “water parcels” are started at selected positions in a flow model and tracked as they move with the flowing water. The particle trajectories provide information on the flow paths from these starting positions, e.g. on where the injected particles leave the model volume. These points are here referred to as “exit points” or “discharge points” (the results are also discussed in terms of discharge areas). They are in most cases points where the particles leave the (saturated) groundwater zone to enter surface waters or the unsaturated zone, but also exit points at vertical boundaries of the model volume are recorded.

In the ConnectFlow groundwater modelling reported in /Follin et al. 2008/, particle tracks were calculated for a release within a tentative repository layout area shown in Figure 5-20. Particles were started on a 100 m spacing in a plane at 500 m depth in a steady state flow field representing the present conditions at the site. There were two distinct types of paths followed in the ConnectFlow particle tracking, one set of short paths towards the shoreline of the Baltic Sea to the north, and one set of longer paths of particles that moved downwards before returning to the Baltic Sea to the east. The short paths are generally associated with the western side of the release area and travel upward until they encounter the sheet joint features in the shallow bedrock aquifer, then track along these until they discharge around the intersect with the Singö deformation zone. Some of these particles cross the zone and discharge in the sea floor around the SFR repository.

These particle tracking results highlight the importance of the property assignment of the Singö deformation zone in influencing the locations of modelled discharge areas. It should be noted that pumping in the SFR repository was not implemented in this application of the so-called “stage 2.3 base model simulation” /Follin et al. 2008/. Particles starting in the eastern side of the release area tended to move horizontally or downward, as shown in Figure 5-20, until they encountered the deformation zones that slope gently south-east. The implications of this division of flow paths into two sets should be the subject of further analysis within the SR-Site safety assessment /Follin et al. 2008/.

In order to give some measure of which deformation zones are most important to transport from the repository target area, the percentage of particles that entered each individual deformation zone was evaluated. The results show that the Singö deformation zone sees 75% of the released particles and the lower sheet joint feature (the horizontal fractures/sheet joints were modelled as three distinct features) sees just over 50% of particles. These two features account for the later stages of transport pathways close to the discharge areas. Other zones probably have greater importance for flows close to the repository volume.

MIKE SHE particle tracking and advection-dispersion results

The transport modelling performed with MIKE SHE and associated transport modules includes particle tracking simulations and modelling with a tool based on the advection-dispersion equation. In the following, we summarise some results obtained using the flow model representing the final result of the calibration on measured surface water and groundwater data. More detailed descriptions of the transport modelling are given in /Gustafsson et al. 2008/ and /Bosson et al. 2008/.

Particle tracking simulations were run with and without including the drainage pumping in the SFR facility. Two different particle injection cases were considered, one case where particles were injected in every cell (i.e. with a 40 m spacing) at 150 m.b.s.l. (bottom level of injection layer) in the whole model area, and one case where particles were injected within the area corresponding to the planned repository only. Also in the second case, the particles were introduced at 150 m.b.s.l. even though the repository is planned to be built at c. 500 m.b.s.l. This is a difference from to the ConnectFlow particle tracking discussed above, where the particles were started at repository depth. The simulation period in the MIKE SHE modelling was 300 years in all four simulations, using the calculated transient flow modelling results obtained for a one-year period as input. A similar 5,000-year simulation was also performed.

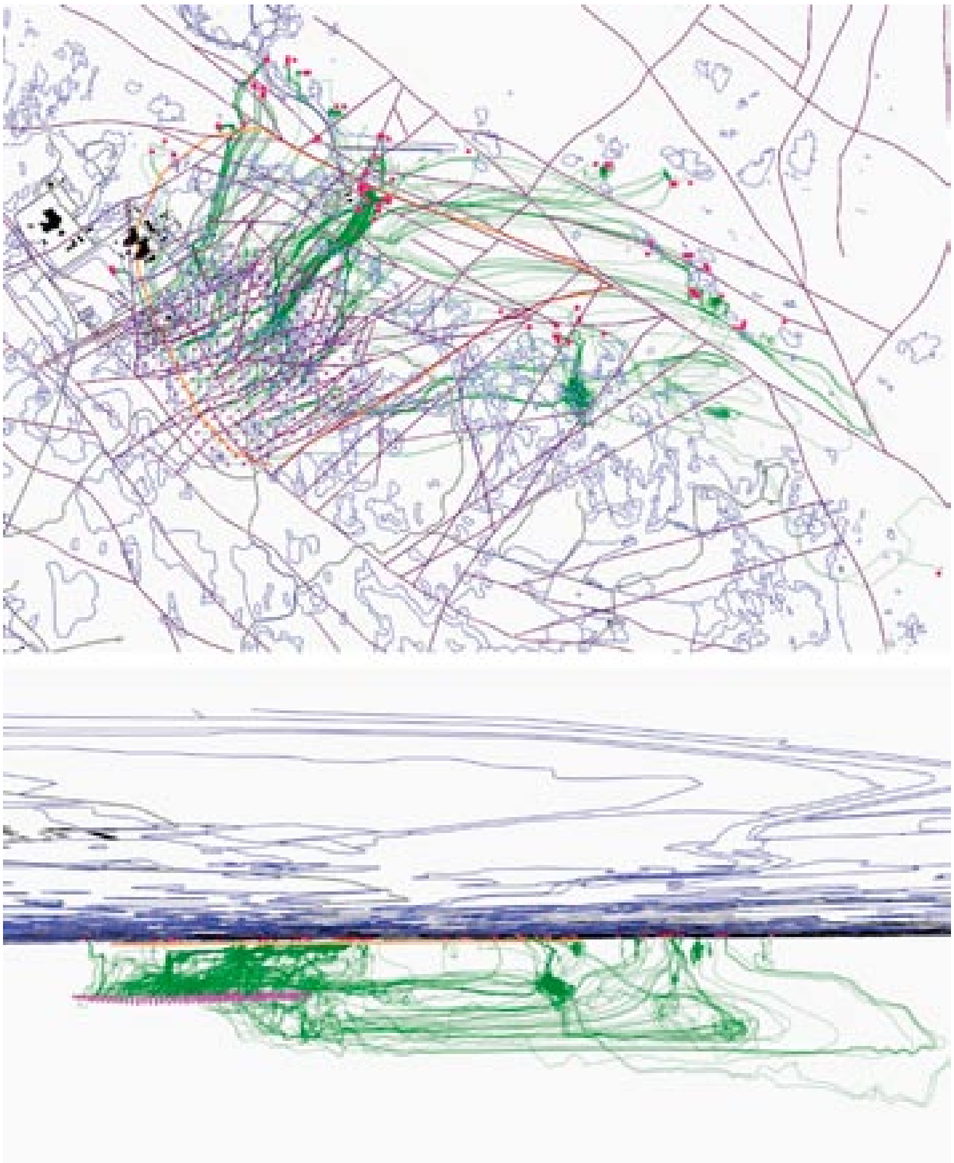

Figure 5-20. Top: Plan view of the target area with predicted flow paths and exit points at the surface (red dots) of c. 300 particles using the "stage 2.3 base model simulation". The nuclear power plant is shown in the upper left part of the figure; the starting positions of the particles are indicated by the regular pattern of points south-east of the power plant. Below: A perspective view of the flow paths towards northwest. Figure reproduced from /Follin et al. 2008/.

Irrespective of whether the SFR pumping was included in the model or not, the results for the case with injection below the whole model area showed that many particles were left in the model after 300 years; c. 65%, of the particles were still in the model volume at the end of the simulation, which implies that it would take more than 300 years for 65% of the particles to reach the ground surface or some other model boundary from 150 m depth. The main sink for particles when the SFR pumping was not included was the combined overland flow-unsaturated zone compartment (i.e. particles either went to the unsaturated zone or to overland water). However, the number of particles discharging in the sea was almost as large, see /Bosson et al. 2008/ for a detailed discussion.

When the drainage pumping in the SFR facility was included in the model, the water extraction there was the strongest particle sink. The overland flow-unsaturated zone compartment attracted almost as many particles, whereas the sea was a much less important sink in this case. Thus, many of the particles that dicharged in the sea when the pumping was not included in the model went to the SFR sink when the pumping was activated.

Figure 5-21 illustrates the results for the case without pumping in SFR. The figure shows the position of each particle where it left the saturated zone and moved to a specific sink, i.e. to the sea, the unsaturated zone, overland water or a stream. The different sinks are marked with different colours. The blue dots represent the particles that moved to the combined overland flow-unsaturated zone sink. Since the majority of the blue dots are situated in the lakes and close to water courses, i.e. in water-saturated areas, it is concluded that the majority of the particles registered in this sink have moved to the overland flow compartment, from where they can be transported further to and within the surface water system. In both simulation cases, with and without pumping in SFR, exit points can be observed in and near lakes and along the streams in areas outside the area of the horizontal fractures/sheet joints (Figure 5-14). However, in the area where these horizontal structures are thought to exist there are only a few exit points.

Figure 5-22 shows the accumulated particle counts for each cell at 150, 130, 110 and 90 m.b.s.l. at the end of the 300-year simulations. The case without the SFR drainage is shown to the left and the case with the SFR drainage is to the right in the figure. The accumulated particle count is a way to present the density of the flow paths. Each time a particle passes a cell, the accumulated particle count of that cell is increased by one. This means that the higher the value for a cell the more particles have travelled along flow paths going through that specific cell. The particle count reflects both horizontal and vertical transport, and since flow is transient a particle can pass the same cell several times.

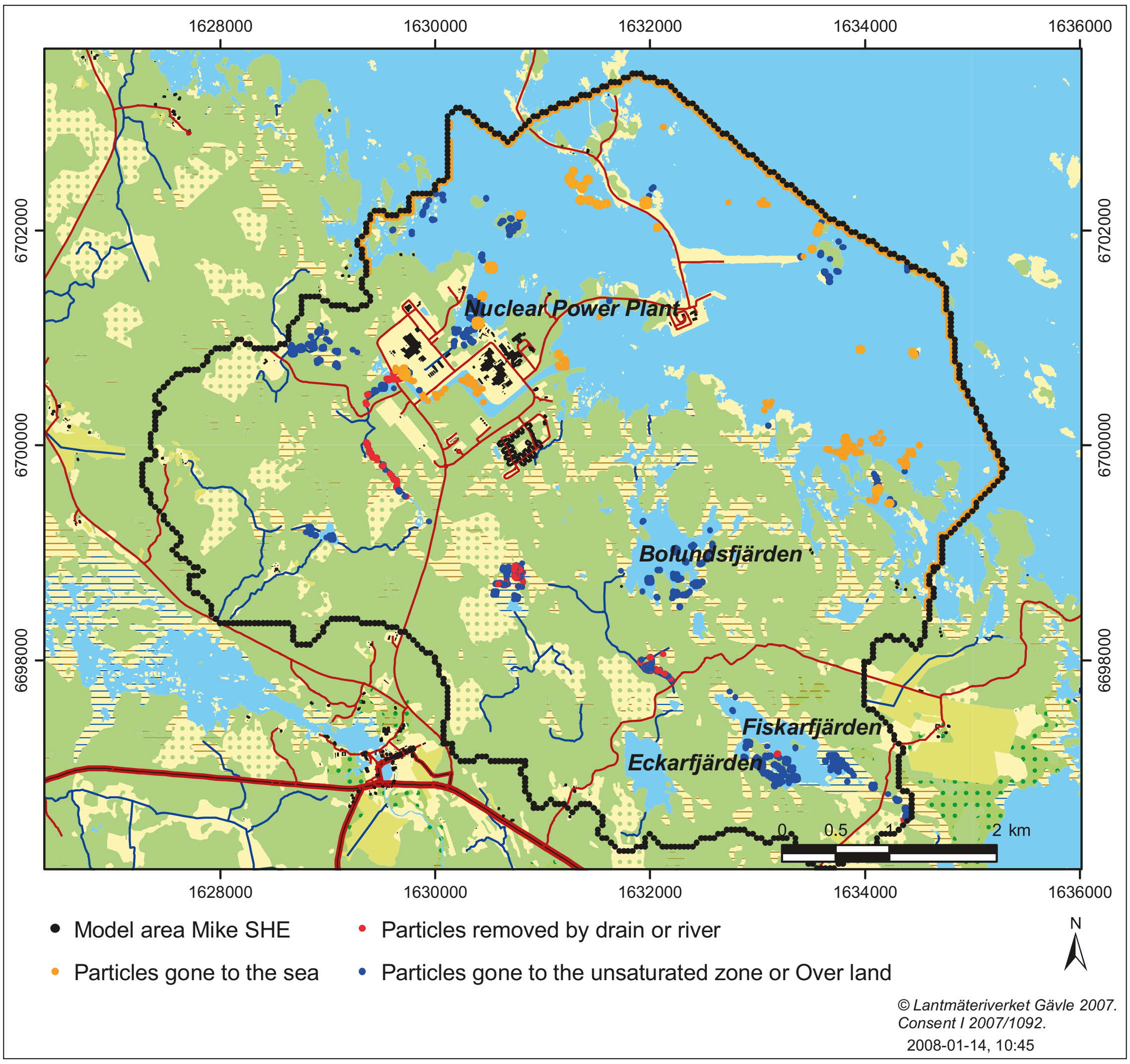

Figure 5-21. *Sinks for the particles in the simulation case with particle injection below the whole model area and without the SFR drainage in the model /Bosson et al. 2008/.*

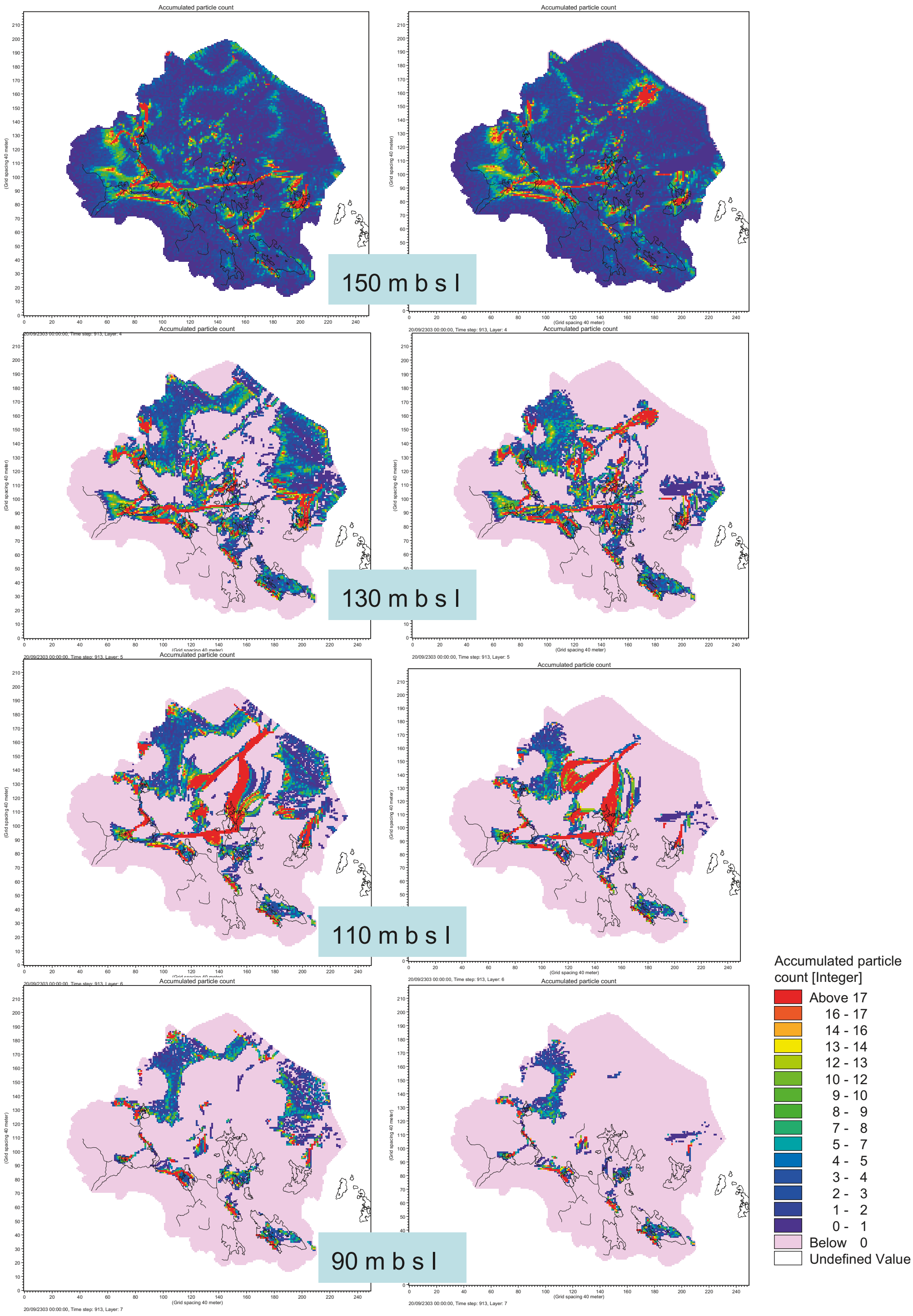

Figure 5‑22. *Accumulated particle counts at selected elevations in the bedrock. The particles move towards the fractures/sheet joints in the layer at 110 m.b.s.l. The figures to the left present the particle tracking results without the SFR drainage, and the figures to the right the corresponding results from case with the SFR drainage activated /Bosson et al. 2008/.*

The particles were introduced at 150 m.b.s.l. and since one particle was introduced in each cell at this level the minimum accumulated particle count in this layer is one (see the uppermost graphs in Figure 5-22). Pink colour indicates cells where no particles have passed. As shown in Figure 5-22, the flow paths concentrate to specific areas on their way towards the surface. At 110 m.b.s.l. one layer of horizontal fractures/sheet joints is represented in the model. It is seen that the particles concentrate there, as indicated by the red areas in the figure. The same overall pattern is seen for both cases. When pumping at SFR, particles released in the north-eastern part of the model area move towards SFR. The majority of the particles are transported in the layer at 110 m.b.s.l. Above this level only 40% of the cells that received a particle at 110 m.b.s.l. are hit by a particle.

Also in the particle tracking simulation cases where particles were started inside the area corresponding to the planned repository, particles were released at 150 m.b.s.l. After the 300-years simulation period only 10% of the particles had left the model volume in the case without pumping in SFR; all these particles had gone to the sea. When pumping in SFR was activated, 18% of the injcted particles left the model volume through the SFR pumping and the remaining 82% were still in the model at the end of the simulation. In both cases, the major part of the particles moved towards the sea in the horizontal fractures/sheet joints at 110 m.b.s.l. (see Figure 5-23).

As indicated in Figure 5-23, the particles concentrate to the sheet joint areas and the horizontal transport is dominating. Above this level only a few cells are passed by a particle. When pumping in SFR, no particles reach higher than 70 m.b.s.l. Thus, there are no exit points at the surface after 300 years simulation time when pumping at SFR. In the case where the pumping in SFR is not activated, a few particles reach the sea. These exit points are located close to the shoreline.

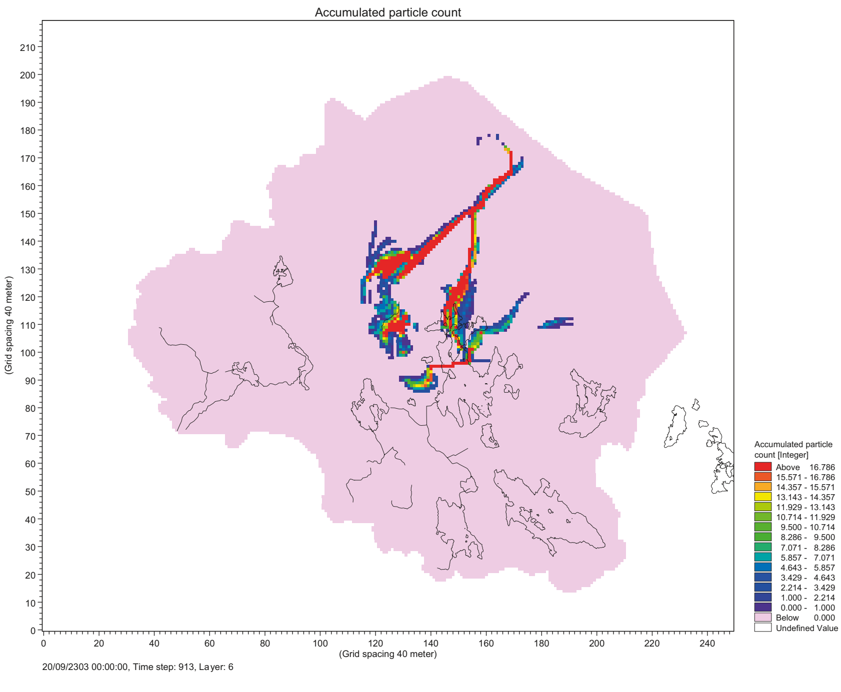

Figure 5-23. *Accumulated particle count at 110 m.b.s.l. for the simulation with particle injection within the planned repository area only and without the SFR pumping in the model /Bosson et al. 2008/.*

Since so many particles were still left in the model volume after 300 years, an additional longer simulation was run using the repository injection area. This particle tracking simulation was run for a period of 5,000 years without pumping in SFR. The exit points at the surface after 5,000 years are shown in Figure 5-24. As a comparison the exit points after 300 years are also shown in the same figure. The transport times are very long and even after 5,000 years the majority, 81%, of the particles are still left in the model volume. No exit points were found in the land part of the model area. All the particles exit the model volume to the sea. The results show that 5% of the total number of particles introduced are stuck in the marine sediments. Apart from them, no particles are found in the upper calculation layers. All the other particles that are left in the model after 5,000 years are found in the deeper bedrock between layer 8 at 110 m.b.s.l. and layer 14 at 600 m.b.s.l.

The MIKE SHE advective-dispersive transport modelling was performed using the "best case" flow model from the calibration and without SFR pumping in the model, see /Bosson et al. 2008/ for a summary and /Gustafsson et al. 2008/ for a detailed description of this modelling. In the first simulation, a uniform concentration solute source was located in the bedrock layer at a depth of approximately 140 m.b.s.l. The uniform source was applied all over the model area for one month, which means that the transport of a solute pulse was studied. Some results from this simulation are exemplified below, followed by a similar brief summary of the results from a simulation with the solute source placed at the upper model boundary.

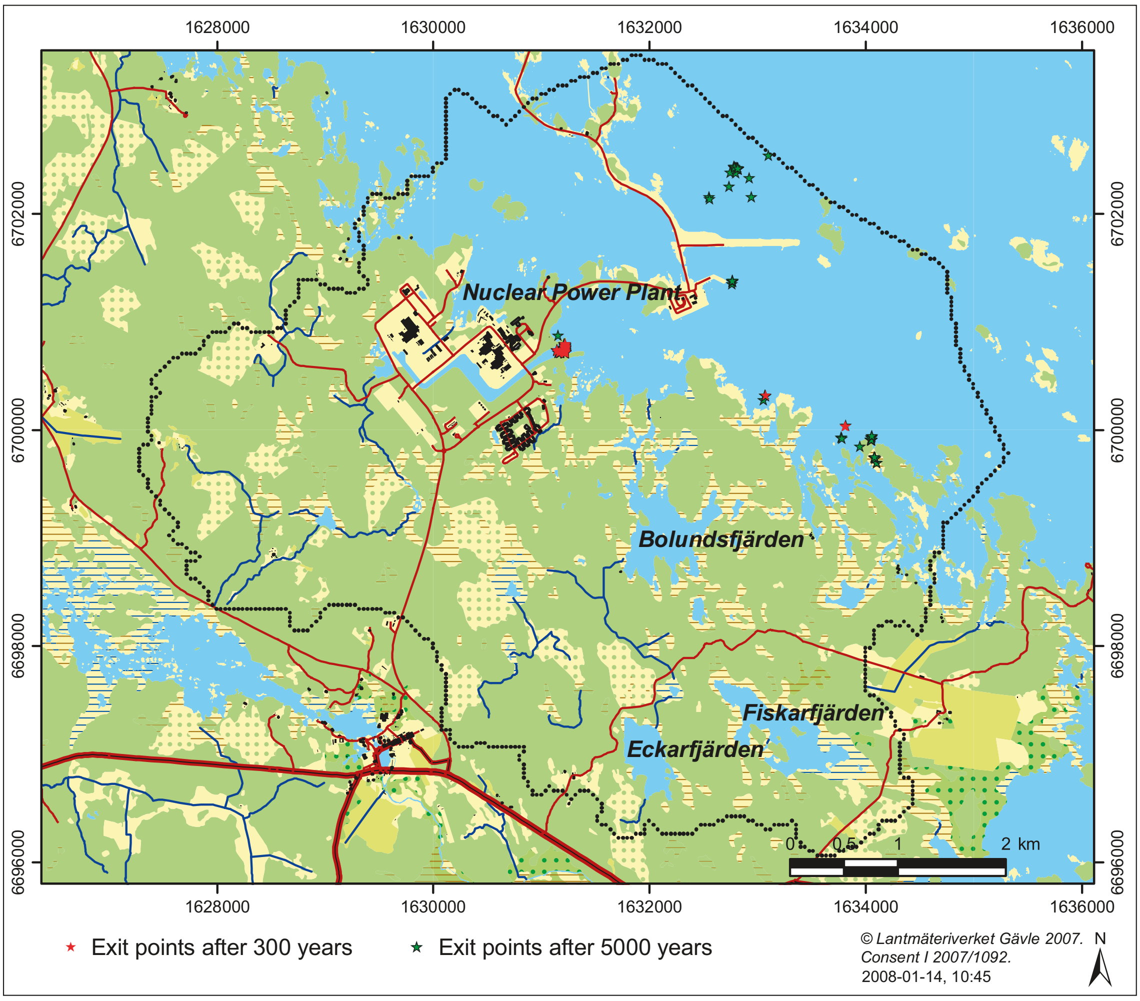

Figure 5-24. *Exit points at the surface or sea bottom after 5000 years for the case with particle injection within the planned repository area only and without the SFR pumping in the model. As a comparison, the exit points after 300 years are also marked in the figure /Bosson et al. 2008/.*

As discussed several times above, fractures/sheet joints with high horizontal hydraulic conductivities exist in the bedrock within the model area. In these zones, solute transport is mainly directed horizontally towards the sea. Figure 5-25 shows the position of the profile for which concentrations are displayed in Figure 5-26. In this profile, there are zones with high horizontal conductivities at depths of approximately 70 and 100 m.b.s.l. Concentrations along the profile are illustrated for simulation times of 10, 20, 50, 100, 150 and 200 years.

The horizontal transport towards the sea is clearly seen in Figure 5-26. The results illustrate that solute is moving mainly in the vertical direction until it reaches the area with the higher horizontal conductivity, located at a depth of approximately 100 m.b.s.l. The solute is then transported mainly in the horizontal direction. After about 100 years, parts of the solute mass are transported to the upper layer with high horizontal conductivity, located at a depth of approximately 70 m.b.s.l., and start moving towards the sea at that level.

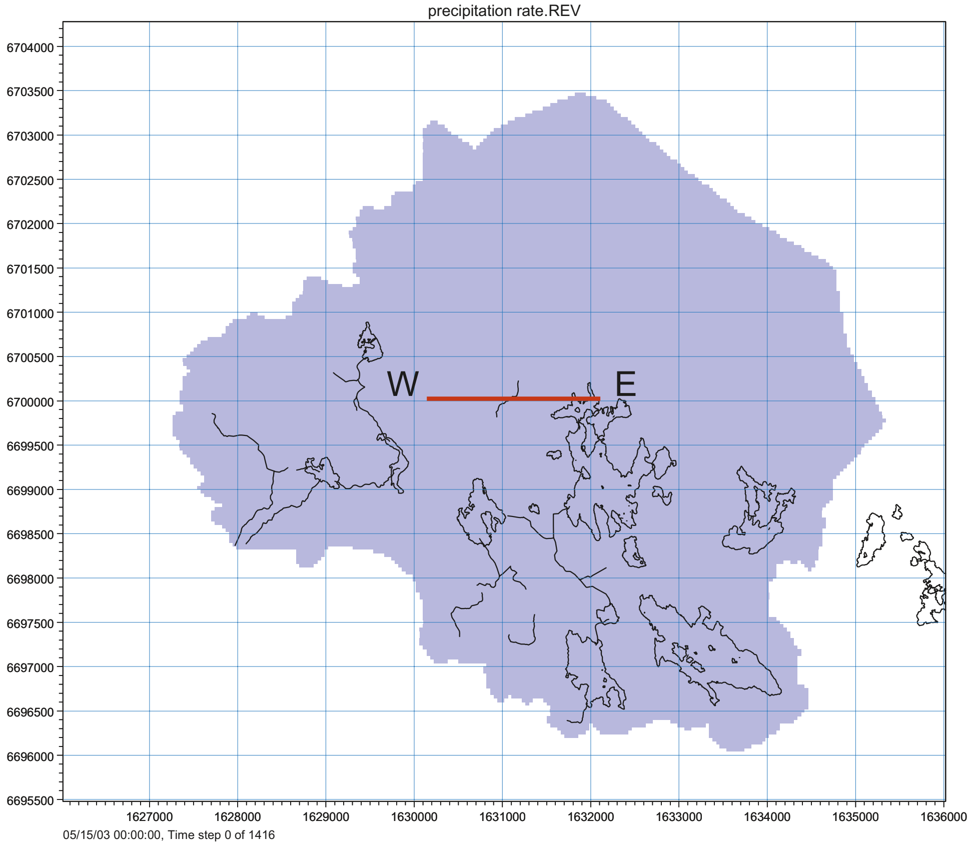

Figure 5-25. *Position of profile in the west-east (W-E) direction through an area of high horizontal conductivity in the upper bedrock /Bosson et al. 2008/.*

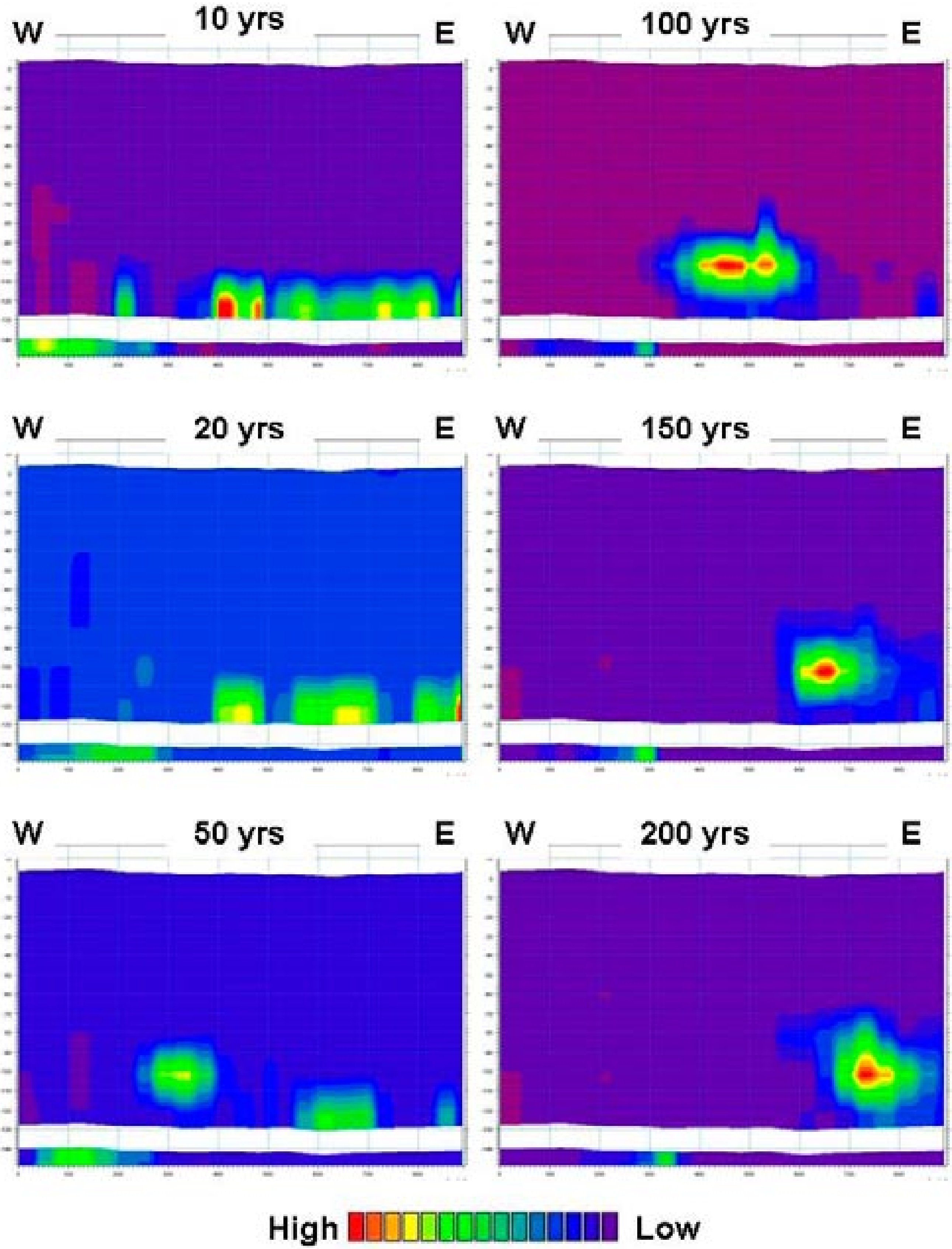

Figure 5-26. *Profile through the model area (location indicated in Figure 5-25) showing the advection-dispersion solute concentrations at six different times during the simulation /Bosson et al. 2008/.*

Concentrations have also been analysed for a SW-NE profile through Lake Bolundsfjärden and to the sea, see Figure 5-27. In the bedrock along the profile, layers with high horizontal conductivities are present at depths of approximately 70 m.b.s.l. and 110 m.b.s.l. Figure 5-28 shows the concentrations along the profile at six different times. These results show that after 20 years only the fast transport close to cell (176,121) has reached the upper layers. With time, solute starts spreading upwards also closer to cell (155,87), and after 40 years it is seen that it has reached the 110 m.b.s.l. level and starts moving horizontally towards the sea. After 50 years, solute has also reached the layer at 70 m.b.s.l. The figures show that solute transport at that level is also towards the sea.

In the second advection-dispersion simulation, the solute source was applied as a continuous infiltration source in the terrestrial part of the model area only. This means that the source was at the upper model boundary and that the solute was transported into the model by the infiltrating water coming from the precipitation. As a consequence, the amount of solute infiltrated to the model depended on the time-dependent rate of precipitation. The source concentration was constant and spatially uniform. Although primarily of interest for the surface system description, some results of relevance for the bedrock-regolith interactions were obtained also in this simulation.

In the surface system, a horizontal solute transport from higher-altitude recharge areas to lower-lying discharge areas, i.e. valleys and other depressions with lakes, wetlands and streams, would be expected. However, the model results indicate that the littoral zones act as hydraulic barriers around some of the lakes, as exemplified by Lake Eckarfjärden in Figure 5-29. This effect is not so obvious around Lake Bolundsfjärden, see Figure 5-30, where the horizontal transport seems to spread the solute also under some parts of the lake. In both cases, the spreading through horizontal transport in the upper layers is much smaller than the effects of vertical flow directions, whereby solute transport is being directed downwards into the rock.

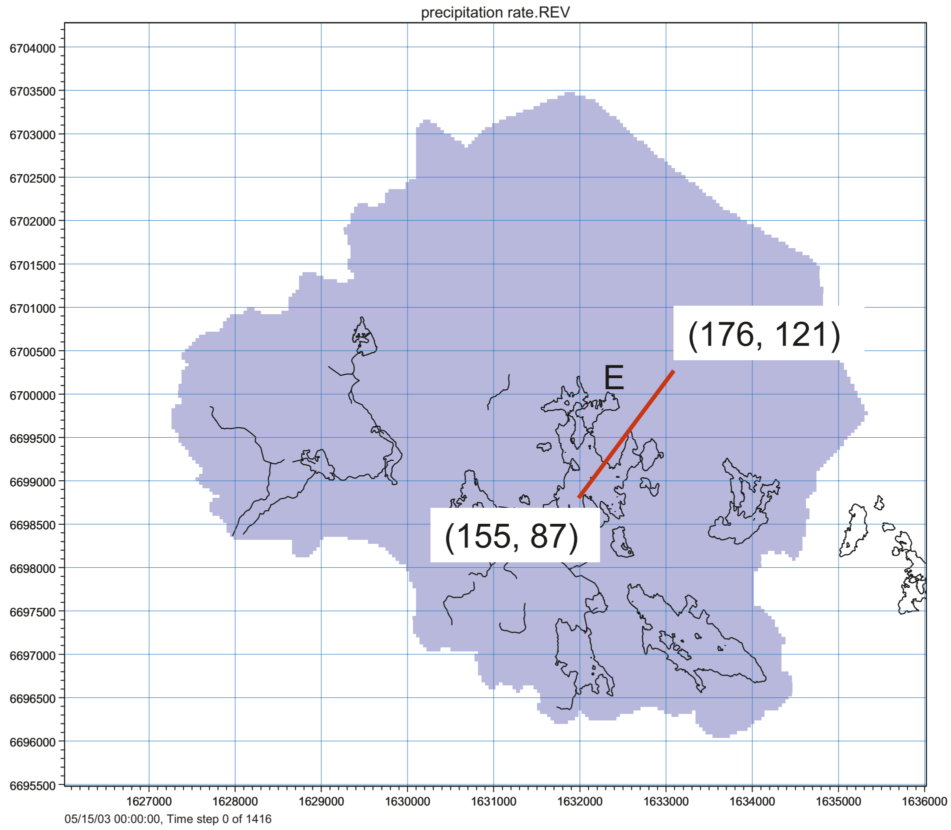

Figure 5-27. *Position of SW-NE profile through Lake Bolundsfjärden and to the sea; (176,121) and (155,87) are cell numbers in the MIKE SHE model /Bosson et al. 2008/.*

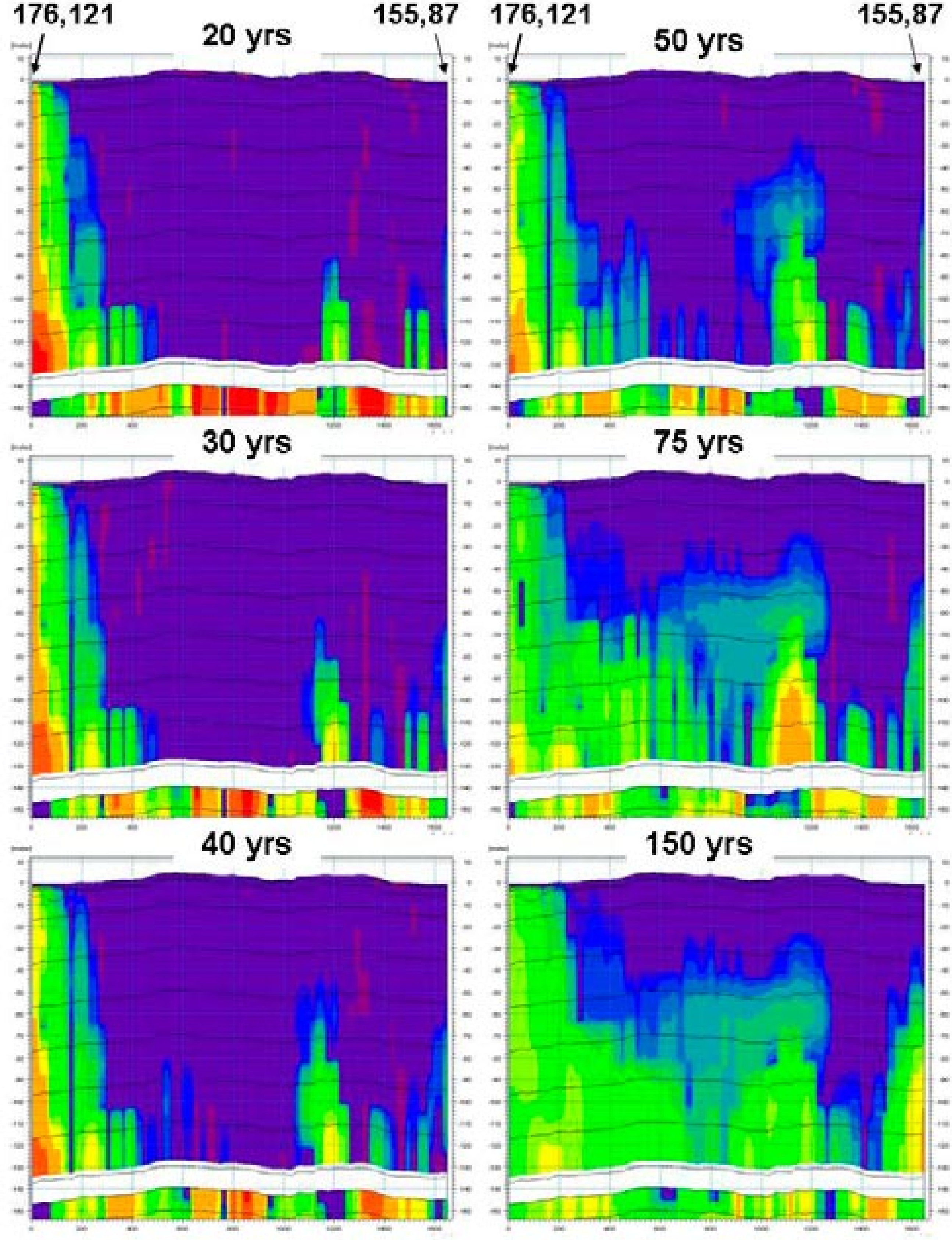

Figure 5-28. Solute concentrations in a SW-NE profile between cells (176,121) and (155,87), with location indicated in Figure 5-27, for six different times during the advection-dispersion simulation. The concentration scale is the same as in Figure 5-26 /Bosson et al. 2008/.

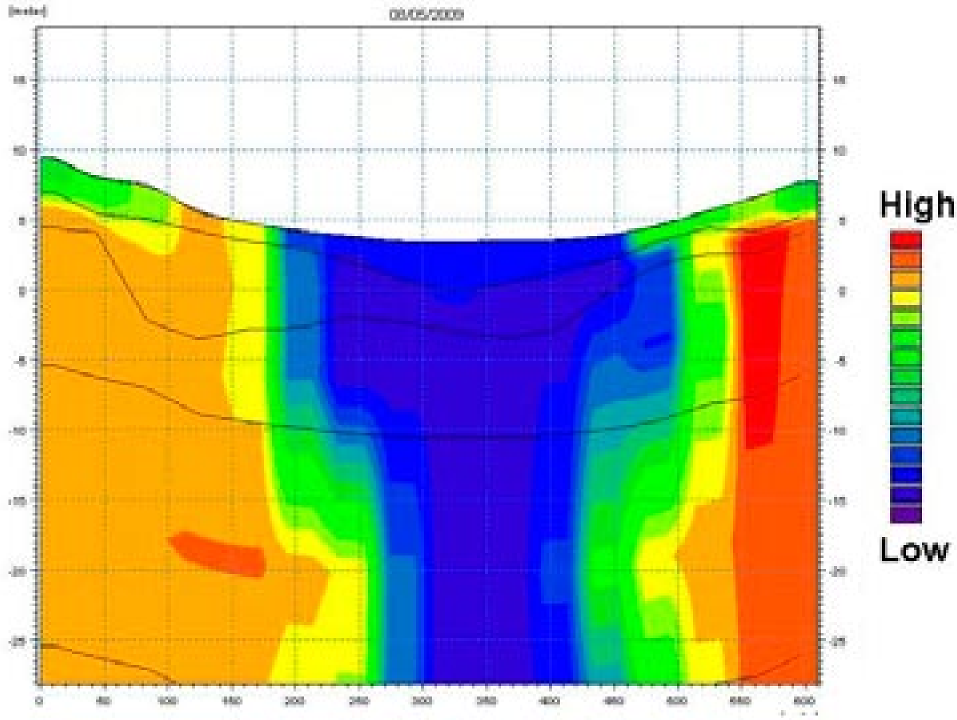

Figure 5-29. Solute concentrations after 5 years in a profile in the west-east direction through Lake Eckarfjärden, from advection-dispersion modelling of transport from a continuous infiltration source /Bosson et al. 2008/.

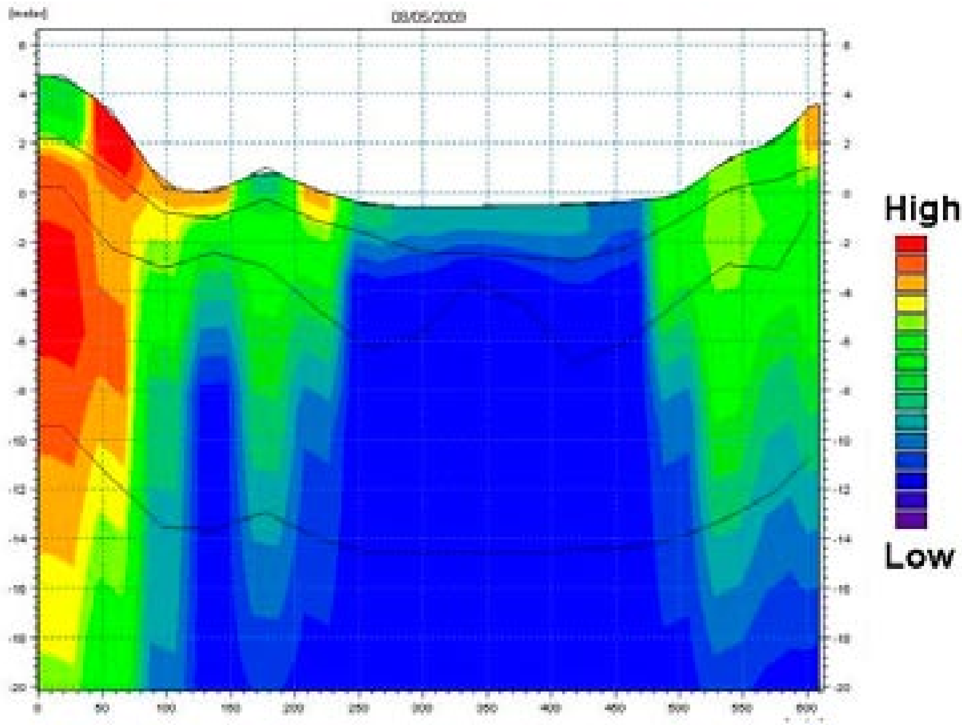

Figure 5-30. Solute concentrations after 5 years in a profile in the west-east direction through Lake Bolundsfjärden, from advection-dispersion modelling of transport from a continuous infiltration source. /Bosson et al. 2008/.

5.4.2 Coupled advective and reactive transport modelling

Modelling of advection coupled with retention and/or transformation has been performed for both relatively simple process models, here exemplified by first-order decay or degradation, and for considerably more complex models based on mechanistic modelling of a set of sorption and precipitation-dissolution processes. Results of modelling with both these types of models are summarised in this section.

Transport modelling with PCRaster-POLFLOW

/Jarsjö et al. 2004, 2005, 2007, 2008/ report on a series of studies where the GIS-based PCRaster-POLFLOW tools were used to model surface hydrology and solute transport in the SKB site investigation areas. Here, the focus is on the /Jarsjö et al. 2007/ study, which is where solute transport primarily is considered. The general theoretical, model-independent conceptualisation of solute transport from inland sources to downstream recipients that is presented in /Jarsjö et al. 2007/ provides a tool that can be useful for inter-model comparisons in the SKB site investigation or safety analysis programmes. However, in the present context we focus on the results of the site-specific modelling of Forsmark that was performed with the dual purpose of illstrating the modelling approach and contributing to the site description.

The Forsmark model application presented in /Jarsjö et al. 2007/ compared two solute transport scenarios similar to those illustrated in Figure 5-1, i.e. upward transport from the deep rock and then towards the recipient (the sea) either along the bedrock-regolith interface or up through the regolith and further to and within the surface water system. For these alternative transport pathways, so-called "mass delivery factors" representing the fraction of solute mass released in a model cell that reached the considered recipient were estimated. The transported solute was assumed to be subject to first-order degradation or decay governed by a temporally and spatially constant rate coefficient.

The results in /Jarsjö et al. 2007/ showed that average delivery factors, representing the whole catchment, could exhibit considerable differences between the considered transport scenarios. The magnitude of these differences in average delivery factors between the different scenarios, as well as between different possible solute release locations, were found to depend on the prevailing degradation rate. This is because for low rates (less than 0.01 year^{-1} considering both scenarios and the entire Forsmark area), practically all solute mass reached the sea regardless of release location and scenario, and for high rates (more than 10 year^{-1} considering both scenarios and the entire Forsmark area) only a small fraction of the released solute mass reached the coast regardless of release location and scenario.

These results generally imply that resulting solute mass delivery to recipients is sensitive to both solute transport pathways and solute entrance locations (or areas) in the Quaternary deposits of Forsmark. Zones of near-stagnant groundwater that have been found below lakes in the Forsmark area may considerably prolong transport times in some cases. Thus, it was considered a key issue to further investigate to which extent the deep groundwater transport pathway to the coast includes predominantly the surface water system, or predominantly the bedrock-regolith interface zone, or a considerable combination of both.

Furthermore, possible uncertainties in coastal discharge predictions (that underpin all transport results), related to uncertain spatial variation of evapotranspiration within the catchment, were shown to be small for the relatively large, focused surface water discharges from land to sea, because local differences were averaged out along the length of the main water flow paths. In contrast, local flux values within the diffuse groundwater flow field from land to sea were found more uncertain, although estimates of mean values and total sums of submarine groundwater discharge along some considerable coastline length may be robust. The results showed that 80% to 90% of the total coastal discharge of Forsmark occurred through focused flows in visible streams, whereas the remaining 10% to 20% was diffuse and occurring through submarine groundwater discharge, small transient streams and/or coastal wetlands (see /Jarsjö et al. 2007/ for details).

Advective-reactive transport with mechanistic retention model

As mentioned in section 5.3.5, the conceptual model of retention processes presented there was used as a basis for numerical modelling of the advective-reactive transport of selected radionuclides. Specifically, in /Grandia et al. 2007/ two-dimensional coupled groundwater flow and reactive solute transport models were developed to simulate the transport behaviour of U, Cs and Sr. This modelling was extended in a second step reported in /Sena et al. 2008/ by considering longer simulation periods, other initial and boundary conditions, and an additional radionuclide (Ra). Furthermore, the /Sena et al. 2008/ study included a sensitivity analysis of some key geochemical parameters and a comparison between the mechanistic models and K_d-based models.

In the two modelling studies, the same two distinct geological-hydrogeological domains were considered: a till system (Figure 5-31) and a clay system (Figure 5-32); by referring to them as "till" and "clay" systems, it is clarified that the transport scenarios investigate radionuclide retention in till and clay, respectively. The first (till) case simulates the intrusion of radionuclide-bearing groundwater from the bedrock into a relatively dynamic till aquifer. In the second (clay) case, the radionuclide-bearing water interacts with a low permeability, reducing clay layer present at the bottom of a potential discharge zone (such as a lake or the Baltic Sea), overlying the till layer. Thus the retention effect of the till, which groundwater coming from the bedrock would have to go through first, is neglected in the second case.

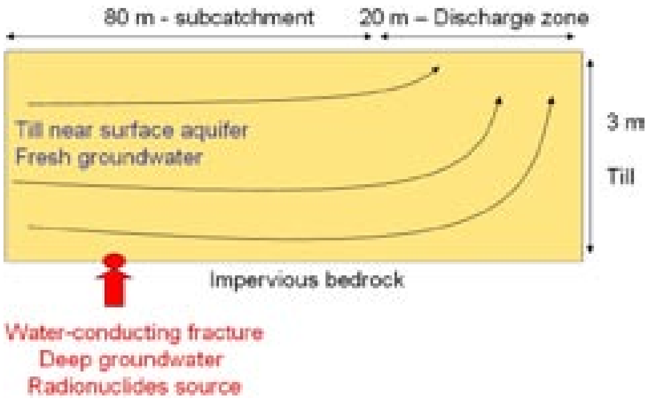

Figure 5-31. *Sketch of the till domain considered in the numerical modelling reported in /Grandia et al. 2007, 2008/. The red arrow marks the location where radionuclide-bearing groundwater from the bedrock enters the till layer.*

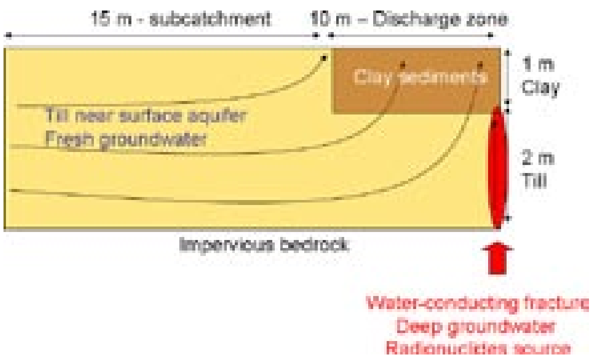

Figure 5-32. *Sketch of the clay domain considered in the numerical modelling reported in /Grandia et al. 2007, 2008/. The red arrow marks the location where radionuclide-bearing groundwater from the bedrock enters the till below the clay layer. Note that the domain is assumed to be symmetric (only the left half is modelled) and that only the clay layer is included in the numerical model.*

Reactive transport results in /Grandia et al. 2007/ indicate that caesium is very strongly retained in the illite in both the till and the clay system. Most of the caesium mass entering from the deep rock is effectively retained in the very close vicinity of the source, independently of the hydrogeological conditions. In the case of uranium, the most effective processes for retention are very different for the two considered hydrogeological systems. In the till aquifer, the dissolved uranium is mainly adsorbed onto the charged surfaces of ferrihydrite. The simulated clay system is much more efficient than the till aquifer for uranium retention due to the precipitation of amorphous uranium (IV) oxides.

Model results indicate that strontium is retained by two different geochemical processes: (1) cation exchange within illite interlayers, and (2) precipitation into a $Sr_xCa_{1-x}CO_3$ solid solution. Even though there are two distinct retention mechanisms affecting strontium, the clay system exhibits the lowest efficiency for retention of this radionuclide compared to the other two simulated radionuclides. Cation exchange is the dominating retention process in both the clay and the till system /Grandia et al. 2007/.

Figures 5-33 and 5-34 show examples of modelling results for Sr, where reactive transport is compared with the corresponding conservative transport cases, i.e. the same transport scenarios in terms of initial and boundary conditions, but without the geochemical retention processes. The results clearly show the effects of retention on solute propagation, and the differences between the two transport domains.

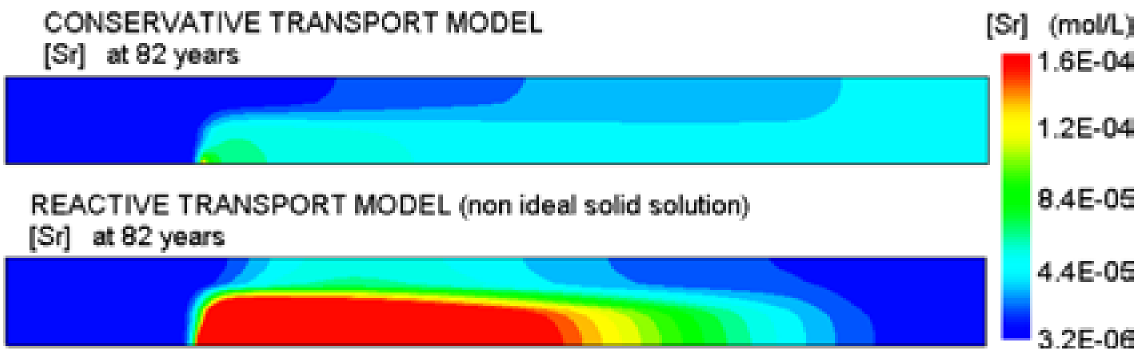

Figure 5-33. *Comparison between the predicted strontium concentration in the modelled till domain and the corresponding conservative transport case /Grandia et al. 2007/.*

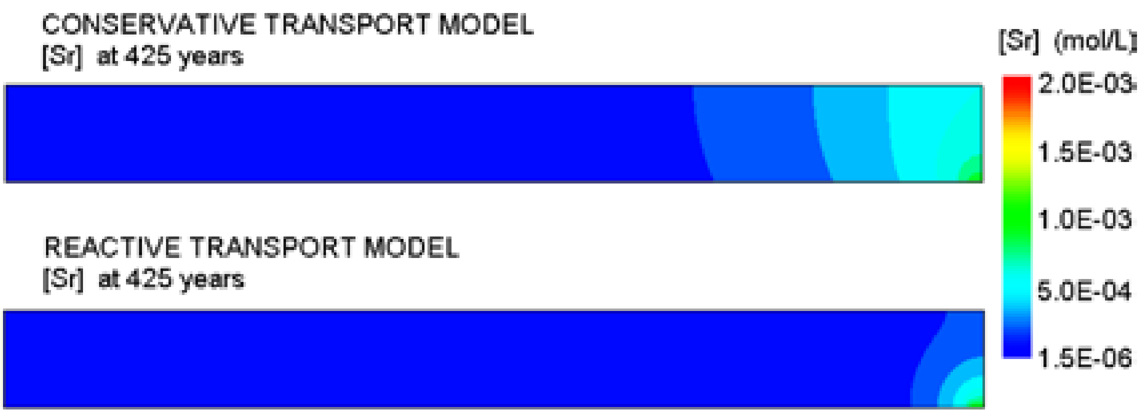

Figure 5-34. *Comparison between the predicted strontium concentration in the modelled clay domain and the corresponding conservative transport case /Grandia et al. 2007/.*

The modelling reported in /Sena et al. 2008/ considered modified boundary conditions such that the geochemical systems were first allowed to stabilise during 2,700 years with the natural concentrations of strontium, caesium, uranium, and the other solutes that characterise till porewater, clay porewater and deep groundwater. After the approach to the geochemical steady state, radionuclide release from the repository was simulated by increasing the concentrations of strontium, caesium, uranium, and radium in the inflowing deep groundwater. Reactive transport after repository release was modelled for another 2,700 years, see /Sena et al. 2008/ for details on the simulations.

In both domains, the simulated release from the repository lead to large increments of the strontium concentrations in the respective discharge areas. This reflected the combined effect of mixing and the relatively limited capacity of illite and $(Ca,Sr)CO_3$ solid solution to retain the added strontium at the concentration levels considered in the modelling (i.e. relatively high concentrations in the groundwater coming from the deep rock).

Uranium, caesium and radium concentrations in the discharge from the till system were only slightly increased after repository release. The relatively small increase in uranium concentration was due to the interaction between three processes: (1) mixing of deep groundwater affected by repository release and natural till groundwater, (2) release of uranium into solution due to dissolution of ferrihydrite, and (3) adsorption of uranium to the remaining ferrihydrite. The relatively small increment of the caesium concentration was caused by the effective retention of this radionuclide in the solid phase of the till. Finally, the relatively small increment of the radium concentration in the till system was due to the combined effect of dilution of the deep groundwater and retention of radium via precipitation of $(Ba,Ra)SO_4$ solid solution (see /Sena et al. 2008/).

The increases in the caesium and uranium concentrations in the discharge area of the clay system after repository release were relatively small. In the case of caesium, the observed small increment was mainly caused by the effective retention of this radionuclide in the illite interlayer, whereas for uranium it was related to the small uranium concentration difference between natural clay porewater and deep groundwater affected by repository release, together with the retention of uranium via precipitation of amorphous uraninite. The evolution of radium release from the clay domain after repository release was exclusively attributed to mixing of deep groundwater and clay porewater, since no retention of radium occured in the solid phase of the clay system.

Concering the application of K_d-based models as an alternative to reactive transport models, it was concluded in /Sena et al. 2008/ that K_d-based models lead to similar results as the ones attained in the reactive transport models only for longer simulation periods (after the approach to the geochemical steady state). In the beginning of the simulated time periods, when major geochemical reactions occur and influence radionuclides partitioning, K_d-based models are unable to reproduce the evolution of radionuclide concentrations. However, the comparison between the different models is obviously also strongly dependent on how K_d is estimated; the implications of different ways of estimating this parameter need to be further studied.

5.5 Concluding remarks

This chapter summarises the data and models available for describing hydrogeological and solute transport interactions between bedrock and surface systems. In particular, relevant parts of the bedrock site descriptive models and the various modelling activities investigating solute transport from bedrock to regolith are discussed.

The description of the bedrock geology and, in particular, the hydrogeological models derived using this description as a basic input, emphasise the special character of the fractured upper part of the bedrock within the target area and its importance for the hydrogeological conditions in that area. Understanding the function of this "shallow bedrock aquifer" is central to the conceptualisation and mathematical modelling of solute transport from repository depth to the surface system and vice versa.

Interactions between and integration of the “surface” and “bedrock” modelling activities and resulting models have been important components of the site descriptive modelling of the hydrological-hydrogeological system at Forsmark. Although there are some differences in the calibrated surface (MIKE SHE) and bedrock (ConnectFlow) groundwater flow models, it is concluded that they provide consistent results and reproduce measured site data.

Data on the radionuclide transport properties of the bedrock are available from the site descriptive modelling. However, since the main focus is on the retention capacity of the rock in the vicinity of the planned repository, no description specifically dealing with the uppermost part of the rock has been developed.

Some of the parameters required for assessing the solute retention conditions in the regolith are presented in this site description, whereas others, most notably K_d values of the different Quaternary deposits at the site, are not yet available. Measurements of concentrations for calculations of site-specific K_d values have been performed, and the results will be presented in connection with the SR-Site safety assessment.

The transport modelling performed to investigate solute advection (flow paths and discharge areas) and retention processes (e.g. sorption) at the site is a work in progress. Some important observations can be made in the results produced to date, but more work, including more thorough evaluations of the existing results, is required before the desired level of site understanding is reached.

6 Concluding synthesis of the surface system at Forsmark

6.1 General description

The Forsmark area is unique in many ways. The area does not represent a typical coastal Swedish site at the shoreline of the Baltic Sea. 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. Shoreline displacement has strongly affected landscape development 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/.

The study area is characterized by a small-scale topography with limited variations in altitude and is almost entirely located below 20 m.a.s.l. Till is the dominant 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 giving rise to 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, 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 QD. 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 QD, will overlie the more large-scale flow systems associated with groundwater flow in the bedrock. Also in the middle of Lake Bolundsfjärden, located in the central part of the study area, the lake level and the groundwater level in till are considerably higher than the levels in the bedrock down to 200 m depth, indicating a downward flow gradient from the lake and QD to the bedrock.

The flow systems around and below the lakes is 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 characterized 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 contains 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 to790 $\mu g\ L^{-1}$ 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 a 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 the calcium. This kind of lake is common in the region, i.e. along the coast of northern Uppland, but is not very common in Sweden as a whole /Nordén et al. 2008/. 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 northeastern part of Uppland County and is manifested in the flora. The Forsmark area has a long history of forestry, which is seen today as a fairly high percentage of younger and older clear-cuts in 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 (ed) 2008/.

In conclusion, the site description of the surface system has developed to provide a general understanding of how the site functions in terms of properties in different components, main functional units, processes and system descriptions from different scientific disciplines. The conceptual model that was developed at the beginning of the work in 2002 has been adjusted to site-specific features, and site data have been used to describe flows and accumulations of matter in and between ecosystems.

The site description will be used in safety assessments to provide input data on properties, identification of relevant processes, and an overall system conceptualisation and understanding.

This will be done by using this report as a pointer to the supporting background reports. The main references developed to be used as input to the safety assessment are:

- Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas. Site descriptive modelling, SDM-Site (R-08-19).
- The terrestrial ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (R-08-01).
- The limnic ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (R-08-02).
- The marine ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (R-08-03).
- Hydrochemistry of surface water and shallow groundwater. Site descriptive modelling, SDM-Site Forsmark (R-07-55).
- Description of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark (R-08-08).
- Description of the regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark (R-08-04).

The present site description covers all information available for the surface system at Forsmark. The wealth of information, both in form of data from the site investigations and of conceptual and numerical models, comprises a comprehensive foundation for the environmental impact assessment (EIA). The main SDM references for EIA are the ecosystem reports covering the biotic and abiotic aspects of Forsmark. The geology, hydrology and the hydrogeological properties of the Quaternary deposits have also been described, together with chemical characteristics of water, soil and biota in the Forsmark area. No specific description or subjective valuation of nature values (nature conservation or environmental protection issues) is made in the SDM itself, but all information needed is stored in the SKB-databases and is readily available.

Beside the general description, various properties and models, are available for use as input to the design of the repository. Important information for planning the above-ground facilities is found in the reports describing Quaternary deposits (regolith), surface hydrology, and the digital elevation model.

6.2 Conceptual models and supporting information

We started the site description task by defining a number of objectives. In the following section, these objectives and issues arising from addressing them are discussed, using supporting information and the current mature conceptualisation of the site. The development of discipline specific models and the integration of understanding between disciplines was the main target. The overall objectives are summarised as follows:

- Develop and document geometrical, ecological, regolith, hydrological and near surface hydrogeological models.
- Develop an integrated site description covering all surface-system disciplines.
- Describe site-specific processes and properties important for understanding the transport of matter within and between the bedrock and surface systems.
- Perform an overall confidence assessment.

To describe our confidence in the site description at this final reporting stage of the project; a short description is given of how each discipline has fulfilled the objectives given above. Finally, in section 6.3, a summary is given of the overall confidence in the site description for the whole surface system.

6.2.1 Regolith models

Since the most elevated areas at Forsmark are situated only c. 25 m.a.s.l., the Forsmark area has been situated below the Baltic sea until the last few thousand years. Thus, the formation, erosion and relocation of postglacial deposits have mainly taken place prior to emergence from the Baltic sea. Postglacial gravel and sand frequently overlie glacial clay, interpreted to mainly represent deposition after erosion and transport by currents on the sea floor. Postglacial clay, including clay gyttja, is predominantly found in the deeper parts of valleys on the sea floor. The ongoing isostatic uplift transforms sedimentary basins to sheltered positions, favouring the accumulation of organic sediments. Clay gyttja is frequent at the surface of the wetlands located at low altitudes, e.g. along the shores of Lake Fiskarfjärden and Lake Gällsboträsket. Gyttja is formed in lakes and consist mainly of remnants from plants that had grown in the lake. In areas with calcareous soils, such as the Forsmark area, calcareous gyttja forms when lime-saturated groundwater enters the lake and/or by biological precipitation by algae. Peatlands in the Forsmark area are generally young and nutrient rich. Bogs do occur but are few and still young, whereas rich fens are the dominant type of peatland. Peat is found most frequently in the south-western part of the model area, i.e. the most elevated areas that have been above the sea level long enough for infilling of basins and peat to form.

A comprehensive description of the regolith at Forsmark has been achieved by intensive data collection and the iterative methodology in the modelling- and sampling programme. We have today a good knowledge of the site characteristics and a conceptual model of how the site has developed since the last glaciation.

6.2.2 Hydrological models

Comprehensive hydrological and near-surface hydrogeological field investigations have been conducted within the site investigation, including monitoring of meteorological data, surface water levels and discharges, and groundwater levels in QD, as well as hydraulic characterization of the QD (slug tests, pumping tests, permeameter tests on undisturbed core samples, pF-analyses). Below follows a brief summary of the conceptual and quantitative modelling (undertaken using MIKE SHE) of the hydrology and near-surface hydrogeology.

There is a close correlation between the topography and the groundwater levels in the QD. 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 candidate area, where the groundwater level gradients in the bedrock are very small, indicating high transmissivity. Here, the groundwater levels in till in general are considerably higher than in the bedrock. Local, small-scale recharge (downward flow) and discharge (upward flow) areas, involving groundwater flow systems restricted to QD, overlie the more large-scale flow systems associated with groundwater flow in the bedrock. Also, in the middle of Lake Bolundsfjärden, located in the central part of the candidate area, the lake level and the groundwater level in the till are considerably higher than the levels in bedrock down to 200 m depth, indicating a downward flow gradient from the lake and QD to the bedrock.

The flow systems around and below the lakes seem 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 groundwaters below the lakes have relict marine chemical signatures, whereas groundwaters in the riparian zones are fresh.

A good understanding of the surface and near-surface hydrology and hydrogeology has been established. Site data and modelling results show a very good correlation and intergration with hydrochemistry data, and the modelling results increase confidence in the conceptual picture of the Forsmark site.

6.2.3 Ecosystem models

Based on an overall conceptual model, it was possible to identify pools of carbons and other elements that are of potential relevance to a safety assessment. These pools may have the potential of becoming large and thereby being a potential sink for contaminants. Moreover, the pools of contaminants may either today or in the future be available for biota. The quantification of pools and fluxes for different ecosystems using different approaches, such as field- and model-based estimates, made it possible to determine their relative importance with regard to elemental accumulation and transport.

We belive that this version of the site description is mature enough to be used in the development of, and as input to, analyses in future safety assessments and environmental impact assessments.

Terrestrial ecosystems

In a static view representing the terrestrial landscape of today, many of the vegetation types are sinks for organic matter. The largest sink is the vegetation, but also the soil accumulates organic material, although in much smaller quantities. The exception is the wetlands which are of significant importance for accumulation of organic matter and other elements, such as phosphorus, in the soil organic pool. In particular, the reed-dominated wetlands surrounding many of the lakes accumulate large amounts of organic matter and accompanying elements. This wetland type is one step in the succession of a lake to a terrestrial area. The comparison of different successional vegetation types in the landscape also highlights the importance of different disturbances, such as clear-cutting and fire, which have the potential for redistributing large amounts of bioavailabile radionuclides from both the vegetation and the soil organic matter pool to downstream areas. A more dynamic temporal view of the terrestrial landscape, where shoreline regression is proceeding, highlights the importance of other vegetation types such as arable land and pasture that have a previous history as wetlands and/or aquatic ecosystems. Both the arable land and the pasture have a high primary production that is used for livestock and human food production and thereby a potential for remobilising bioavailable radionuclides, especially as this type of land-use often is preceded by ditching. The export of carbon and organic matter is low in comparison with the internal fluxes of terrestrial areas.

Lake ecosystems

The most important inflow of elements to lakes is the inflow via water from the terrestrial area. The larger lakes at Forsmark may be important sinks of elements in the landscape, whereas some of the smaller lakes probably function more as flow-through systems. In the larger lakes, the internal ecosystem processes primary production and secondary production involve large amounts of carbon, compared with carbon amounts entering the lake from the surrounding catchment. Thereby, there is a large potential for carbon entering the lakes from the surroundings to be incorporated into the lake food web. In some of the smaller lakes, on the other hand, the amounts of carbon involved in internal ecosystem processes are small compared with the flow of carbon into and out of the lakes, and elements entering the lake will be incorporated into the food web only to a small extent.

Only a minor fraction of the carbon produced by primary producers in the lakes is directly consumed by consumers and transported upwards in the food chain. Instead, most of the incorporated carbon circulates within the microbial food web and is transported into the abiotic carbon pools. In the larger lakes, there is a large degree of sediment accumulation and this sediment can be a permanent sink of pollutants and radionuclides. The sink may be regarded as permanent in time perspectives of decades or centuries, but elements may in a longer time perspective be released due to altered redox conditions caused by e.g. anthropogenic influence when the lakes have become terrestrial areas. In many of the smaller lakes, on the other hand, sediment accumulation is small compared with outflow via water, and pollutants and radionuclides present in these lakes would primarily be transported further downstream. In the lakes, a major part of the production and consumption take place in the benthic habitat. Therefore, pollutants settling on sediments in the lakes could easily be reincorporated into the food web.

Marine ecosystems

Transport from land, lakes and streams gives only a minor contribution of organic matter to the marine ecosystem. The major fluxes of organic matter in the marine ecosystem are governed by advective water fluxes. At Forsmark, parts of the coastal area is heterotrophic, i.e. more carbon is released than fixed by the ecosystem. However, the near-shore coastal basins generally tend to be autotrophic, whereas the outer basins are heterotrophic and supported by carbon from the inner basins and surrounding areas, and as a mean, the marine ecosystem in the whole regional model area is autotrophic.

The major pool of carbon in the ecosystem is the sediment, followed by the pools present in the dissolved phase (DIC and DOC), in the producers and in the consumers. The sediment content of carbon is around 20 times larger than that in the other pools. The advective flow of carbon is the overall dominant flux, and advective flow is several orders of magnitude larger than any other flux, such as photosynthesis by primary producers, runoff and burial.

The most abundant element in the marine ecosystem (biotic and abiotic pools taken together) at Forsmark, is Cl (31 kg m^{-2}), followed by Na, Mg and S. All these elements are important components of sea water. Carbon appears as the 7^{th} most common element at 0.3 kg m^{-2}. The only elements with a proportion larger than 1% in the biotic pools are nitrogen (6%), phosphorous (6%), carbon (5%), silicon (3%), manganese (2%) and iodine (1%). The three elements studied in detail; iodine, thorium and uranium, are all most abundant in the abiotic pools. For thorium the sediment pool dominates and uranium and iodine is most abundant in the dissolved pool.

6.3 Discussion on uncertainties

As described in this report, the SDM for the surface system at Forsmark consists of a large number of sub-models, covering a wide range of disciplines. Generally, the different sub-models are based on a wealth of site data and, accordingly, the problem of introducing an unknown uncertainty by using generic data has been reduced to a minimum. In many cases, sub-models are combined and used as input for new, aggregated models. For example, in the modelling of surface hydrology, the following sub-models are used as important input data; the digital elevation model (DEM), the horizontal distribution and stratigraphy of the regolith, the hydraulic properties of QD, and the distribution of different vegetation types. Each sub-model has its own uncertainties, and in the aggregated models these uncertainties are accumulated, together with uncertainties associated with the assumptions and simplifications made in the development of the aggregated model.

Our approach to evaluating the uncertainties in aggregated models is firstly to assess uncertainties in the underlying sub-models upon which the aggregated model is built, and secondly to evaluate the assumptions made within the aggregated model. Uncertainties associated with the sub-models are, in most cases, thoroughly evaluated in each of the discipline-specific background reports (see section 6.1.1), and therefore no attempt is made here to quantitatively describe these uncertainties. Instead, a brief summary of the main uncertainties and the confidence that there is in some of the most important sub-models and aggregated models is given here.

6.3.1 Geometric models

The digital elevation model (DEM) is constructed by interpolation from irregularly spaced elevation data using a Kriging interpolation method. Kriging weights the surrounding measured values to derive a prediction for an unmeasured location. Weights are based on the distances between the measured points, the prediction locations, and the overall spatial distribution of the measured points. A validation procedure is then used in order to optimise the Kriging parameters to minimise the prediction errors. An indisputable best combination of Kriging parameters is impossible to find, but in the development of the DEM the validation procedure was performed until only minor changes were noted in the prediction errors. The final choice of parameters is presented in /Brydsten and Strömgren 2008/.

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

The model of total depth and stratigraphy of regolith in the area (RDM) is produced by combining data from several different investigation methods, both direct observations (corings and excavations) and indirect interpretation of geophysical measurements. The model is constructed in accordance with the conceptual model of the Quaternary geology of the Forsmark area, which means that the spatial distribution of different Quaternary deposits is an important input to the model. The quality of the model varies with the density of direct observations reaching the bedrock surface, and is, accordingly, highest in the central parts of the candidate area. However, the quality of the model is high also in the shallow coastal parts of the marine area, even though the model in this area is based almost exclusively on geophysical data /Hedenström et al. 2008/. In large parts of the model area, especially in the outer parts, the regolith depths are almost always represented by average depth values from geophysical data. Comparisons between direct observations and geophysical data indicates that the latter may produce regolith depths that are too shallow /Hedenström et al. 2008/

The spatial resolution of the model is 20 × 20 m. Detailed studies of the bedrock surface at Forsmark show a pronounced small-scale topography, although the regolith surface is remarkably flat. The limited spatial resolution of the model, and the use of average regolith depths in large parts of the model area, means that the regolith depth model contains large uncertainties at the local scale (tens of metres). The RDM should mainly be regarded as a general geometric model of the area on a landscape level.

6.3.2 Shoreline displacement and salinity changes in the Baltic

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

It is also notable that the oldest empirical data in the curve (dated samples from isolated basins) is c. 6,500 years old /Hedenström and Risberg 2003/. The ages are initially based on radiocarbon dates of various types of material, i.e. both terrestrial macrofossils and samples of gyttja clay and other sediment. The isolation age of each basin cannot be stated with an uncertainty of less than ±150 year, and the uncertainty is often larger. The uncertainty in the altitude is based on the geological conditions at the isolation threshold and is specific for each site. The altitude of the isolation thresholds included in the curve is stated with ±0.5 m. This implies that the chronology is associated with a larger degree of uncertainty than the altitude /Lindborg (ed) 2005/.

The interpreted variations of past salinity (Figure 4-2) are mainly based on studies of the composition of molluscs and other fossil organisms, e.g. diatoms, preserved in sediments. However, these organisms can tolerate a span of salinity and it is therefore difficult to reconstruct the past salinity exactly by the use of fossils. Furthermore, the salinity curve presented in Figure 4-2 is mainly based on studies from the Baltic proper, south of the Forsmark site. The palaeosalinity of the northern part of the Baltic Sea has been studied by reference to the isotopic composition of strontium in molluscs /Widerlund and Andersson 2006/. According to this study, salinity during the Littorina Sea stage was 7.3–10.3‰ in the Bothnian Sea. Since the Forsmark site is situated in the southernmost part of the Bothnian Sea it is possible that the salinity was lower during the Littorina Sea stage than shown in Figure 4-2.

The timing of the salinity variations has been determined by using radiocarbon dates. Many of these dates were obtained from bulk analyses of sediments. The organic carbon in some sediment may have been redeposited from older deposits and the obtained radiocarbon ages may consequently in certain cases be too old. The salinity curve presented by /Westman et al. 1999/ has recently been questioned by /Kortekaas et al. in press/, who claim that true brackish conditions were established in the Baltic c. 4,500 BC instead of 6,500 BC. That conclusion is based on the results of optically simulated luminescence (OSL) datings. That study is the first attempt to use OSL results to date Baltic Sea sediments, and future investigations will hopefully resolve the issue of whether this method produces reliable ages of these sediments.

6.3.3 Surface hydrology and near-surface hydrogeology

The comprehensive investigation and monitoring programme forms a strong basis for the developed conceptual and descriptive model of the hydrological and near-surface hydrogeological system of the site investigation area. In particular, the evaluation of time series of local meteorological, hydrological and hydrogeological data, enabling comparisons between different processes and hydrological subsystems, has been crucial for the development of the site understanding expressed in the site descriptive model.

Numerical modelling of groundwater and surface water flows and their interactions with atmospheric water and vegetation has provided additional support to the descriptive modelling. Specifically, comparisons between measured and calculated discharges and water levels using different parameterisations in the numerical model has been important for assessing and reducing uncertainties related to the qualitative and quantitative aspects of the site descriptive model. With few exceptions, the results obtained from the numerical modelling show excellent agreement with the measured data and the data-based conceptualisation of the hydrological system at the site.

The present overall descriptive model of the surface hydrological and near-surface hydrogeological system is considered acceptable in a qualitative sense, which means that the general description of the hydrological and hydrogeological driving forces and the overall flow pattern and hydrological interactions are well understood. As indicated above, also most of the quantitative aspects of the model are believed to be adequately described. However, there are some remaining uncertainties regarding the interaction of deep and near-surface groundwater that are of importance for the surface system. These uncertainties, which primarily concern the hydraulic influence of the SFR repository and the origin of the groundwater below some of the lakes in the area, are discussed in /Johansson 2008/.

6.3.4 Regolith

The evaluation of uncertainties in the description of the regolith can be divided in two parts: spatial distributions and quantification of properties. The spatial distribution of the surface layer of the regolith is presented in a mosaic of geological maps. The map of QD has been produced by the use of several methods, and the reliability of the map therefore varies considerably within the model area. In the central parts of the regional model area, the map was produced after extensive field investigations, thus both the spatial resolution and the quality of the map in these parts is high. In the marine areas, which have been mapped using regular marine geological methods, the quality of the map is regarded as high, especially in the near-shore areas. Areas with the highest uncertainties are those based on interpretations from point observations, i.e. in the very shallow coastal region. The quality of the soil-type map is partly determined by the quality of the map of QD, since the soil-type map is based on relatively few field evaluations extrapolated by GIS analyses of the geological map.

The spatial distribution of the water-laid sediments in lakes and small ponds is well known from the central part of the regional model area, and the uncertainties in the description are judged as very low. The descriptions of the spatial distribution and chemical properties of peat are based on investigations of only three peatlands. However, these are representative of the area, and the resulting descriptions have relatively low uncertainties. The chemical and physical properties of the till have been determined with a number of methods. Most analyses were made at laboratories with long experience, and the site data can therefore be considered to have high reliability. The majority of the samples analysed are from the central part of the regional model area. Grain-size distribution and $CaCO_3$ content are the most reliable parameters since they were analysed for all the occurring deposit types. The chemical and physical properties of marine sediments are based on few samples, but the information is acceptable since the lithological units probably have the same properties as on land.

The accumulation rates in marine, coastal, limnic and terrestrial areas have been quantified, but are based on only 1-2 sites per type area. Thus, the uncertanties are judged to be moderate to relatively large.

6.3.5 Chemistry

In the evaluation of chemical data and interpretation of results, uncertainties at several levels have to be considered. Some examples of uncertainties are those associated with analytical precision, and sampling methodology, as well as those associated with use of supporting data and sub-models (e.g. land use characterizations and hydrological measuresments and models). Moreover, uncertainties in the hydrochemical models are introduced as a consequence of the varying representativity of samples with respect to disturbances during the site investigations, and to spatial as well as temporal (seasonal and between-year) variations.

In order to reduce uncertainty in hydrochemical models, the primary data have undergone several quality checks and been selected according to different selection criteria prior to the evaluation. These quality checks and selection criteria are described in detail in /Tröjbom et al. 2007/. Much of the report by /Tröjbom et al. 2007/ comprises an explorative evaluation of a vast amount of hydrochemical data from surface waters and shallow groundwater at Forsmark. Relationships and patterns identified in this explorative analysis are generally not especially sensitive to uncertainties in individual data points.

The largest uncertainties in the hydrochemical models presented in /Tröjbom et al. 2007/ are associated with a combination of hydrochemical data, data on water flow and spatial data on land use and vegetation categories, in order to produce mass transport estimations and mass balance-models for different elements. This is especially true for the transport estimations of trace elements, due to the use of scale factors that relate a particular trace element to a major element for which transport estimations have been conducted. The orders of magnitude in these estimates are probably correct, but the absolute figures should be used with caution.

6.3.6 Ecosystems

The descriptions of the terrestrial, limnic and marine systems are generally based on large amounts of site-specific data. Estimates of biomasses of different functional groups are generally within the range of values reported in the scientific literature. Accordingly, the robustness and confidence in the descriptions of the different ecosystems at Forsmark is high. Detailed accounts of the uncertainties in different parts of the ecosystem descriptions are presented in /Löfgren (ed) 2008/, /Nordén et al. 2008/ and /Wijnbladh et al. 2008/.

The ecosystem models are highly dependent on the choice of conversion factors from biomass. This is a weak point in the models; most of the available site-specific information is on biomass, whereas conversion factors based on generic information have been used to quantify biological processes. The exception is primary production, which has been investigated in both aquatic and terrestrial ecosystems, and respiration which has been investigated in the terrestrial system.

The quantifications of ecosystem processes from site data are associated with large uncertainties. However, the collection of site data on respiration and consumption of different functional groups require an enormous research effort at different scales. Many of the studies needed are very time- and effort-consuming, and it is unclear whether site-specific studies on respiration and consumption of different functional groups would offer more understanding of the sites than the literature data already used in the existing ecosystem models.

Overall, both the ecosystem models and mass balances are built from a large amount of site-specific data, and the robustness of the models must be considered relatively high. Although the absolute numbers are uncertain, the general and relative magnitudes of amounts and flows in the models are thought to be correct.

7 References

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