R-09-01

Surface system Laxemar-Simpevarp

Site descriptive modelling SDM-Site Laxemar

Björn Söderbäck, Tobias Lindborg
Svensk Kärnbränslehantering AB

May 2009

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

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

SKB

ISSN 1402-3091
SKB Rapport R-09-01

Surface system Laxemar-Simpevarp

Site descriptive modelling SDM-Site Laxemar

Björn Söderbäck, Tobias Lindborg
Svensk Kärnbränslehantering AB

May 2009

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 in the Laxemar-Simpevarp area. The project is a preparatory step for an overall site description of Laxemar-Simpevarp (SDM-Site Laxemar), intended to support the safety assessment, environmental impact assessment and the design of a potential repository for nuclear waste.

Björn Söderbäck has edited the report together with the undersigned, who has also 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 hydrogeology: Kent Werner, *EmpTec*, Sten Berglund and Emma Bosson, *SKB*.

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

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

Geometrical modelling: Lars Brydsten 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 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 Associates 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, May 2009

Tobias Lindborg

Project leader SurfaceNet

Summary

The Swedish Nuclear Fuel and Waste Management Co. SKB, has undertaken site characterisation 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 characterisation comprises both the bedrock and the surface systems. This report focuses on the site descriptive modelling of the surface system at Laxemar-Simpevarp. 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 characterisation 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, and also current and historical land use. The report presents available input data, the methodology adopted 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 Laxemar-Simpevarp area is located along the coastline of the Baltic Sea in Småland within the municipality of Oskarshamn, about 230 km south of Stockholm. The area is characterised by a relatively flat topography in a fissure valley landscape. The predominantly thin Quaternary overburden is mainly located in the valleys, whereas the higher-altitude areas are dominated by exposed bedrock or thin layers of till and peat. The mean annual precipitation and runoff in the area are 600 and 160 mm, respectively. Generally, the hydraulic conductivity of the till in higher situated parts of the area is relatively high, whereas that in the valleys is considerably lower.

Forests, dominated by Scots pine and Norway spruce, cover approximately 73% of the land area of the main catchments in the Laxemar-Simpevarp regional model area, whereas wetlands are less frequent and cover only 1% of the area. A total of 5 lakes are situated entirely within the regional model area. The lakes are small and shallow, and are characterised as mesotrophic brown-water lakes, i.e. with moderate nutrient concentrations and with brown water colour. Most lakes are affected by human activities, e.g. by lowering of the water level.

Most of the streams in the Laxemar-Simpevarp area are small with mostly calm or slowly flowing water. As in the case of the lakes, the streams are characterised as mesotrophic brown-water systems. The largest stream in the area is Laxemarån which, together with two other streams, are the only ones that have permanent water flow throughout the year. The streams are, to a great extent, influenced by human activities, which have altered the channels by various technical encroachments.

The marine area in Laxemar-Simpevarp is separated from the open sea in the east by the island of Öland, forming a funnel-like strait with its wide end to the north and the narrow end southwards. The bottom along the coast slopes gradually in the offshore direction. The maximum depth recorded in the regional model area is c. 45 m. The average light penetration depth (Secchi depth) at the sampling sites is 5.5 m, which is low compared to the national monitoring station located further out in the Baltic Proper (8.7 m), but the light penetration varies considerably within the area. The salinity in the outer, exposed parts of the regional model area is 6.8 psu (practical salinity units), which is similar to that in the Baltic Proper.

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 carbon dynamics provides a way of analysing how different ecosystem components are linked to each other through fluxes of energy. 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, many of the vegetation types are sinks for organic matter. The largest sink is the vegetation itself, but the soil also accumulates organic material, although in smaller quantities. The exception is the wetlands where the soil organic pool is of significant importance for accumulation of organic matter and other elements, such as phosphorus.

The most important inflow of elements to lakes in the area is via water from the surrounding terrestrial areas. The lakes receive large inputs of organic matter, and these inputs are, to a large extent, mineralized to CO_2 and emitted to the atmosphere. Generally, ecosystem respiration in lakes in the area is much larger than primary production, and the lakes are net heterotrophic. However, a large part of the carbon influx also contributes to sediment accumulation, and lakes in the area are, as with the wetlands, important sites for accumulation of organic matter and many elements. Transport from land, lakes and streams makes 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 dominant pools and fluxes of elements 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 quantification 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 radiation doses to humans and to other biota in the safety assessment. Moreover, the description will contribute to site adaptation of the repository design, 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 av använt kärnbränsle. Platsbeskrivningarna görs för både berg- och ytsystemet. Denna rapport fokuserar på den platsbeskrivande modellen för ytsystemet i Laxemar-Simpevarp. Det övergripande syftet med detta arbete har varit att utveckla och dokumentera en integrerad beskrivning av ytsystemet, baserad på tillgängliga data från platsundersökningarna. Denna beskrivning utgör en grund för platsanpassad utformning av slutförvarsanläggningen, liksom för en värdering av denna anläggnings långsiktiga säkerhet. Dessutom utgör beskrivningen underlag för en miljökonsekvensbeskrivning för slutförvaret.

Karakteriseringen av biosfären på platsen har främst byggts upp 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 för det ytliga systemet med motsvarande beskrivningar och modellresultat för det djupa berget.

Laxemar-Simpevarpsområdet är beläget vid kusten i Oskarshamns kommun, ungefär 230 km söder om Stockholm. Området har en relativt flack topografi och det består av ett sprickdalslandskap med dalgångar som huvudsakligen löper i nordvästlig riktning. Jordtäcket domineras av sand- och grusmorän tillsammans med mindre områden med torv. I de mer höglänta delarna av området är jordtäcket tunt eller saknas helt, medan det i sprickdalarna kan uppnå betydligt större mäktighet . I vissa dalgångar har moränlager på uppemot 30 m tjocklek noterats. Årsmedelnederbörden i området är ca 600 mm och avrinningen är ca 160 mm per år. Den hydrauliska konduktiviteten i moränen är relativt hög i höglänta områden, medan den i dalgångarna är betydligt lägre.

Ungefär 73% av det regionala modellområdets yta täcks av skog dominerad av tall och gran. Våtmarker är relativt ovanliga och täcker bara ungefär 1 % av områdets yta. Totalt finns 5 sjöar belägna helt eller delvis inom det regionala modellområdet. Sjöarna är små och grunda och klassificeras som mesotrofa brunvattensjöar, vilket innebär att de uppvisar måttliga halter av närsalter, medan höga humushalter gör vattnet starkt brunfärgat. Sjöarna är ofta påverkade av mänskliga aktiviteter, t ex i form av sjösänkningsprojekt. De flesta vattendrag är små och långsamflytande. Förutom det största vattendraget i området, Laxemarån, är det bara två ytterligare vattendrag som uppvisar permanent vattenflöde under hela året. De flesta av vattendragen är starkt påverkade av mänskliga aktiviteter i form av dikning och uträtning av strömfåran.

Kustområdet i Laxemar-Simpevarp avgränsas mot det öppna havet i öster av Öland. Närmast kusten finns en skärgård med flera relativt avgränsade fjärdar. Havsbottnen utanför skärgården sluttar långsamt mot öster och det maximala djupet i det regionala modellområdet är ca 45 m. Det genomsnittliga siktdjupet vid provtagningsstationerna i modellområdet är 5,5 m, vilket är lågt i jämförelse förhållandena längre ut i Östersjön (8,7 m), men siktdjupet varierar starkt inom modellområdet. Salthalten i de yttre, exponerade delarna av det regionala modellområdet är 6,8‰, vilket motsvarar salthalten längre ut i Östersjön.

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 för använt kärnbränsle. Dessa pooler och flöden kvantifierades sedan för olika ekosystem med hjälp av data från både fältmätningar och modelleringar. En särskild vikt har lagts vid beskrivningen av transport och ackumulation av organiskt kol, eftersom en detaljerad kunskap om kolflöden landskapet gör det möjligt att analysera hur olika delar av ekosystemet är sammankopplade med varandra genom flöden av energi. Den resulterande beskrivningen av dominerande pooler och flöden av kol i landskapet kan sedan användas som ett verktyg för att bedöma den relativa betydelsen av olika processer för ackumulation och transport av andra grundämnen inom och mellan ekosystem.

I det terrestra landskapet 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.

Det viktigaste inflödet av olika grundämnen till sjöar är det som kommer via vatten från det omgivande terrestra systemet. En stor del av det organiska material som transporteras till sjöarna bryts där ner, och det ingående kolet avges till atmosfären i form av CO_2. Generellt är nedbrytningen i sjöarna i området mycket större än primärproduktionen, vilket innebär att sjöarna som helhet är heterotrofa, dvs de är beroende av tillförsel av organiskt bundet kol från omgivande landområden för sin ämnesomsättning. I både sjöarna och i våtmarkerna sker dock även en betydande ackumulation i sedimenten av organiskt kol och av många andra grundämnen. I det marina ekosystemet utgörs de helt dominerande flödena av olika ämnen av det som följer med vattenströmmarna till och från de olika bassängerna. Transporten av organiskt material från land, sjöar och vattendrag ger bara ett obetydligt bidrag till den totala kolbalansen.

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 för använt kärnbränsle.

Contents

1 Introduction

1.1 Background

Radioactive waste from 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 major milestones in the form of permit applications for an encapsulation plant and a deep geologic repository. For siting of the geological repository, SKB has undertaken site characterisation 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 for geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, bedrock transport properties and a description of the surface system.

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 ongoing natural processes affecting its long-term development. Prior to this report, earlier versions of surface system descriptions have been produced for the Laxemar-Simpevarp 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 focussed on the Simpevarp subarea, was completed during 2004. In version 1.2, the surface-system description was presented in two separate reports, first for the Simpevarp subarea /Lindborg (ed.) 2005/, and later for the Laxemar subarea /Lindborg (ed.) 2006/. The preliminary site description version 1.2 for Laxemar concluded the initial site investigation work. It formed the basis for a preliminary safety evaluation, a preliminary repository layout, and the first evaluation of the long-term safety of this layout for KBS-3 repositories in the context of the SR-Can project /SKB 2006/.

This report presents the surface system description part of the final SDM for the Laxemar-Simpevarp area, produced in the site investigation stage. This SDM version is refered to as SDM-Site Laxemar. The main report describing all modelling disciplines in SDM-Site Laxemar is "Site description of Laxemar at completion of the site investigation phase" /SKB 2009/. 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 that 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 the site descriptive modelling work at Laxemar-Simpevarp 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 has been achieved by analysing the reliability and assessing the reasonableness of the assumptions made with respect to the current state of the Laxemar-Simpevarp area and to 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 freezes Laxemar 2.2 and 2.3, together with other representative data covering the Laxemar-Simpevarp 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 Laxemar-Simpevarp 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 from the regional model area. All new data that were available at the date defined for data freeze 2.3, i.e. on August 31 2007, have been used for complementary analyses and verification of the models. Since the site investigations have carried on beyond the date of data freeze 2.3, although at a much lower intensity, additional data have become available after 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 Laxemar-Simpevarp area is located along the coastline of the Baltic Sea in the province of Småland, some 230 km south of Stockholm, within the municipality of Oskarshamn (Figure 1-1). The regional model area contains two smaller areas; the Laxemar and the Simpevarp subareas. The Simpevarp subarea includes the Simpevarp peninsula, which hosts the Oskarshamn nuclear power plants and the Central interim storage facility for spent fuel (Clab), and the islands Hålö and Ävrö (cf. Figure 1-1). The island of Äspö, under which the Äspö Hard Rock Laboratory (Äspö HRL) is located, is found some three kilometres northeast of the central parts of Laxemar. The Laxemar subarea covers some 12.5 km^2, compared with the Simevarp subarea, which is approximately 6.6 km^2.

The Laxemar-Simpevarp area is characterised by a relatively flat topography in a fissure valley landscape. The predominantly thin Quaternary overburden is mainly located in the valleys, whereas the higher-altitude areas are dominated by exposed bedrock or thin layers of till and peat. The bedrock formed approximately 1.8 billion years ago (1.8 Ga) and is dominated by medium-grained intrusive rocks, ranging from greyish red granite to grey quartz monzodiorite. The bedrock is generally well-preserved and only weakly affected by ductile deformation. On a regional scale, deformation zones oriented NE-SW, N-S and E-W, with both low-temperature ductile and brittle deformation, are present.

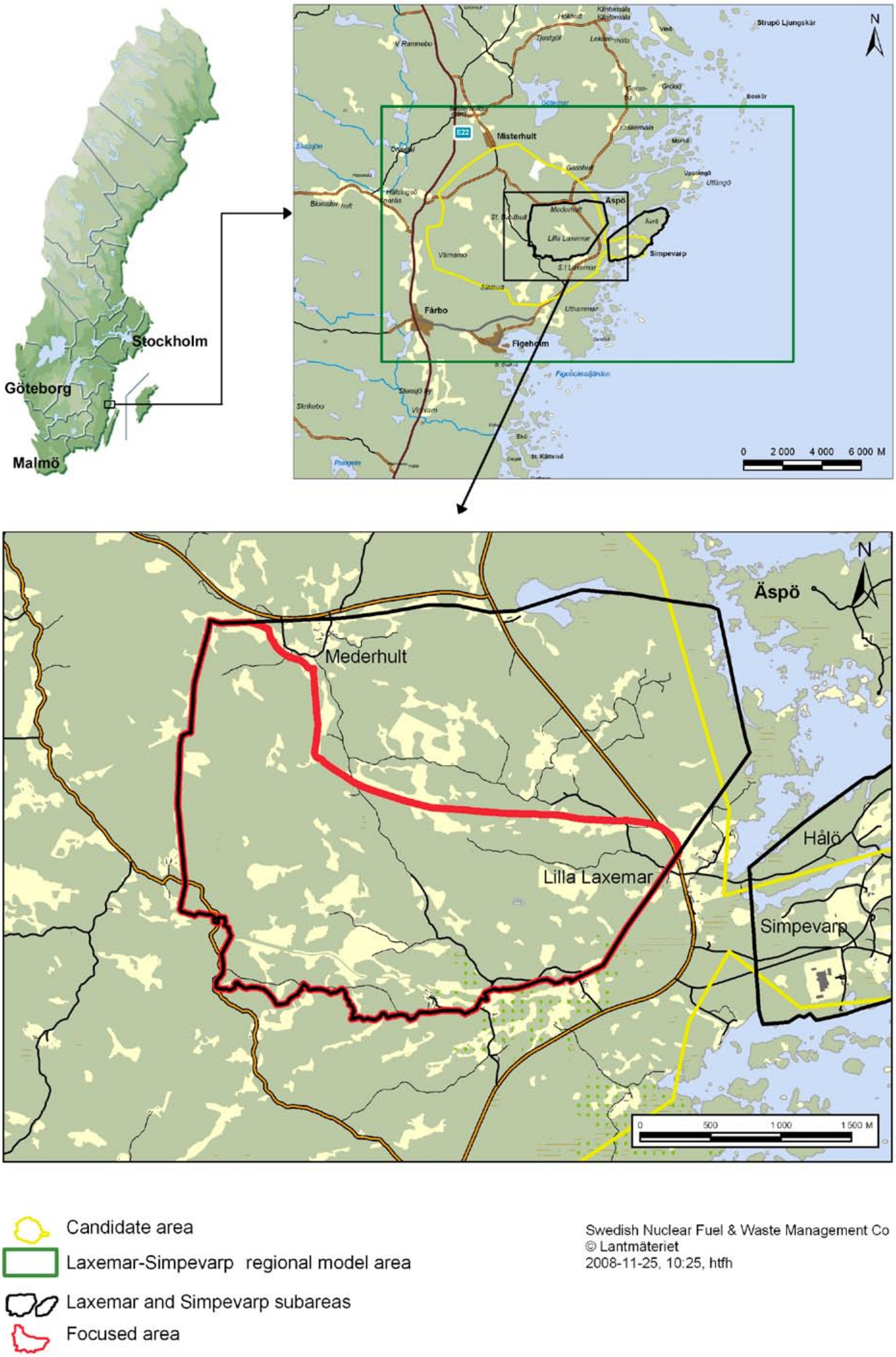


Figure 1-1. *Overview of the Laxemar-Simpevarp regional model area and identification of the Laxemar and Simpevarp subareas. The black rectangles show the spatial extension of the enlarged map.*

1.4 This report

This report presents the integrated description of the surface system at Laxemar-Simpevarp 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 1-2 and is further described below.

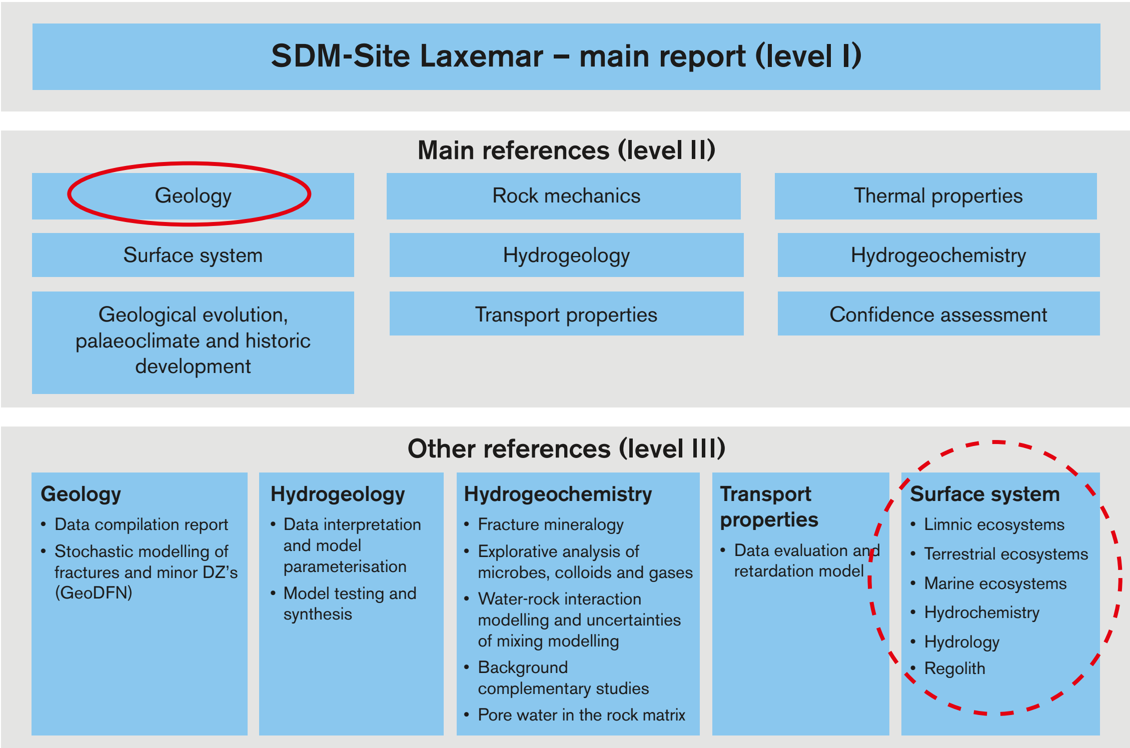


Figure 1-2. *SDM-Site main report and background reports at different levels produced during modelling stages 2.2 and 2.3. DZ = Deformation Zones, DFN = Discrete Fracture Network and DF = Data Freeze. This report is circled in a red line and supporting subreports are circled in dotted red.*

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 regolith at Laxemar, Site descriptive modelling, SDM-Site Laxemar (R-08-05)
- Description of surface hydrology and near-surface hydrogeology at Laxemar-Simpevarp, Site descriptive modelling, SDM-Site Laxemar (R-08-71)
- Hydrochemistry of surface water and shallow groundwater, Site descriptive modelling, SDM-Site Laxemar (R-08-46)

The reader should use this report as a summarizing guide to the discipline-specific descriptions covering the surface system at Laxemar-Simpevarp. 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 (Chapter 1) 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 the 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 then 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 the different domains is described and an overall conceptualization, 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 conceptualization and overall synthesis. Finally, our confidence in the description is discussed.

Appendix 1 presents a map of the Laxemar-Simpevarp regional model area.

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 such 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 the term is used synonymously with primary producer.
Biotic	Caused or induced by living organisms.
Conceptual model	A qualitative description of the components of an ecosystem.
Descriptive model	A quantitative description of the components of 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 quantifying these as 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, bio-chemical, environmental response or trophic criteria.
Gross primary production (GPP)	Net carbon input to an ecosystem – that is, net photosynthesis expressed at an ecosystem scale (gC $m^{-2}y^{-1}$) /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 decomposers, 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/.
Regolith	The layer of loose, heterogeneous material covering solid rock. It includes dust, soil, broken rock, and other related materials
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 for the Laxemar-Simpevarp area 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 performed by SKB, to give the reader an overview of the input sources available. Then, two tables are presented (Table 2-1 and Table 2-2) which provide the information needed to understand and evaluate the actual input data used in the description of the surface system of Laxemar-Simpevarp, as it is presented in this report. Input data are 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 (QD) was initiated in 2003 and the field work has continued through 2003–2006. Data are both surface-based and of stratigraphical character. The major components of data from the initial stage of the site investigations are:

- A map and associated description based on the mapping of Quaternary deposits in the whole terrestrial part of the regional model area.
- A map showing the distribution of Quaternary deposits in parts of the marine areas.
- A map showing the distribution of soil-types in the whole terrestrial part of the regional model area.
- Stratigraphical and analytical data from drilling and machine-cut trenches.
- Estimations of regolith depths from Vertical Electrical Sounding.
- Estimation of bedrock topography (and regolith thickness) along refraction seismic profiles.
- Investigations of peat and marine and lacustrine sediments – stratigraphical and analytical data.
- Estimations of regolith depth and stratigraphy from seismic and sediment echo sounding data from the marine areas.

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

- Interpretation of the geographical distribution of Quaternary deposits in marine areas not included in the mapping programmes.
- Interpreted map of Quaternary deposits for the lakes.
- Stratigraphical and analytical data from drillings and machine-cut trenches from the valleys.
- Petrographical analyses of boulders and gravel in till.
- Radiometric datings of sediments and peat.
- Chemical and mineralogical analyses of the most frequently occurring Quaternary deposits.
- Additional interpretations of regolith depths from refraction seismic data.
- Interpretations of regolith depths from resistivity measurements along profiles.

2.2 Meteorology, hydrology and near-surface hydrogeology

The meteorological, hydrological and near-surface hydrogeological investigations have comprised the following major components:

- Establishment of two stations for meteorological monitoring.
- Monitoring of ”winter parameters”, such as snow depth, ground frost and ice freeze/breakup.
- Identification and characterisation of surface-water catchments.
- Establishment of nine surface-discharge gauging stations for monitoring of discharge, temperature and electrical conductivity.
- Surveys of lake thresholds, lake bathymetries and brook geometries.
- Installation of surface-water level gauges for monitoring of lake- and sea-water levels.
- Installation of groundwater monitoring wells in the QD for monitoring of groundwater levels.
- Estimation of the hydrogeological properties of the QD based on particle-size distribution (PSD) curves, permeameter tests, slug tests and hydraulic single-hole and interference tests in groundwater monitoring wells.

In addition to the investigations listed above, the present modelling is based on data from the SKB Sicada and GIS (Geographical Information System) databases on:

- Topography and other geometrical properties.
- Surface-based investigations of the QD, soil types and vegetation.
- QD stratigraphy from boreholes, pits and trenches.
- Hydrogeological properties of the rock (delivered from the HydroNet project) and point-water-head data from percussion and core boreholes.
- QD 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 different sampling stations (cf. Section 3.2 in /Tröjbom and Söderbäck 2006/), whereas surface-water samples from 4 lakes, 5 sea sampling sites and 18 streams were collected monthly, and periodically even more often, from the start of the site investigations in 2002 (cf. Tabel 3-1 in Tröjbom and Söderbäck 2006/). From 2007, the monitoring sampling programme involved monthly sampling in one lake, two sea bays and five stream sampling sites.
- Shallow groundwater samples. Samples of shallow groundwater from more than 60 soil tubes and 7 private wells have been analysed (cf. Figure 2-7 in /Tröjbom et al. 2008/). From 2007, the monitoring programme has involved 8 soil tubes sampled 4 times per year
- 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. Section 3.4.2 in /Tröjbom and Söderbäck 2006/).
- Biota samples. Organisms from different functional groups in the lake, sea and terrestrial ecosystems have been sampled /Engdahl et al. 2006/.

2.4 Ecology

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

- Surface water sampling at the same sampling points as described above for hydrochemistry. 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 and chemical parameters are measured in the field, e.g. pH, temperature, light, oxygen, turbidity and Secchi depth.
- 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 mapping with satellite data of the Laxemar-Simpevarp regional model area and vegetation inventory in parts of the area.
- Biomass and primary production of terrestrial vegetation.
- Investigation of the amount of dead wood.
- Surveys of mammal populations in Laxemar-Simpevarp over the period 2003–2007.
- Age composition and reproduction of the local population of moose. Data since 2002.
- Semiquantitative sampling/inventory of fish populations in lakes, streams and in the sea.
- Inventory of amphibians and reptiles.
- Monitoring of bird populations in the regional model area 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 ten localites.
- Water velocity, bottom substrate, vegetation, shading and technical encroachments in streams.
- Chemical composition of deposits and biota in both terrestrial and aquatic environments.
- Sedimentation rates in a wetland, a lake and shallow sea bays.
- Inventory of bat species.
- Investigations of benthic vegetation and fauna in lakes and shallow sea bays.
- Measurements of primary production and respiration in shallow sea bays.
- Biomass of benthic and planktonic bacteria in a lake and in marine basins.
- Oceanographic measurements.

Table 2-1. Available abiotic data from the surface system at Laxemar-Simpevarp and their handling in the final site description, SDM-Site Laxemar.

Available data Data specification	Ref	Usage in SDM-Site Analysis/Modelling
Geometrical and topographical data		
Digital Elevation Model (DEM)	P-04-03, P-04-254 R-05-38	Basic input to flow and mass transport models, descriptions and modelling of the marine ecosystem
Surveying of streams	P-06-05	Description of stream chacateristics. Input to quantitative water-flow modelling (MIKE SHE)
Geological data		
Map of Quaternary deposits in the terrestrial part of the Simpevarp regional model area	P-04-22 P-05-49	Description of surface distribution of Quaternary deposits in the terrestrial part of the regional model area
Maps of Quaternary deposits covering a large part of the sea bottom in the regional model area	TR-99-37 P-04-254 P-05-35 P-06-296 R-08-06	Description of surface distribution of Quaternary deposits at the sea floor
Map of soils in the terrestrial part of the Simpevarp regional model area	P-04-243 R-05-15	Distribution of soil types in the regional model area
Deposits on the bottom of watercourses	P-05-40	Evaluation of the map of Quaternary deposits
Stratigraphical studies in machine cut trenches	P-05-47 P-05-49 P-06-121	Stratigraphy and total depth of Quaternary deposits
Stratigraphy and total depth of Quaternary deposits of the sea and lake floors	R-02-47 P-04-254 P-04-273 P-05-35 P-06-144 R-08-05	Description of stratigraphical distribution and total depth of Quaternary deposits of the sea and lake floors
Drilling and sampling of Quaternary deposits	P-03-80 P-04-22 P-04-121 P-04-317 P-05-49 P-06-121 P-06-248 P-07-91	Description of stratigraphical distribution and total depth of overburden in the terrestrial parts of the Simpevarp and Laxemar subareas
Helicopter-borne survey data	P-03-100	Description of surface distribution of Quaternary deposits in parts of the Simpevarp regional model area
Resistivity measurements	P-03-17 P-06-284	Total depth of Quaternary deposits
Refraction seismic	P-04-134 P-04-201 P-04-298 P-05-155 P-06-49	Total depth of Quaternary deposits
Chemical and mineralogical analyses of Quaternary deposits	R-02-47 R-04-72 P-04-273 R-05-15 P-05-35 P-05-49 R-06-18 P-06-121 P-06-301 P-06-320 P-06-321 P-07-30 P-07-222	Chemical and minerological properties of Quaternary deposits

Available data Data specification	Ref	Usage in SDM-Site Analysis/Modelling
Physical analyses of Quaternary deposits	R-02-47 P-04-17 P-04-243 P-04-273 R-05-15 P-05-49 P-06-121 P-07-91	Physical properties of Quaternary deposits
Dating of sediment and peat	P-06-250 P-06-301	Accumulation rates of sediment and peat
Meteorological and oceanographic data		
Regional data		
Meteorological data from surrounding stations prior to and during the site investigations	TR-02-03 R-99-70 P-05-227 P-06-19 P-07-38 P-07-172	General description of meteorology, comparison with site investigation data
Regional oceanographical data	TR-97-14 R-99-70 TR-02-03 TR-08-02	Description of coastal basins. Quantitative modelling
Site-investigation data		
Meteorological data from the stations on Äspö (Sep. 2003–Aug. 2007) and in Plittorp (Jul. 2004–Aug. 2007); Sicada data up to Dec. 2007 are used.	P-05-227 P-06-19 P-07-38 P-07-172	Description of meteorology and comparison with data from surrounding stations. Input to quantitative water-flow modelling (MIKE SHE).
Hydrological data		
Regional data		
Hydrological data from surrounding hydrological stations prior to and during (Sicada data only) the site investigations	R-99-70 TR-02-03	General description of hydrology Comparison with site investigation data
Site-investigation data		
Investigation of potential locations for hydrological stations	P-03-04	Size of catchment areas for manual and automatic surface-water discharge measurements
Geometrical data and descriptions of catchment areas, lakes and streams	P-04-242	Delineation and general characteristics of catchment areas, lakes and streams. Input to quantitative water-flow modelling (MIKE SHE)
Manual discharge measurements in streams	P-04-13 P-04-75 P-04-246	Description of spatial and temporal variability of surface-water discharge
Monitoring of surface-water discharges in streams	P-05-227 P-06-19 P-07-38 P-07-172	Description of spatial and temporal variability of surface-water discharge. Calculation of specific discharge. Calibration of quantitative water-flow models (MIKE SHE)
Monitoring of surface-water levels in lakes and the sea	P-05-227 P-06-19 P-07-38 P-07-172	Description of spatial and temporal variability of surface-water levels. Input to quantitative water flow modelling (MIKE SHE)
Characterisation of streams, including vegetation, bottom substrate and technical encroachments	P-05-40	Description of streams and land improvement and drainage operations
Field checks of streams and land improvement and drainage operations	P-05-70 P-05-238	Description of streams and land improvement and drainage operations. Input to quantitative water-flow modelling (MIKE SHE)

Available data Data specification	Ref	Usage in SDM-Site Analysis/Modelling
Hydrogeological data		
Hydrogeological inventory in the Oskarshamn area	P-04-277	General description of hydrogeology, water operation permits and land-improvement and drainage operations
Inventory of private wells	P-03-05	General description of private wells
Monitoring of groundwater levels in the QD and point-water heads in the rock	P-05-205 P-05-282 P-07-219 P-08-28	Conceptual hydrogeological model Calibration of quantitative water-flow models (MIKE SHE)
Geological data from drilling in QD and installation of groundwater-monitoring wells	P-03-80 P-04-46 P-04-121 P-04-317 P-05-167 P-06-121 P-06-248 P-07-91	Conceptual hydrogeological model
Hydraulic conductivity from slug tests in groundwater-monitoring wells	P-04-122 P-04-318 P-06-149 P-06-150 P-06-248 P-07-91	Conceptual hydrogeological model Hydrogeological parameterization of the QD
Hydraulic conductivity from particle-size distribution curves	P-04-273 P-05-47 P-05-49 P-06-121 P-07-91	Conceptual hydrogeological model Hydrogeological parameterization of the QD
Hydraulic conductivity and storage-properties data from single-hole and interference tests in groundwater-monitoring wells	P-07-173	Conceptual hydrogeological model Hydrogeological parameterization of the QD
Hydraulic interference and tracer tests in percussion boreholes and groundwater-monitoring wells	P-06-151 P-07-187	Conceptual hydrogeological model
Groundwater-flow velocities from tracer-dilution tests in groundwater-monitoring wells	P-07-197	Conceptual hydrogeological model
Chemical data		
Surface-water sampling	P-04-13 P-04-14 P-04-75 P-05-118 P-05-175 P-06-155 P-06-324	Characterisation and description of spatial and temporal variability of surface-water chemistry
Shallow groundwater	P-03-80 P-04-46 P-04-121 P-04-317 P-06-13 P-06-248 P-06-325 P-07-222	Characterisation of the chemistry in shallow groundwater
Chemical composition of biota and deposits	P-06-250 P-06-320 P-07-32	Modelling
Overburden	P-03-80 P-04-46 P-04-121 P-04-243 P-04-273 P-04-317 P-06-250 P-06-301 P-06-320 P-07-222	Characterisation of the chemistry in the regolith
Sediment, suspended material and pore water	P-08-81	Modelling

Table 2-2. Available biotic data from the surface system at Laxemar-Simpevarp and their handling in the final site description, SDM-Site Laxemar.

Available data Data specification	Ref	Usage in SDM-Site Analysis/Modelling
Terrestrial biota		
Compilation of existing information 2002	R-02-10	Description
Bird-population survey	P-04-21 P-05-42 P-06-298 P-07-226	Description, modelling
Mammal-population survey	P-04-04 P-04-237 R-05-36 P-07-122 P-07-136	Description, modelling
Amphibians and reptiles	P-04-36	Description, modelling
Mammal ecological data and carbon budget	R-05-36	Description, modelling
Vegetation inventory	P-04-20	Description
Vegetation mapping	P-03-83	Description, modelling
Leaf Area Index (LAI) and tree-stand data	TR-06-29	Description, modelling
Litter fall and litter decomposition	R-07-23	Description, modelling
Dead wood	P-05-87	Description
Successional birch habitats	P-04-315	Description
Biomass and Net Primary Productivity (NPP) of the vegetation	R-08-01 P-05-80	Description, modelling
Fine-root biomass, turnover and depth	R-06-121 R-07-01 TR-07-11	Description, modelling
Data from soil mapping	R-05-15 P-04-243	Description, modelling
Respiration measurements	P-06-278 TR-06-28 TR-07-13 R-06-125	Description, modelling
Bioturbation	R-06-123	Description, modelling
Ecosystem modelling	R-06-121 R-08-01	COUP model LPJ-GUESS model
Wetlands; properties and function	TR-04-08	Description
Limnic biota		
Limnic producers	P-04-253 P-05-40 P-05-173 P-06-232	Description, modelling
Habitat borders	P-04-242	Description
Limnic consumers	P-04-253 P-04-251 P-04-252 P-06-232 P-06-251	Description, modelling
Ecosystem modelling	R-08-02	
Marine biota		
Compilation of existing information 2002	R-02-10	Description
Light penetration depth	P-04-13	Description
Zooplankton, phytoplankton	P-04-253	Description, modelling
Bacteria	P-06-232	
Identification of dominating species	P-03-68	Description
Macrophyte communities	P-03-69	Description, modelling
Soft-bottom infauna	P-04-17	Description, modelling

Available data Data specification	Ref	Usage in SDM-Site Analysis/Modelling
Benthic fauna	P-04-17 P-04-82 P-04-252 P-05-45 P-06-303	Description, modelling
Reed	P-04-316	Description, modelling
Fish sampling	P-04-19	Description, modelling
Fish population estimates	P-05-57 P-06-10	Description, modelling
Bird population survey	P-04-21 P-05-42 P-06-298 P-07-226	Description
Spatial distribution of marine organisms	R-07-50	Modelling
Ecosystem modelling	R-08-03	
Humans and land use		
Humans and land use	R-04-11	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 users of the site description.

The interface between the surface and bedrock systems has been considered in the evaluations regolith and the shallow bedrock system, of the deep and shallow groundwater movement, as well as in the chemical description of the groundwater. The present conceptualization 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 /Werner et al. 2008a, Rhén et al. 2009/.

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 sub-models 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 hand 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 then 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 introduced into the site descriptive modelling from the databases Sicada and GIS only. Information regarding the procedures for data collection and factors of importance in the interpretation of data can be extracted 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 characterisation of the biosphere can primarily be made by identifying and describing important properties in different surface ecosystems, e.g. properties of hydrology and climate /Werner et al. 2008ab/, Quaternary deposits and soils /Sohlenius and Hedenström 2008/, chemistry /Tröjbom et al. 2008/ and vegetation /Löfgren (ed.) 2008/, but also current and historical land use, as these 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 catchment areas. By placing the emphasis on the fluxes of matter, ecological and physical constraints on a system are 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 of any released elements 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 by 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 categorization 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 that can be used 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 a landscape.

3.1.1 Conceptual models

A conceptual model is the 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 have been 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 categorization and classification of the landscape into more easily handled units. In this report, the landscape is divided into three large-scale units: terrestrial, limnic and marine ecosystems. Further classification was done using units that potentially constitute a basis for budget calculations of organic matter amounts and fluxes. The units were then further divided using functional groups within the food web.

The spatial resolution of the collected data is context dependent. However, the resolution of the terrestrial landscape is, in our case, a function of the resolution of satellite classification techniques and the diversity of major vegetation types. Similarly, the spatial resolution of lakes is 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 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.

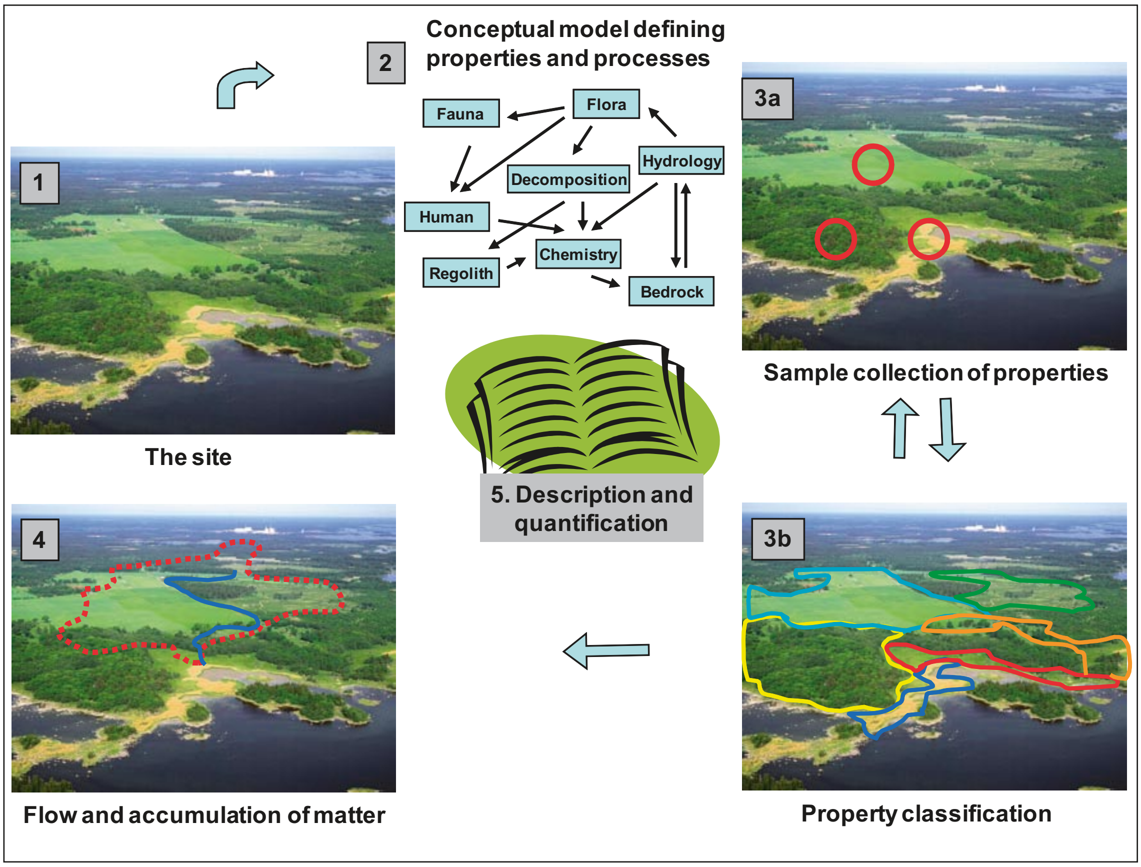


Figure 3-1. *The process of building a site-descriptive ecosystem model. The site (1) is defined. A conceptual model (2) is produced, describing functional units, their properties and the fluxes of matter/energy between them. Samples are collected at the site (3a) using quantitative statistics to describe 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).*

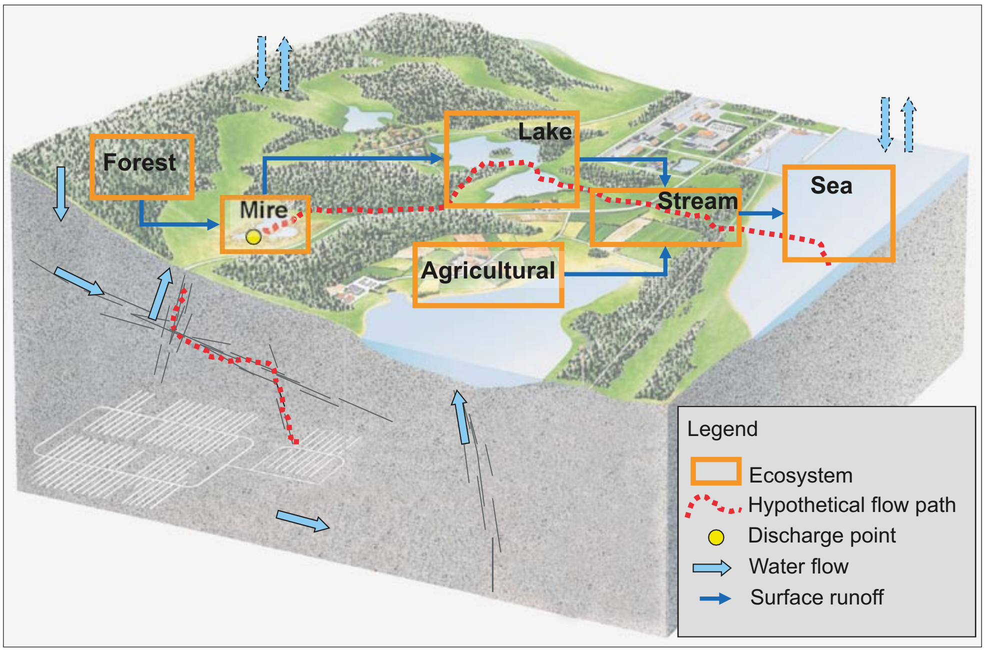


Figure 3-2. *An overall conceptual model describing the different domains and the transport of matter at a landscape level.*

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, agricultural land, wetlands, lakes and sea. By using the conceptual model and site-specific data we establish 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 organic matter in living organisms from different functional groups, such as tree layer, shrub layer, field layer and ground layer.

3.1.3 Description and quantification of transfer- and accumulation processes

Carbon and energy (e.g. expressed in 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 relative 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 ploughing old lake beds or harvesting peat. In the long-term cycling, matter is leached from the terrestrial ecosystem into watercourses, 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 is 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 for determining transport of matter /Blomqvist et al. 2002/, and is thus subject 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 means 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 beds. 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 transport of matter into running water and lakes. By quantifying recharge and discharge, it is possible to calculate input and loss of matter into and from a lake. Transport of matter in streams represents loss from terrestrial systems, making it possible to compare estimated and actual losses from the 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, through which important exchanges of matter may occur depending on water currents and on the topographic relief.

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.

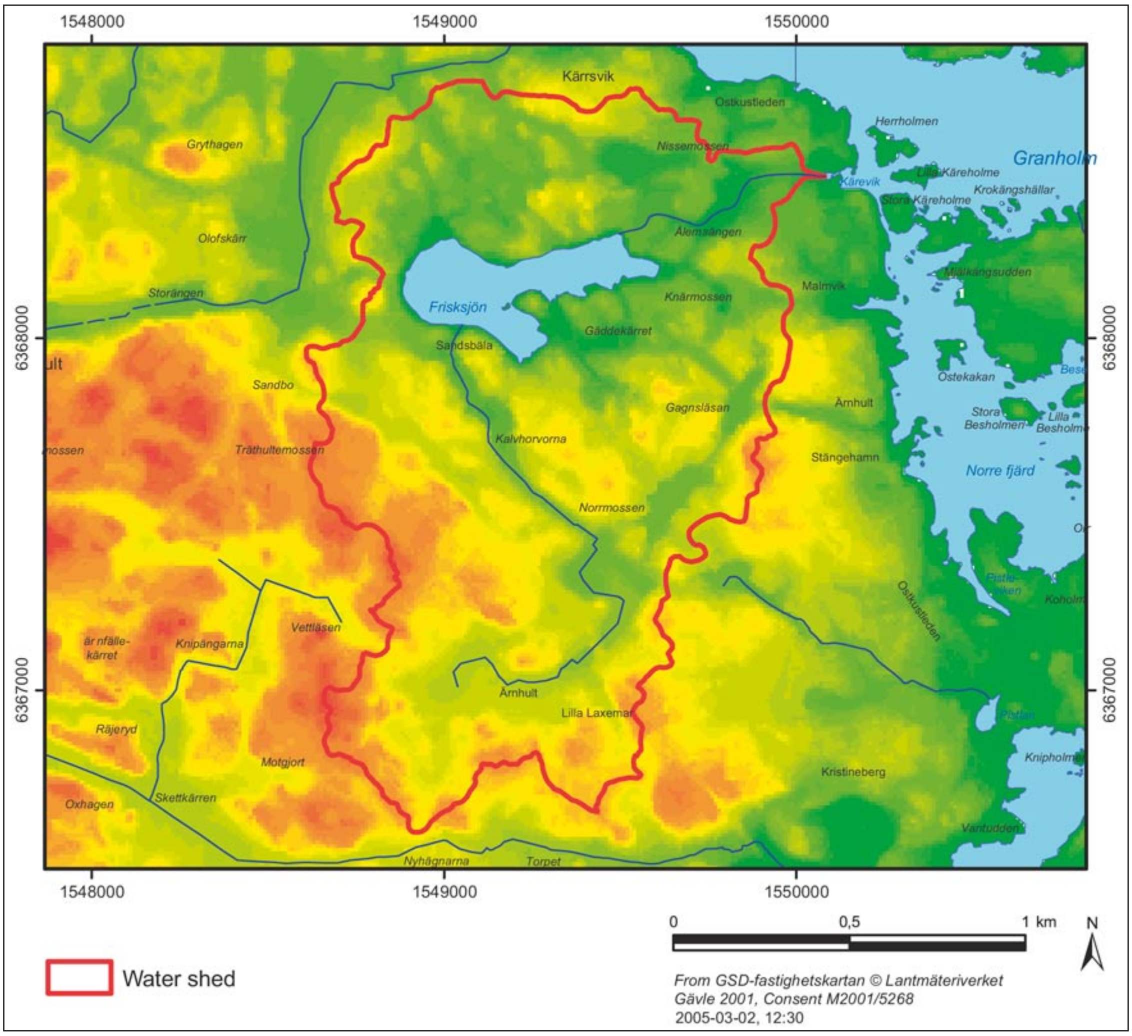


Figure 3-3. *The Lake Frisksjön catchment area. An example of a catchment in Laxemar-Simpevarp used for modelling of transport and accumulation of elements and matter.*

One important challenge of the work is to integrate all the collected data into a common model. During the integration, a number of simplifying assumptions have to be made. However, it is always 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 transport of 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 constrain 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 site-specific limitations that are introduced.

If we describe standing stocks and flows of matter accurately, we will establish 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 (DEM)

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

To construct a DEM, a number of input data from different sources are used. Sources like the 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/, the high resolution DEM (0.25 m) produced from the laser scanning in the central parts of the Laxemar-Simpevarp area /Nyborg 2005/, elevation lines from digital topographical maps, digital nautical charts and paper nautical charts (from the Swedish Maritime Administration), depth soundings in lakes /Brunberg et al. 2004/ and in the sea /Ingvarson et al. 2004, Elhammer and Sandkvist 2005/, interpreted depth data in the sea /Brydsten and Strömgren 2005/, measurements of brooks /Strömgren et al. 2006/ and available fixed points. 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 alternative DEM's were produced for the Laxemar-Simpevarp area. One version describes the land surface, the sediment level at lake bottoms, and the sea bottom. The other version describes the land surface, the lake water surfaces, and the sea bottom. Ordinary Kriging in the Geostatistical Analysis extension in ArcGis 9 was chosen as interpolation method /Davis 1986, Isaaks and Srivastava 1989/ for the interpolation of the DEM's. In the version that displays lake water-surface levels, the cells representing lake beds 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 the sea surface and a constant value for lake surfaces. However, for Laxemar-Simpevarp, 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 for the Laxemar-Simpevarp area were merged into a database of 1,920,000 points.

The database for the Laxemar-Simpevarp 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 as described by the auto-correlogram or semi-variogram. 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 (some of the data are removed and the rest of the data are used to construct the spatial structure and to predict the removed data) before the interpolation is conducted. Cross-validation with different Kriging parameters was performed and the models with the most reasonable statistics were chosen for the Laxemar-Simpevarp DEM model area /Strömgren and Brydsten 2008/. 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 Laxemar-Simpevarp area. The DEM describing the land surface, sediment levels at lake bottoms, and sea bottom is illustrated in Figure 4-5.

3.3.2 Regolith depht and stratigraphy model (RDM)

A geometrical model of the regolith at Laxemar-Simpevarp, based on data obtained from drillings and corings, excavations and geophysical investigations, has been constructed /Nyman et al. 2008/. The model describes the total regolith depth from the ground surface down to the bedrock surface, subdivided into six layers (Z1-Z6) that are schematically illustrated in Figure 3-4. The layers in the model are purely geometrical, but are constructed according to the conceptual understanding of the geographical distribution of Quaternary deposits at the site. Properties of the layers are subsequently assigned by the user of the model. 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. For the most part, the model coincides with the Laxemar-Simpevarp regional model area, but the area is somewhat extended in order to include present and future catchments (Figure 3-5).

The detailed topographical DEM and the map of Quaternary deposits were used as input to the model, together with data from 319 boreholes and 440 other stratigraphical observations. Furthermore, a large number of depth data interpreted from geophysical investigations were used; refraction seismic measurements from 51 profiles, 11,000 observation points from resistivity measurements and almost 140,000 points from seismic and sediment echo-sounding data (Table 3-5 and Figure 3-9).

The results from the refraction seismic and resistivity measurements give information only on total regolith depths, whereas most other data also give information on the stratigraphy of the regolith. Some of the observations used did not reach the bedrock surface. However, as they at least describe a minimum regolith depth at each location, they were used where the estimated regolith depth would have been thinner without using the observation point.

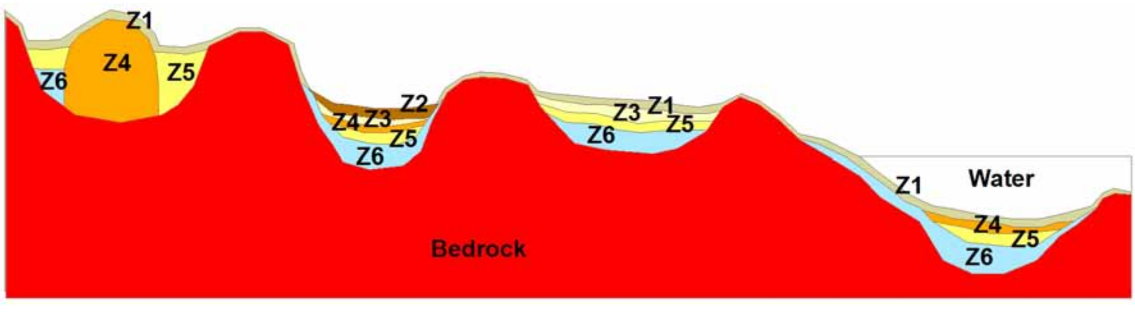


Figure 3-4. *Conceptual model used for the Regolith Depth Model, showing the spatial distribution of the six layers. See Table 3-1 for description of the layers.*

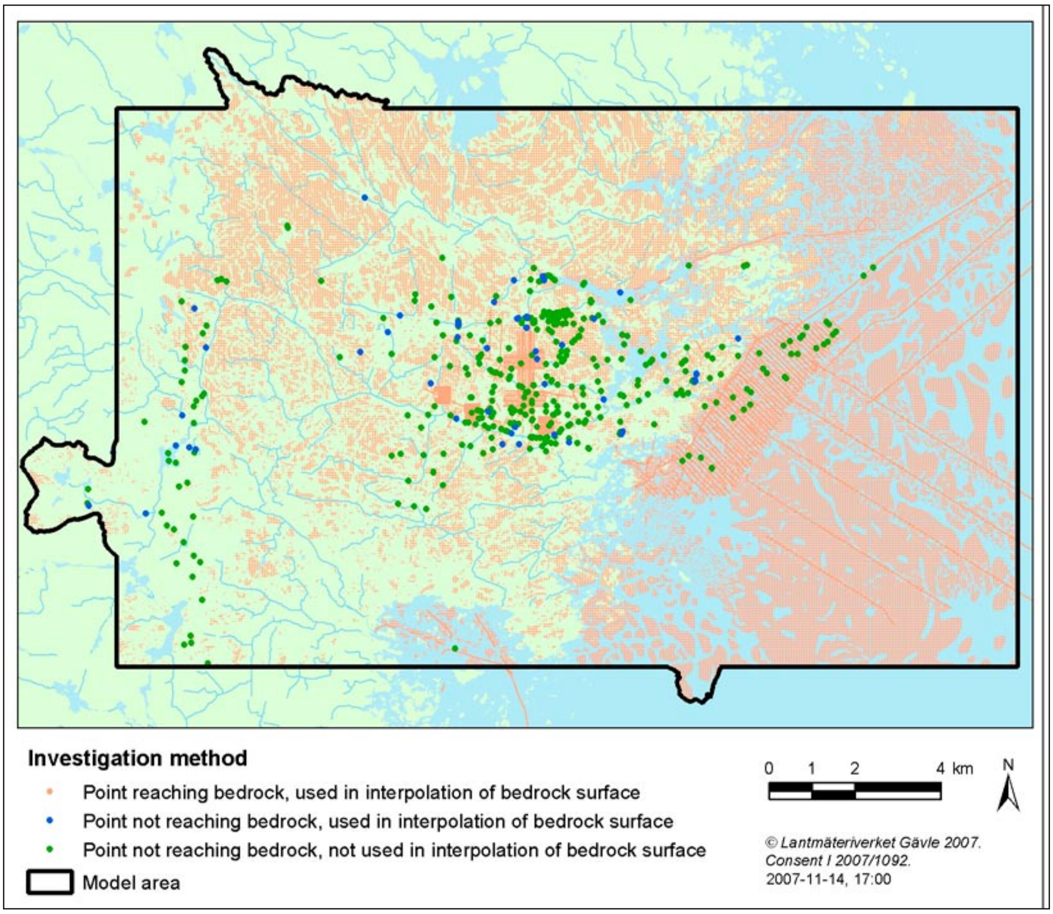


Figure 3-5. *Model area and data used for the modelling of regolith depth in the Laxemar-Simpevarp area /from Nyman et al. 2008/. A large proportion of the data represents bedrock outcrops (see Table 3-3).*

The geographical distribution of the data used for the model is shown in Figure 3-5 and the different data sets are further discussed in Section 3.5. Large parts of the modelled area have a low data density and the area was therefore divided into nine domains (Figure 3-6 and Table 3-2). These domains were defined based on the geographical distribution of Quaternary deposits. The average regolith depth in each domain was estimated from available data (Table 4-9 and Table 4-10), and then used together with measured depths to interpolate the regolith depths in the model area. The layer Z1 has a fixed depth in areas with bedrock outcrops (0.1 m), and another fixed depth in other areas (0.6 m, see Table 3-1). The lower level for Z6 was interpolated from data on total regolith depth, together with data on the elevation of bedrock outcrops. Thus, the lower level of Z6 represents the bedrock surface, regardless of whether it is covered by any regolith or not. The data used for interpolation of Z6 are shown in Table 3-3.

Almost half of the data used for the interpolation of the bedrock surface are average values. Raster surfaces for the lower levels of Z2–Z6 were calculated by using the Geostatistical Analyst extension in ArcGis 9.2. The resolution was set to 20 m. Kriging was chosen as the interpolation method /Davis 1986, Isaaks and Srivastava 1989/. The resulting interpolated surfaces are presented in a GIS-environment. The GeoModel program /DHI Water & Environment 2005/ was used for the final stage of developing the Regolith Depth Model. The concept of the GeoModel is to provide a simple GIS-based model in which the user can view existing observational data, interpolate geological formations based on observation points, evaluate and adjust the interpolated layers, and present the results as layers in profiles. For details regarding the modelling methodology, see /Nyman et al. 2008/.

Table 3-1. Description of the layers used in the Regolith Depth Model. The stratigraphical distribution of the Z-layers is shown in Figure 3-4.

Layer	Description
Z1	Represents the **uppermost regolith** and is present within the entire modelled area, except in areas covered by peat. On bedrock outcrops, the layer is set to 0.1 metre and in other areas to 0.6 metre. If the regolith depth is less than 0.6 m, Z1 will be the only layer. In the terrestrial areas, this layer is supposed to be affected by soil-forming processes.
Z2	Is present in all areas where **peat** is shown on the QD map. The peat areas have been subdivided into deep and shallow peatlands (see Table 3-2).
Z3	Represents **postglacial clay gyttja, gyttja** or **recent fluvial sediments**.
Z4	Represents **postglacial coarse-grained sediments (mostly sand and gravel), artificial fill** and **glaciofluvial sediments**. Z4 is equivalent to artificial fill or glaciofluvial sediments in areas shown as these deposits on the QD map. In all other areas, Z4 represents the postglacial sediments. Two different average depths were used for the glaciofluvial deposits, one for the Tuna esker and another for all other, shallower deposits (see Table 4-1). The glaciofluvial sediments and artificial fill rest directly upon the bedrock. The postglacial sand and gravel are always underlain by glacial clay (Z5) and till (Z6).
Z5	Represents **glacial clay**. Z5 is always overlain by postglacial sand/gravel (Z4).
Z6	Represents **glacial till**, which is the most common QD in the model area. Z6 is set to zero thickness if the total QD depth is <0.6 metre (e.g. at bedrock outcrops) or if Z4 (see above) rests directly on the bedrock surface. The lower limit of Z6 represents the bedrock surface, i.e. Z6 represents a DEM for the bedrock surface.

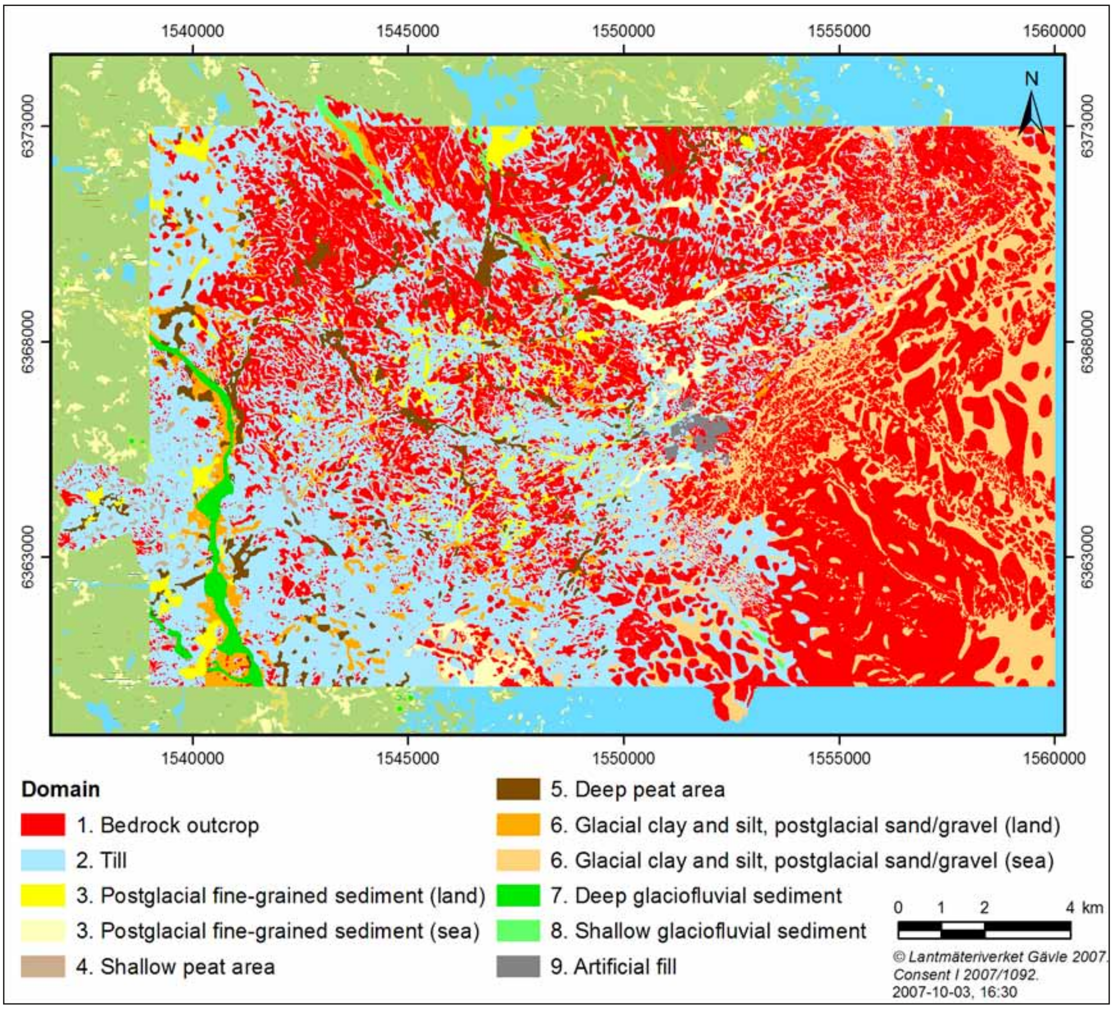


Figure 3-6. The model area classified into nine types of domains, which were used in the Regolith Depth Model. The domains are explained in Table 3-2.

Table 3-2. The different domains used for the Regolith Depth Model. The artificial fill has not been related to any of the type areas. The different Z layers used for the stratigraphy are explained in Table 3-1 (see also Table 4-1). Domains 7 and 8 have the same stratigraphy, but the thickness of Z4 is larger in domain 7.

Domain	Quaternary deposit	Stratigraphy from the ground surface and downwards
1	Bedrock outcrops with no or almost no regolith coverage	Z1/bedrock
2	Till, shingle and boulders	Z1/Z6/bedrock
3	Clay gyttja, gyttja and recent fluvial sediments	Z1/Z3/Z4/Z5/Z6/bedrock
4	Peat, shallow. (Peat areas that do not border on areas with clay or postglacial sand/gravel and are forested or clear-cut)	Z2/Z6/bedrock
5	Peat, deep	Z2/Z3/Z4/Z5/Z6/bedrock
6	Glacial clay and postglacial sand/gravel	Z1/Z4/Z5/Z6/bedrock
7	Glaciofluvial deposits, deep	Z1/Z4/bedrock
8	Glaciofluvial deposits, shallow	Z1/Z4/bedrock
9	Artificial fill	Z1/Z4/bedrock

Table 3-3. Number of data points from different data types used for interpolation of the bedrock surface, which corresponds to the lower level of Z6.

Data type	Bedrock reached	No of points used for interpolation of Z6
Seismic and sediment echo-sounding data	Yes	138,571
Refraction seismic data	Yes	2,860
Percussion drilling, percussion drilling soil observations	Yes	93
Geotechnical drilling soil observations	Yes	112
Well from SGU´s well archive	Yes	57
Core drilling	Yes	37
Quarten. deposit mapping, stratig. obs.	No	30
Geotechnical drilling soil observations	No	25
Inorganic sediment mapping	No	–
Peat land mapping	No	–
Ocean sediment core sampling	No	–
Neotectonic stratigraphic observation	No	–
Resistivity measurements		10,971
Bedrock outcrops		270,125
Average regolith depth values		378,652
Total no. of points used for interpolation of Z6		**801,533**

3.4 Surface hydrology and near-surface hydrogeology

The overall methodology for hydrogeological investigations during the site investigation is presented in Figure 3-7. A preliminary conceptual model, mainly based on the data gathered and analysed in the Oskarshamn pre-study /Follin et al. 1998, SKB 2000/, was the starting point for 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 section includes data on meteorology, surface-water levels and discharges, groundwater levels, and the geometry and hydrogeological properties of the hydrogeological flow domains. These data sets were first evaluated separately, and then subject to an integrated analysis. This integrated analysis, supported by data from related site-investigation disciplines as well as by generic data, formed the basis for the elaboration of a site-specific conceptual and descriptive model integrated with quantitative water-flow modelling. This procedure has been iterative and repeated for the different model versions.

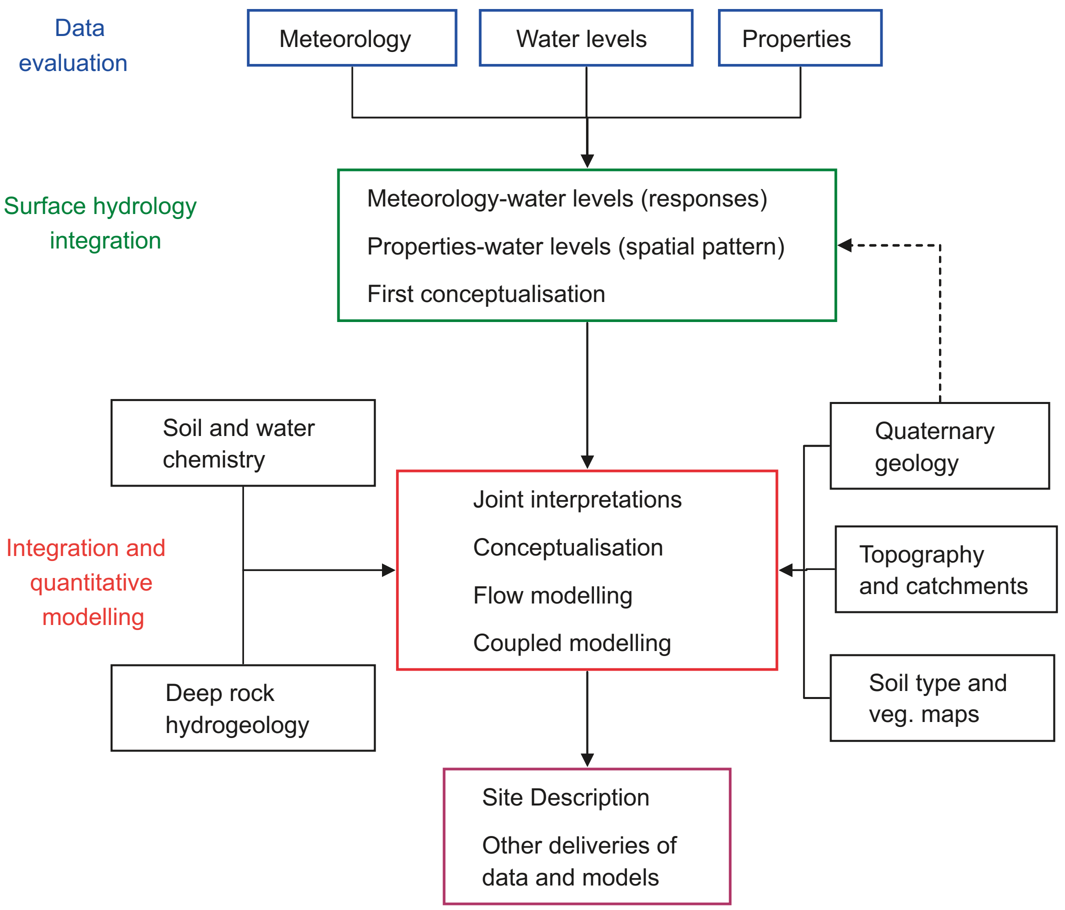


Figure 3-7. *Overall description of the methodology for the hydrological and near-surface hydrogeological work performed within the site investigations.*

/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 those 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 includes groundwater levels and hydraulic parameters for unsaturated and saturated 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-rock hydrogeology*. The main reason was the high resolution in time and space needed in the description of the surface and near-surface system. Shallow flow paths 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 characterising 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 parameterization and identification of boundary conditions. In the present report, groundwater-level data from the percussion and core boreholes are included. For detailed description of the conceptual hydrogeological modelling of the rock, see /Rhén et al. 2008, 2009/.

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

In SKB´s systems approach to hydrogeological modelling, three hydraulic domains (or flow domains) are defined: (*i*) hydraulic soil domain (HSD), (*ii*) hydraulic conductor domain (HCD), and (*iii*) hydraulic rock-mass domain (HRD). For surface water, the flow domains are (i) overland flow, (ii) streams, (iii) lakes, and (iv) the sea. Wetlands are described separately, but are not regarded as a separate flow domain in the quantitative water-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" /UNESCO 1992/. 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 is adopted according to which groundwater recharge and discharge areas are areas where groundwater has a downward or an upward flow component. Groundwater is shallow in most parts of the 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. Based on the adopted definition, such areas are characterised as groundwater discharge areas.

The term *stream* is used throughout the present description, regardless of size and flow conditions; most streams in the Laxemar-Simpevarp area are influenced by land-improvement and drainage operations.

The term *groundwater level* is used as a common term for the position of the groundwater table under unconfined conditions and the potentiometric head under confined conditions. However, it should be noted that due to differences in salinity with depth, measured groundwater levels in percussion and core boreholes should be considered as so called *point-water heads*. Strictly, these point-water heads should be transformed to *freshwater*- and/or *environmental-water heads* for interpretation of horizontal and vertical groundwater-flow directions, respectively. For definitions of point-water head, freshwater head and environmental-water heads, and the influence of groundwater-density differences on groundwater-flow direction in the site investigation area, the reader is referred to /Werner et al. 2008/.

The modelling of hydrology and near-surface hydrogeology within and related to the surface system has been performed as part of the SurfaceNet project.

3.5 Regolith (soils, sediments and Quaternary deposits)

Regolith refers to the unconsolidated material overlying the bedrock. In this report, the term Quaternary deposits (QD) is often used synonymously with regolith since all known regolith in the Laxemar-Simpevarp area was formed during the Quaternary period (the last 2.6 million years). The regolith includes marine and lacustrine sediments, peat and glacial deposits. In terrestrial areas, the upper part of the regolith is referred to as the soil. In this report, the term soil is therefore used to describe the upper c. 0.6 metre of the regolith in terrestrial areas, whereas the term Quaternary deposits is used when discussing the regolith below that level. Soils are formed by the interaction of the regolith with climate, hydrology and biota. Different types of soils are characterised by diagnostic horizons with specific chemical and physical properties.

3.5.1 Surface distribution of soils and QD

The QD map shows the distribution of QD at a depth of 0.5 m below the ground surface in the whole Laxemar-Simpevarp regional model area. Some surface layers thinner than 0.5 m were also marked on the map (e.g. peat overlaying other deposits). The geographical distribution of QD was used together with other data to produce a soil-type map covering the whole of the Laxemar-Simpevarp regional model area.

Different methods were used for mapping of QD (see Figure 3-8 and Table 3-4). First, the distribution of QD in the whole terrestrial part of the model area was interpreted from aerial photos. In the following field checks, the uppermost deposits were investigated using a spade and a hand-driven probe. In the Laxemar and Simpevarp subareas, QD were mapped for presentation on a scale of 1:10,000 (Area 1 in Figure 3-8). This means that the part of the map that includes the two subareas shows all identified bedrock exposures and QD with a surface extent exceeding 10 by 10 metres. The remaining parts of the River Laxemarån drainage area and the glaciofluvial deposit, Tunaåsen, were mapped for presentation on a scale of 1:50,000 (Area 2 in Figure 3-8). The smallest marked area here is about 40 by 40 metres. However, smaller observed bedrock outcrops have been symbolised with crosses. The area mapped using the two methods described above is referred to as *the local area* in the following text (Areas 1 and 2). Remaining terrestrial parts of the Laxemar-Simpevarp regional model area were also mapped for presentation on a scale of 1:50,000 (Area 3 in Figure 3-8). The distribution of QD in this part of the map was, however, to a large extent interpreted from aerial photos. These interpretations were field-checked along the road network. A more generalised method for classification was used in this area. It was not possible to access Area 4 (see Figure 3-8) during the site investigations, and the distribution of QD in that area was therefore interpreted entirely from aerial photos.

During the mapping of QD, directions of glacial *striae* were observed and measured at about 130 localities. The results are presented and discussed in /Söderbäck (ed.) 2008/. The distribution of QD on the floors of lakes and ponds (Area 11 in Figure 3-8) has been interpreted by Sohlenius (SGU) after evaluating the results from sediment cores and after comparison with the terrestrial map of QD. That interpretation has not been presented in any report.

In the area close to the Simpevarp peninsula and the island of Ävrö, /Elhammer and Sandkvist 2005/ collected data in profiles with a spacing of 100 metres (Area 5 in Figure 3-8). This area is referred to as *the detailed marine area*. Further away from the shore in the Laxemar-Simpevarp regional area, a spacing of 1 km was used (Area 6 in Figure 3-8). This part of the mapped area is referred to as *the local marine area*. The survey includes echo sounding, sediment echo sounding, seismic reflection and side scan sonar. Samples were taken to verify the interpretation from the acoustic measurements. /Ingvarson et al. 2004/ mapped the distribution of QD in parts of the coastal area and archipelago (Area 9 in Figure 3-8). The stratigraphy and geographical distribution of QD on the sea floor were investigated with multibeam echo-sounder side-scan sonar and with shallow seismic survey. /Ingvarson et al. 2004/ took no samples to verify their interpretations of QD. Area 7 was mapped both by /Ingvarson et al. 2004/ and /Elhammer and Sandkvist 2005/. The original map by /Ingvarson et al. 2004/ shows the distribution of QD at the surface of the sea floor, whereas the map by /Elhammer and Sandkvist 2005/ shows the distribution of QD at a depth of 0.5 m below the sea floor.

The QD data from the sea floor were therefore re-interpreted by /Kjellin 2007/. The results were used to produce a map showing the distribution of QD at a depth of 0.5 metre below the sea floor. That map covers both the areas mapped by /Ingvarson et al. 2004/ and the areas mapped by /Elhammer and Sandkvist 2005/. /Kjellin 2007/ also made an interpretation that shows the supposed distribution of QD in areas that was not included in the marine geological mapping programme (Area 10 in Figure 3-8). That interpretation was based on bathymetric information together with the known distribution of QD in the mapped marine and terrestrial areas. The interpretation by Kjellin should not be regarded as an ordinary QD map, but more as a general view of the likely composition of the regolith cover.

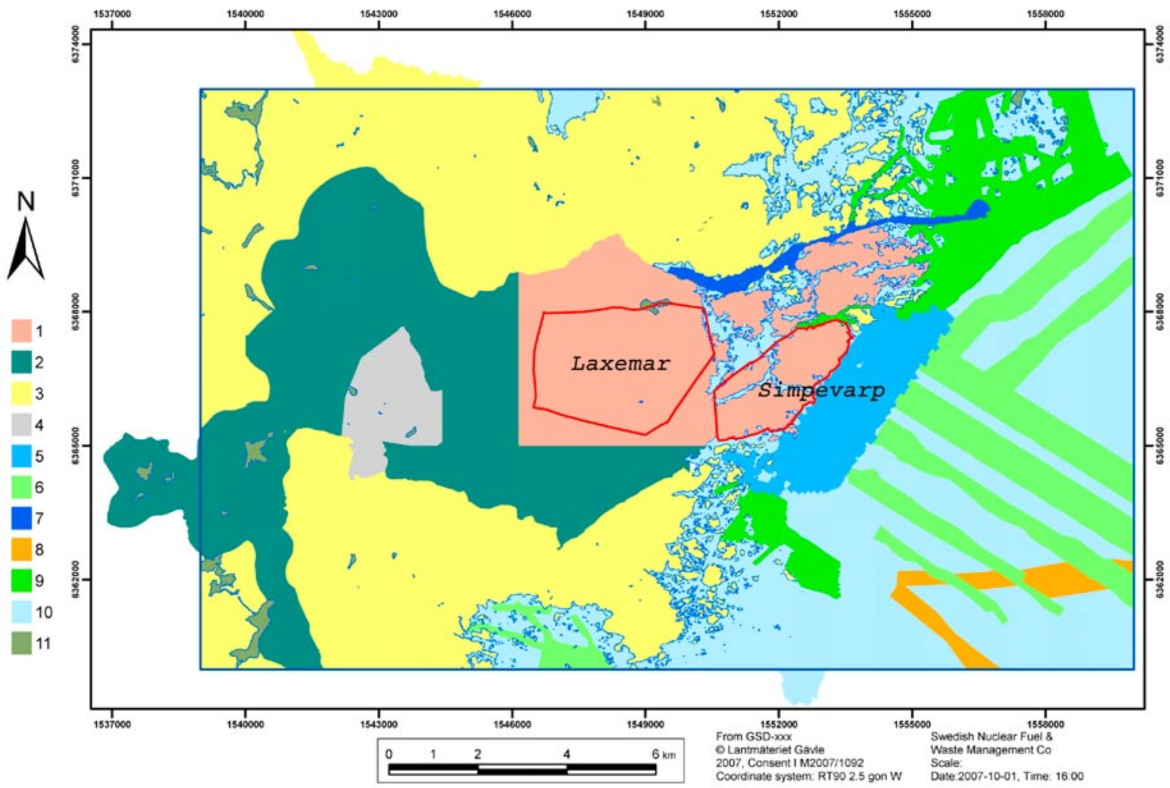


Figure 3-8. *The QD map was produced by means of several methods, represented by different colours on the map. The methods used for the different areas are explained in the text and in Table 3-4. The boundaries of the Laxemar and Simpevarp subareas are marked with a red line on the map and the boundary of the Laxemar-Simpevarp regional model area is marked with a dark blue line. A regolith depth model was produced for the whole area mapped for QD /Nyman et al. 2008/. In addition, a soil type map covering the whole terrestrial part of the regional model area was produced by /Lundin et al. 2005/.*

Table 3-4. Short description and references to the data used to produce the QD map of the regional model area. The geographical distribution of the different areas is shown in Figure 3-8. T = terrestrial areas, M = marine areas, L= lakes. Digital aerial photos were used to interpret the distribution of QD on land. The digital elevation model (DEM) was used in the construction of the regolith depth and stratigraphy model.

Area	Type of data	Reference
1 (T)	Detailed information for presentation on a scale of 1:10,000	SKB P-05-49
2 (T)	Information for presentation on scale of 1:50,000	SKB P-05-49
3 (T)	Interpretations from aerial photos and field checks	SKB P-05-49
4 (T)	Interpretations only from aerial photos	SKB P-05-49
5 (M)	Detailed marine information (SGU, line spacing 100 m)	SKB P-05-35 modified by Kjellin 2007 (SGU report)
6 (M)	Local marine information (SGU, line spacing 1 km)	SKB P-05-35 modified by Kjellin 2007 (SGU report)
7 (M)	Local marine information (SGU and MMT*)	SKB P-05-35/ SKB P-04-254 modified by Kjellin 2007 (SGU report)
8 (M)	Mapped from SGU's regular survey programme	Kjellin 2007 (SGU report)
9 (M)	Mapped by MMT*	SKB P-04-254 modified by Kjellin 2007 (SGU report)
10 (M/L)	Interpreted from bathymetry and surrounding geology (SGU)	Kjellin 2007 (SGU report)
11 (L)	Interpreted from surrounding geology and bathymetry	Sohlenius (no report)
All areas	Digital Elevation Model (DEM)	SKB P-04-03, R-05-38
All areas	Digital aerial photos	SKB P-02-02

* Marin mätteknik

Soils within the Laxemar-Simpevarp regional model area were classified into 10 different land classes /Lundin et al. 2004, Lundin et al. 2005/. The land classes were defined based on vegetation, land use, and wetness. Classifications of soil types and QD were carried out in eight spade-dug profiles at two sites from each land class. The aim of the soil classification was to define soils with special properties that were then compared with soils from other areas of Sweden. The soils were classified according to /WRB 1998/. The 2-3 uppermost soil horizons were sampled and analysed for pH, organic carbon, nitrogen and calcium carbonate. The QD map was used together with other information, such as land use, distance to the sea and vegetation maps (tree, field and ground layer) /Boresjö Bronge and Wester 2003/, to interpret the geographical distribution of soils in the model area /Lundin et al. 2005/. Some changes have been made in the original soil type map class definition presented by /Lundin et al. 2005/. That was done by Johan Stendahl at the Swedish University of Agricultural Sciences (SLU). The new definition specifically includes thin soils and bedrock, as the amount of exposed bedrock and thin soils was previously underestimated in comparison with thicker soil deposits.

3.5.2 Stratigraphic data

Data on the stratigraphy and total depth of the regolith have been obtained from a number of different investigations (see Figure 3-9 and Table 3-5). The results from these investigations have been used together with the QD map to produce a model showing the stratigraphy and total depths of regolith in the whole Laxemar-Simpevarp regional model area as described in Section 3.3.2.

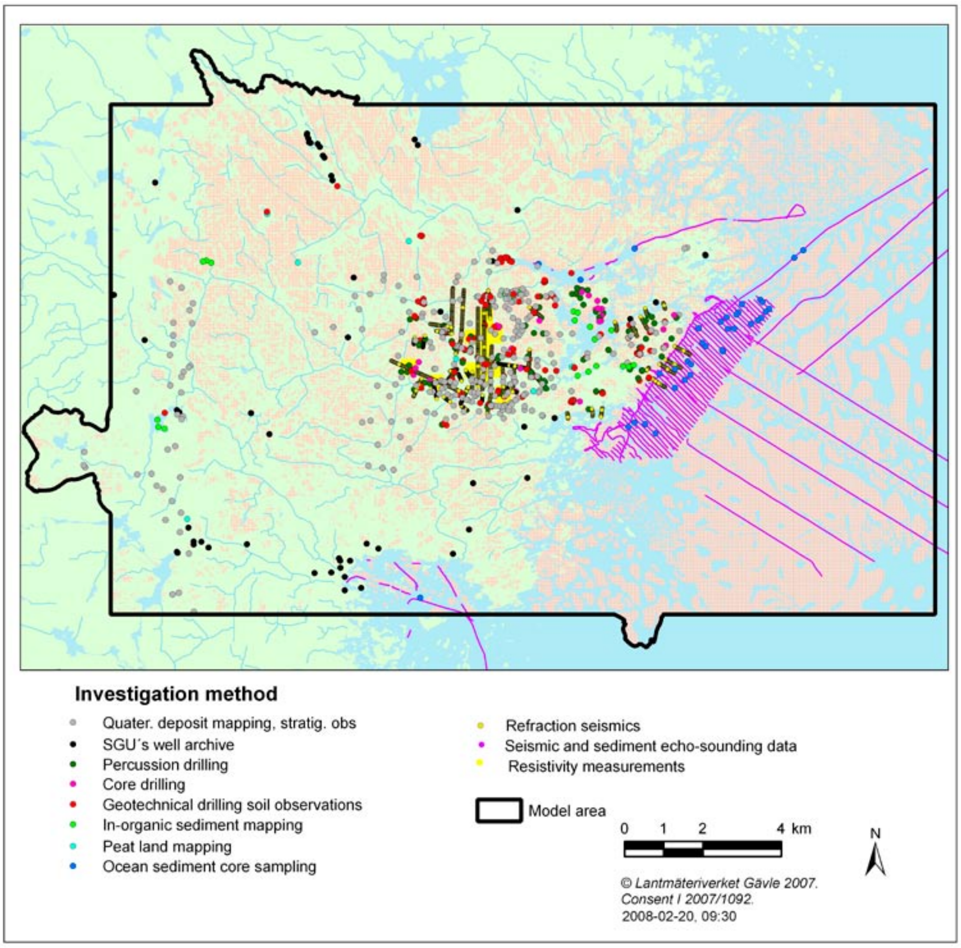


Figure 3-9. Data used by /Nyman et al. 2008/ for modelling the surface and stratigraphical distribution of QD in the Laxemar-Simpevarp area. Data from the marine areas mapped by /Elhammer and Sandkvist 2005/ include stratigraphy and total depth data of regolith from 138,571 points. The refraction seismic and resistivity transects include regolith depth data from a total of 2,860 and 10,971 points, respectively (see Table 3-3).

Table 3-5. Available data on regolith depth and stratigraphy from the Laxemar-Simpevarp area. Most of the data were utilized in the construction of the Regolith Depth Model /Nyman et al. 2008/. The geographical location of the sites is shown in Figure 3-9.

Data	Description	No. of observations	Reference
Refraction seismic data	Each observed point along the transects has coordinates, a surface elevation and an estimated smoothed bedrock elevation	51 transects including 2,860 observation points.	P-04-134, P-04-201, P-04-298, P-05-155, P-06-49
Detailed geophysical measurements: resistivity measurements	wEach observed point along the transects has coordinates and an estimated regolith depth	10,971 observations	P-03-17 P-06-284
Vertical electrical soundings (VES)	Observation points from vertical electrical soundings (VES) where a estimated depth to bedrock is used	49 observation points	P-06-284 P-03-17
Seismic and sediment echo-sounding data	Data include estimated depth to bedrock and stratigraphy for each site.	138,571 sites	P-05-35
Quaternary deposit mapping and observations of stratigraphy	Mostly shallow observation points with detailed information on stratigraphy	303 observations	P-05-47, P-05-49, P-06-121
Inorganic sediment mapping and peat land mapping	Information on stratigraphy	44 observations	P-04-273
Ocean sediment core sampling	Information on stratigraphy	37 observations	P-05-35
Geotechnical drilling soil observations	Stratigraphy and regolith depth from drilling and weight sounding	189 observations	P-04-121,P-04-317, P-06-248, P-07-91, P-06-121
Percussion drilling	Regolith depth from percussion drilling in bedrock	93 observations	*
Core drilling	Regolith depth from core drilling in bedrock	37	*
The SGU well archive	Private wells mapped by SGU. Data includes depth to bedrock. The quality of the coordinates in the well archive is quite varied	57 wells	/SGU 2007, www/

Soil/rock drilling /e.g. Johansson and Adestam 2004ab, Sohlenius et al. 2006, Morosini et al. 2007/ provides information on the stratigraphy and total depth of QD. Weight soundings and auger drilling were done in transects across depressions to collect information regarding the spatial variations of the stratigraphy of the uppermost metres of the regolith. During the auger drilling, samples of regolith were characterised in the field. Certain samples were taken for further analysis of grain-size distribution. The weight soundings give information about the physical properties of the deposits. These properties were used to identify different types of regolith.

A spade and two different hand-driven probes were used for direct observations of the QD (altogether 250 observations) during mapping of the terrestrial areas /Rudmark et al. 2005/. Most of these holes did not exceed 2 metres depth below the ground surface. The thickness and stratigraphical distribution of peat and water-laid fine-grained sediments in shallow bays, wetlands and lakes in the Laxemar-Simpevarp regional model area was investigated by /Nilsson 2004/. The sediments were sampled with a hand-operated Russian peat corer.

The stratigraphical distribution of sediments from the marine areas was described in four cores sampled with a six metre piston corer /Elhammer and Sandkvist 2005/. Samples from two of these cores were later used for biostratigraphical studies and radiocarbon dating /Kaislahti Tillman and Risberg 2006/.

In the terrestrial area, the stratigraphy was determined in 25 machine-cut trenches at localities with relatively thick regolith layers /Bergman et al. 2005, Rudmark et al. 2005, Sohlenius et al. 2006/. These studies included descriptions of bed geometry, sedimentary and deformational structures, lithology, sorting, particle roundness, colour etc.

The geophysical surveys included both seismic and resistivity measurements. In the terrestrial areas, the geophysical measurements were mainly used to estimate the total depth of QD (Figure 3-9). The results from the reflection seismic survey in the marine areas /Elhammer and Sandkvist 2005/ were used to estimate the stratigraphy and thickness of till, glacial clay, postglacial sand and clay gyttja (data from almost 140,000 points). These results were also used to estimate the total thickness of QD.

In terrestrial areas, refraction seismic measurements were mainly carried out in areas with a low frequency of bedrock outcrops /Lindqvist 2004abc, 2005, 2006, 2007/. The measurements were made along transects of which several cross the pronounced valleys that characterise the model area. The results provide information on the total depth of the regolith. These results were used to determine the locations of some of the machine-cut trenches that were used for studies of the QD and underlying bedrock.

Electrical resistivity was measured along transects on the ground in selected areas within the Laxemar subarea /Thunehed and Triumf 2005, 2006/ (Figure 3-9). The resistivity data were used, together with the results from the refraction seismic surveys /e.g. Lindqvist 2004/, to calculate the total depth of the regolith /Thunehed 2006/.

3.5.3 Analytical methods and sampling programme

The results of analyses of physical properties include parameters such as grain-size distribution, porosity and density of the most commonly occurring QD and soils (Table 3-6). The wet bulk density and porosity have been calculated from the organic and water contents. The organic content was calculated as 1.7 times the carbon content, based on the van Bemmelen factor /Jackson 1958/. Grain-size analyses on material < 20 mm were carried out on a total of 148 samples. The grain-size distribution for the coarse material (grain size 0.063-20 mm) was analysed by sieving and the fine fraction (< 0.063 mm) was analysed using sedimentation in a hydrometer. The analytical methods used are national standard methods /Standardiseringskomissionen i Sverige 1992ab/.

Also, the chemical and mineralogical results comprise data from the most commonly occurring QD and soils in the regional model area. Most data were obtained from the site investigation, but there are also data from SKB investigations conducted before the start of the site investigations. Moreover, some data from geochemical analyses of till carried out within the SGU's regular mapping programme have been used.

The geochemistry of 77 samples (till, peat, sand, glacial clay and clay gyttja) was analysed /Sohlenius et al. 2006, Engdahl et al. 2006, Lundin et al. 2007/. For the analyses of As, Cd, Cu, Co, Ni, Pb, B, Sb, Se and S, the samples were digested in 7M HNO_3 and analysed with ICP-MS. The total content of other elements was also analysed with ICP-MS, but after fusion in a carbon crucible with a flux (lithium metaborate) at 1,000°C.

During the soil survey, /Lundin et al. 2005/ took samples of the upper regolith from ten land classes. A total of 20 sites, with four to eight soil pits on each site, were sampled. The samples were analysed for pH, carbon (C) and nitrogen (N).

Mineralogy analyses by X-ray diffraction were performed on eight clay, one sand and five till samples /Sohlenius et al. 2006, Lundin et al. 2007/. In another investigation, radiometric methods were used to determine the rate of sediment accumulation and the rate of peat formation. The uppermost deposits were dated with ^{210}Pb, whereas the deeper and older deposits were dated with ^{14}C /Sternbeck et al. 2006/.

Table 3-6. Available data used for modelling the properties of the regolith. Some data were used to obtain a general understanding of the Quaternary development of the Laxemar-Simpevarp area.

Available site data Data specification	Usage in Analysis/Modelling	Reference
Map of QD in the Laxemar-Simpevarp regional model area	Description of surface distribution of QD in the Laxemar-Simpevarp regional model area. Quaternary development of the area	P-04-22, P-04-254, P-05-35, P-05-49, P-06-296
Map of soils in the terrestrial part of the Laxemar-Simpevarp regional model area	Distribution of soil types in the Laxemar-Simpevarp regional model area	P-04-243, R-05-15
Deposits on the bottom of watercourses	Evaluation of the QD map	P-05-40
Stratigraphy and total depth of QD from the sea and lake floors	Description of stratigraphy and total depth of QD on the sea floor Quaternary development of the area	R-02-47, P-04-254, P-04-273,P-05-3 5, P-06-121, P-06-144
Stratigraphy and total depth of QD in the terrestrial areas	Description of stratigraphy and total depth of regolith in the terrestrial parts of the Simpevarp and Laxemar subareas Quaternary development of the area	P-03-80, P-04-22, P-04-121, P-04-317, P-05-49, P-05-47, P-06-121, P-07-91
Stratigraphical studies outside the Laxemar-Simpevarp regional model area	Stratigraphy of QD in the Laxemar-Simpevarp area. Quaternary development of the area	P-04-192, P-05-232, P-06-160
Bedrock geology	Mineralogical and chemical composition of the regolith	P-05-180
Physical properties of QD	Physical properties of Quaternary deposits	P-04-243, P-04-273, P-05-49, P-04-17, R-02-47, R-05-15, P-07-91, P-06-121
Dating of sediment and peat	Accumulation rates of sediment and peat	P-06-301, P-06-250
Chemical and mineralogical analyses of QD	Chemical and mineralogical characteristics of QD	P-04-273, P-05-49, R-02-47, R-04-72, R-05-15, R-06-18, P-06-121, P-05-35, P-07-30, P-06-301, P-06-320, P-06-321, P-07-222

3.6 Chemistry of water, regolith and biota

3.6.1 Hydrochemical data and evaluation methods

Hydrochemical evaluations presented in this report are based on data from the data freeze Laxemar 2.3. This data set includes observations from surface waters, hydrological measurements and characterization of shallow groundwater in the regolith, as well as groundwater data from the bedrock. Hydrochemical data from the following sample categories are available.

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

The different sample categories are schematically shown in Figure 3-10, and Figure 3-11 gives an overview of the locations of sampling sites for surface water and shallow groundwater.

A large number of parameters have been measured in the different sampling campaigns in the Laxemar-Simpevarp area. The parameters may be grouped into a number of categories, based on the chemical characteristics and on the sampling interval of each parameter (Table 3-7). These large sets of data require statistical methods in order to simplify visualisation and to identify major patterns, as well as anomalies.

In /Tröjbom et al. 2008/, ordinary 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. 2008/ 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 and deposits

Terrestrial vegetation including roots, the uppermost soil and sediment layers, aquatic vegetation, as well as terrestrial and aquatic fauna, were sampled for chemical analyses during the site investigations /Engdahl et al. 2006/. Among the terrestrial fauna, small rodents were sampled within the site investigation programme, whereas samples from moose, roe deer and fox were provided by local hunters. Biota samples (and also samples from soils and sediment) were analysed for macronutrients (CNP) using standard spectrometry methods, and for c. 60 other elements using different ICP-techniques, as described in /Engdahl et al. 2006 /.

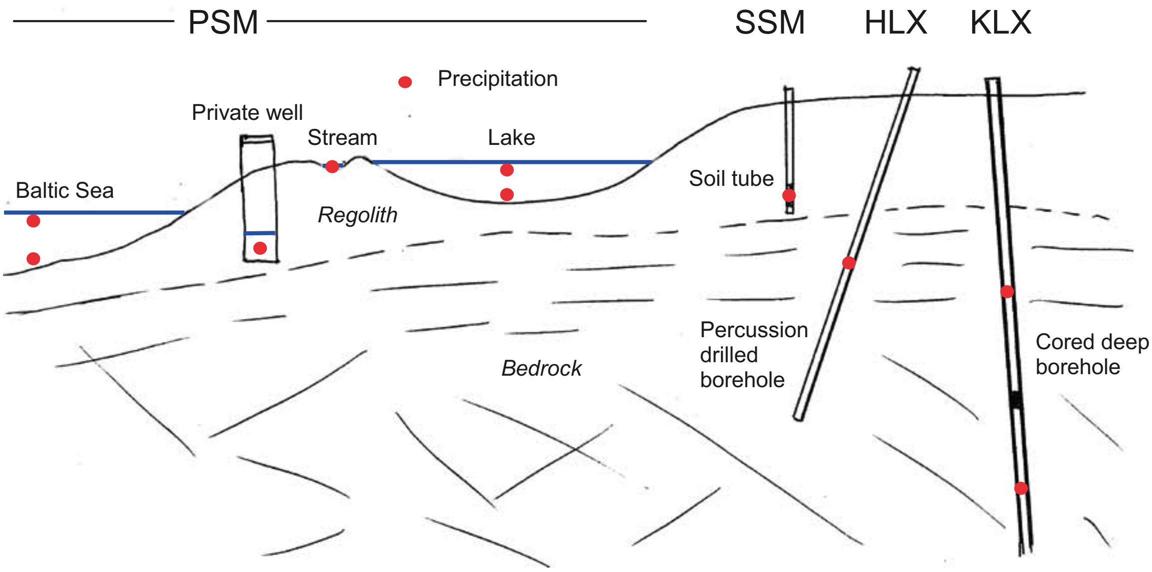
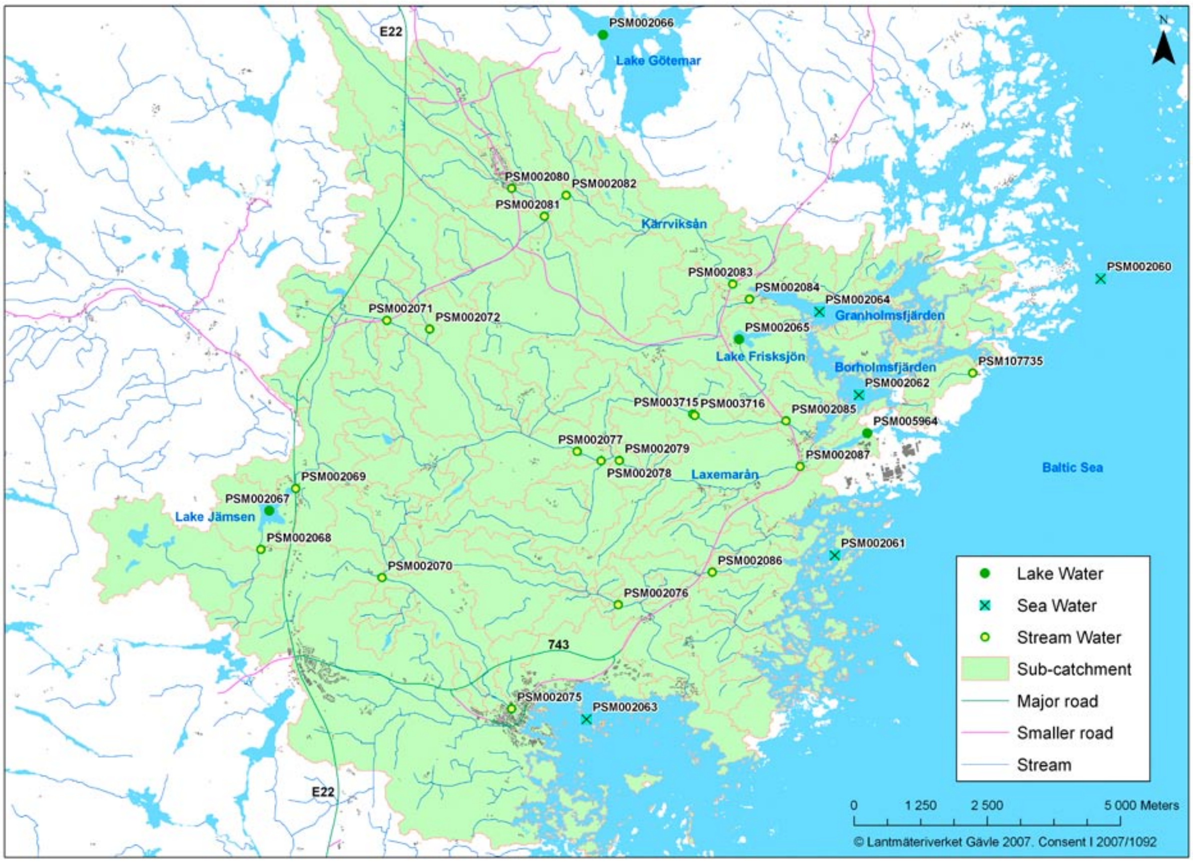


Figure 3-10. *Schematic picture showing the different object types that are sampled for hydrochemistry in the Laxemar-Simpevarp area. Objects with the ID "PSM" includes all point objects in the surface system, "SSM" represents soil tubes, and "HLX" and "KLX" represents percussion boreholes and cored boreholes, respectively.*



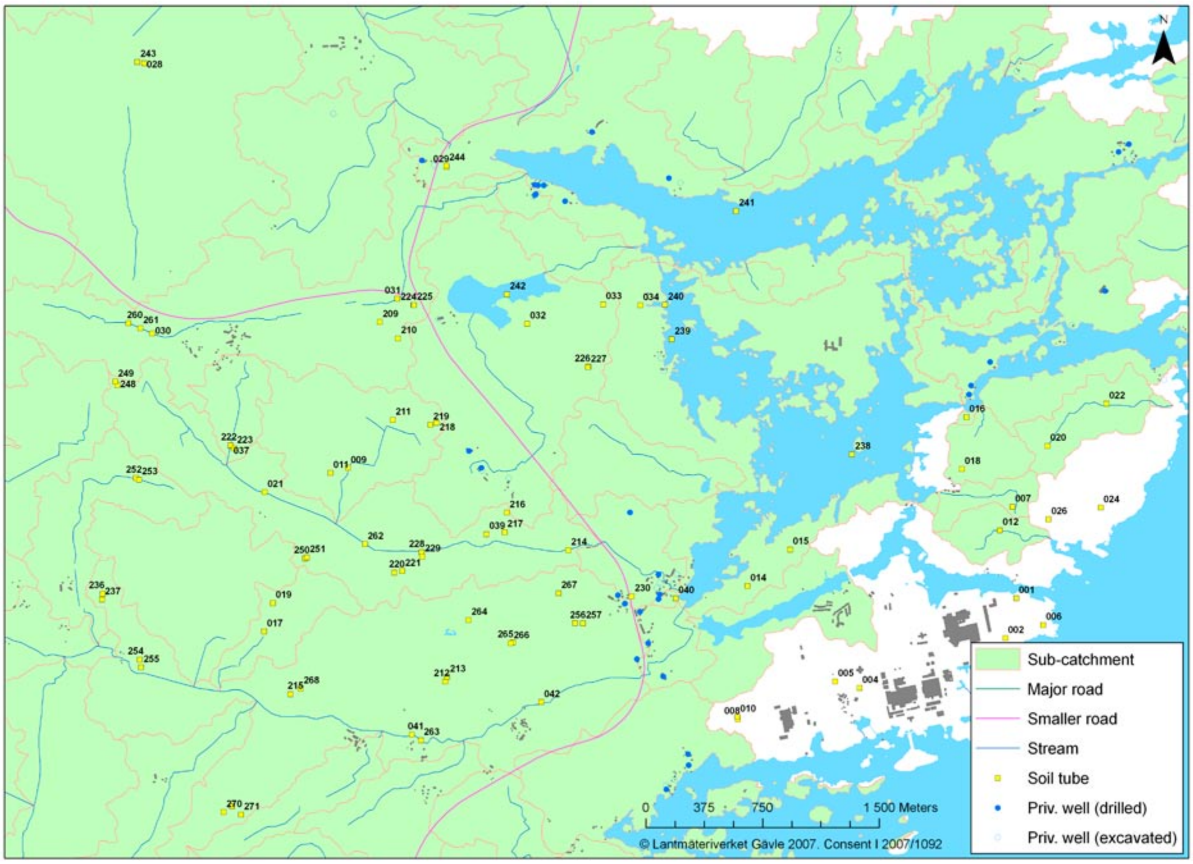


Figure 3-11. *Sampling points in the Laxemar-Simpevarp area: above) surface water, and below) shallow groundwater (soil tubes and private wells).*

Table 3-7. Different parameter categories and representative parameters in the Sicada database. The grouping is based on the chemical characteristics of each parameter and on the sampling intervals in surface water objects.

Representative parameter	Other parameters in category
Parameters sampled each month (in most surface water objects)	
pH	Conductivity
Cl	Na, K, Ca, Mg, HCO_3 SO_4
Sr	Li, I, F, Br
Si	SiO_2
Fe	Mn
Tot-N	NH_4-N, NO_{23}-N, tot-P, PO_4-P, TOC, DIC
DOC	
Parameters sampled 4 times per year or more seldom	
S_2	O_2*
^{2}H	^{3}H, ^{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

* Dissolved oxygen is measured in the field during monthly samplings of surface waters, whereas laboratory analyses are conducted only when field measured oxygen levels are low.

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, and quantitative descriptions of a number of ecosystem properties that relates to biomass, production and energy budgets, e.g. consumption, egestion and respiration for mammals, 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 of Laxemar-Simpevarp has been studied in a number of different investigations (see Section 4.2 in /Löfgren (ed.) 2008/), of which the aims can be summarised as; 1) to describe which species or functional groups are present in the area, 2) to establish reliable density estimates for larger animals and birds, and to quantify important pools/fluxes of matter for use as input for the ecosystem models, and 3) to establish a baseline for an ongoing monitoring programme that can be used to relate different kinds of disturbances to wildlife population changes.

3.7.2 Ecosystem models

Field-estimated local carbon balances for three ecosystems

Pools and fluxes of organic matter were investigated at three localities and compiled according to the component structure in Figure 3-12. The three localities represent vegetation types considered to be important, both with respect to area coverage and as potential sinks for organic matter (Section 6 and Table 6-1 in /Löfgren (ed.) 2008/). One oak forest, one Norway spruce forest and one forested wetland with alder were studied. The intention was to describe the carbon balance using site-specific data whenever possible, but in some cases such data were missing and literature data were used instead.

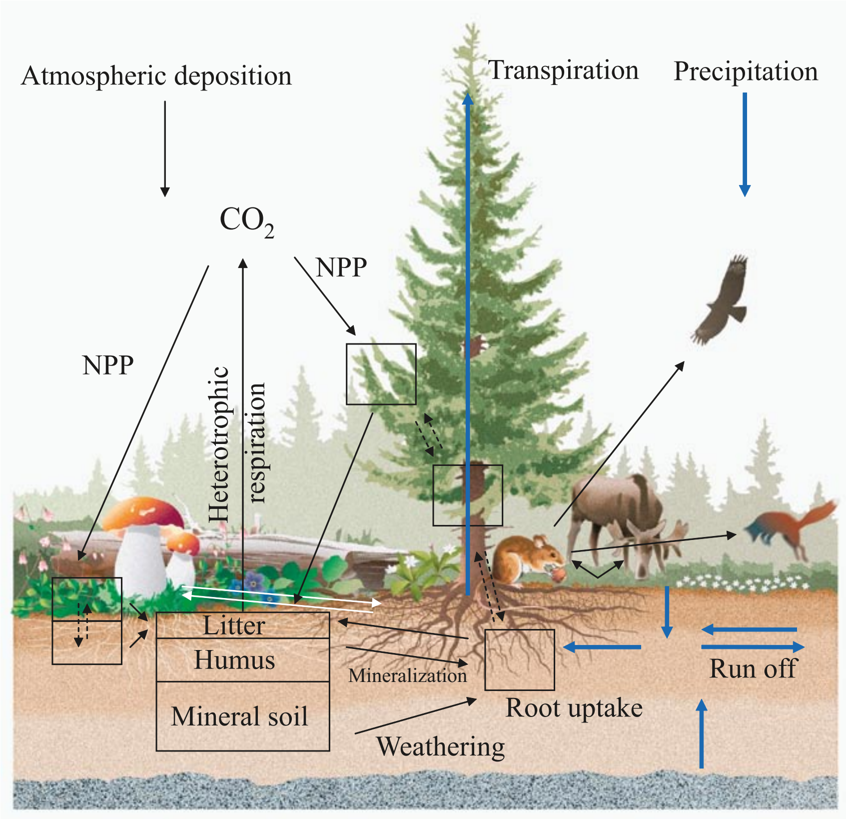


Figure 3-12. *A conceptual description of pools and fluxes in an ecosystem, where boxes symbolise pools of carbon/organic matter and arrows symbolise fluxes of carbon/organic matter. Fluxes to herbivores and carnivores were not estimated in the detailed description of the three ecosystems, but were included in the description food webs (see Table 4-20).*

Tree-layer data for the different localities were derived from tree height and breast height diameter, measured on ten representative trees at each locality /Tagesson 2006b/. Equations in /Marklund 1988/ were used to calculate fractions of green tissue, stem and living branches for Norway spruce (*Picea abies*). Above- and below-ground biomass for oak (*Quercus robur*) was estimated using equations presented in /Balboa 2005/, whereas the equations presented in /Johansson 2000/ were used for alder (*Alnus glutinosa*). The fractions of biomass present in the stumps, coarse roots and fine roots down to approximately 5 mm diameter, and for those between 5 mm and 2 mm, were calculated using functions presented in /Petersson and Ståhl 2006/. Birch root functions were 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/. The fine root production at all the three localities is assumed to be equal to the biomass for the fraction < 2 mm, where the assumption is based on data from Forsmark and a literature review /Persson and Stadenberg, 2007b/. Turnover of larger root fractions was neglected. 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 increments of leaf/needle and fine root biomass were assumed to be zero.

The above-ground biomass and Net Primary Production (NPP) for the field and bottom layers was investigated by removing and measuring all biomass at the time of peak biomass, and by estimating moss shoot elongation in 2004 /Löfgren 2005/. The below-ground biomass of fine roots was estimated by /Persson and Stadenberg 2007a/. Litter production was assumed to be equal to the above-ground

NPP (including production of the bottom layer) plus the total biomass of the fine (< 2 mm) root fraction, which was assumed to be replaced during the year. Estimates of biomass and NPP for ectomycorrhizal 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 2005/ in all vegetation types with a tree layer according to the vegetation map of both sites. The litter layer was investigated as described in /Löfgren 2005/. The soil organic carbon pool was estimated using eight lateral transects down to approximately one metre below the surface for each locality, according to the methodology of the National Forest Soil Inventory /Lundin et al. 2004/. Soil respiration in the different vegetation types was measured in 2004/2005 and 2005/2006, using a closed chamber technique, along with measurements of soil temperature and soil moisture /Tagesson 2006a, 2007/.

Estimates of regional carbon balances by dynamic modelling

The dynamic vegetation model LPJ-GUESS /Sitch et al. 2003/ was used to give a regional description of carbon balances for the most common vegetation types in 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 were used together with literature data (see Section 7 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 Oskarshamn, Gladhammar, Högmasten and Äspö /Larsson-McCann et al. 2002, Lärke et al. 2005/ and the NORDKLIM climate stations Krokshult, Växjö, Kalmar and at the North cape of Öland /SMHI 2003, www/. The other model parameters, such as soil and vegetation characteristics, were set to correspond to the conditions at the site (see Section 7 in /Löfgren (ed.) 2008/).

The model results cover the following 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 results were 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 biomasses of all mammals, birds, amphibians and reptiles were estimated based on their densities in the area. Moreover, production, consumption, egestion and respiration was calculated 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 inputs and outputs of a large number of elements were constructed at the catchment scale in accordance with the conceptual illustration in Figure 3-13. The estimated inputs included atmospheric deposition and weathering, and the output consisted of horizontal transport by water. The pools of different elements were also estimated for four ecosystem components within each catchment. The regional ecosystem description of organic matter was combined with estimates of site-specific element concentrations within different ecosystem components /Engdahl et al. 2006/ to estimate the four pools within each catchment. By using the ratio between carbon and a specific element for pools and fluxes within ecosystems, it was possible to estimate their elemental contents, concentration and fluxes.

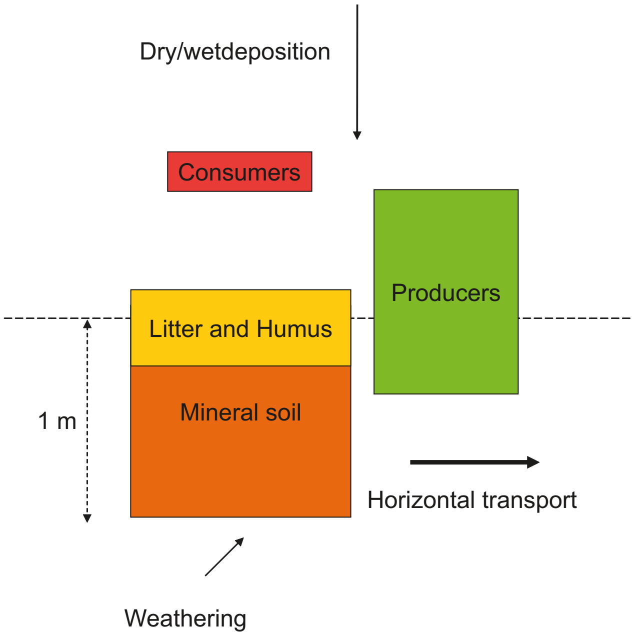


***Figure 3-13.** The conceptual mass-balance model of the pools and fluxes that were used to describe terrestrial catchments.*

In this report, a mass balance for phosphorus is presented. In Chapter 10 in /Löfgren (ed.) 2008/, detailed mass balances are presented also for uranium, thorium and iodine, together with more elementary evaluations for a number of other elements, and the underlying assumptions for the calculations. The atmospheric wet deposition at the site was estimated to be 0.027 gP $m^{-2}y^{-1}$ /Knape 2001/, 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 the Laxemar-Simpevarp area /Appendix C in Tröjbom et al. 2008/.

Wetlands were not covered in the regional estimates obtained from LPJ-GUESS, and the wetland in the ecosystem model was instead parameterised using field-estimated site data and, in some cases, literature data (see 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, on the other hand, may principally be 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 simplified view of the limnic ecosystem has been used in the 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, macrophytes, bacterioplankton, benthic bacteria, zooplankton, benthic fauna and fish) have been used in the description of lakes and streams in the Laxemar-Simpevarp area.

3.8.2 Ecosystem models

An ecosystem model was produced to describe the flow of carbon within and also to and from the lake ecosystem of Lake Frisksjön in the Laxemar-Simpevarp area. In ecosystem models, major functional groups and the flows of elements or energy between them, are included.

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 is defined as the benthic area reached by enough light to enable photosynthesis. Finally, the profundal is defined as the benthic habitat below the photic zone. It is difficult to identify the border between the lake and the surrounding land at Frisksjön, as the reed belts surrounding Frisksjön may be 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 classified into 9 functional groups according to feeding and habitat preferences (Table 3-8).

Site-specific data on biomass of functional groups are used in the ecosystem carbon model. Benthic community respiration has been measured at one occasion, but other than that no site-specific data on primary production, respiration or consumption are available. Instead, these processes were estimated from biomass 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 aim of the mass-balance model is to give an overview of major fluxes of different elements to and from the lake ecosystem. In order to do so, the following influxes to and outfluxes from the lake ecosystem were identified and estimated:

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

In the carbon mass balance, two additional fluxes were identified; outflux by birds feeding in the lake and influx/outflux 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 may potentially 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, also can be neglected for other elements.

Table 3-8. Functional groups in lake ecosystems.

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

Data to estimate all 4 fluxes in the mass balances are available for 16 elements (C, Ca, Cl, Fe, I, K, Mg, Mn, N, Na, P, S, Si, Sr, Th, U). For another 28 elements, the only flux missing is the deposition from atmosphere, a flux contributing a minor part of the total inflow for all elements for which data are available /Nordén et al. 2008/. In this report, we present mass balances for Frisksjön. As a complement to the mass balances, the chemical composition (64 elements) of important components in the lake ecosystem are described, i.e. 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 Laxemar-Simpevarp comprises the marine area included in the Laxemar-Simpevarp regional model area. The studied area has been divided into 19 sub-basins, based on today's bathymetry and the inferred future drainage areas /Brydsten 2006/. By dividing the area into sub-basins, we were able to construct a site evolution model, 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 Laxemar-Simpevarp. The basin delimitations were made to fit the overall strategy of the project to assess the long-term safety of a deep repository for nuclear waste. The method for identification of basin delimitations is described in detailed in /Brydsten 2006/. Physical and chemical characteristics for the basins are presented in Chapter 4 and 5 in /Wijnbladh et al. 2008/.

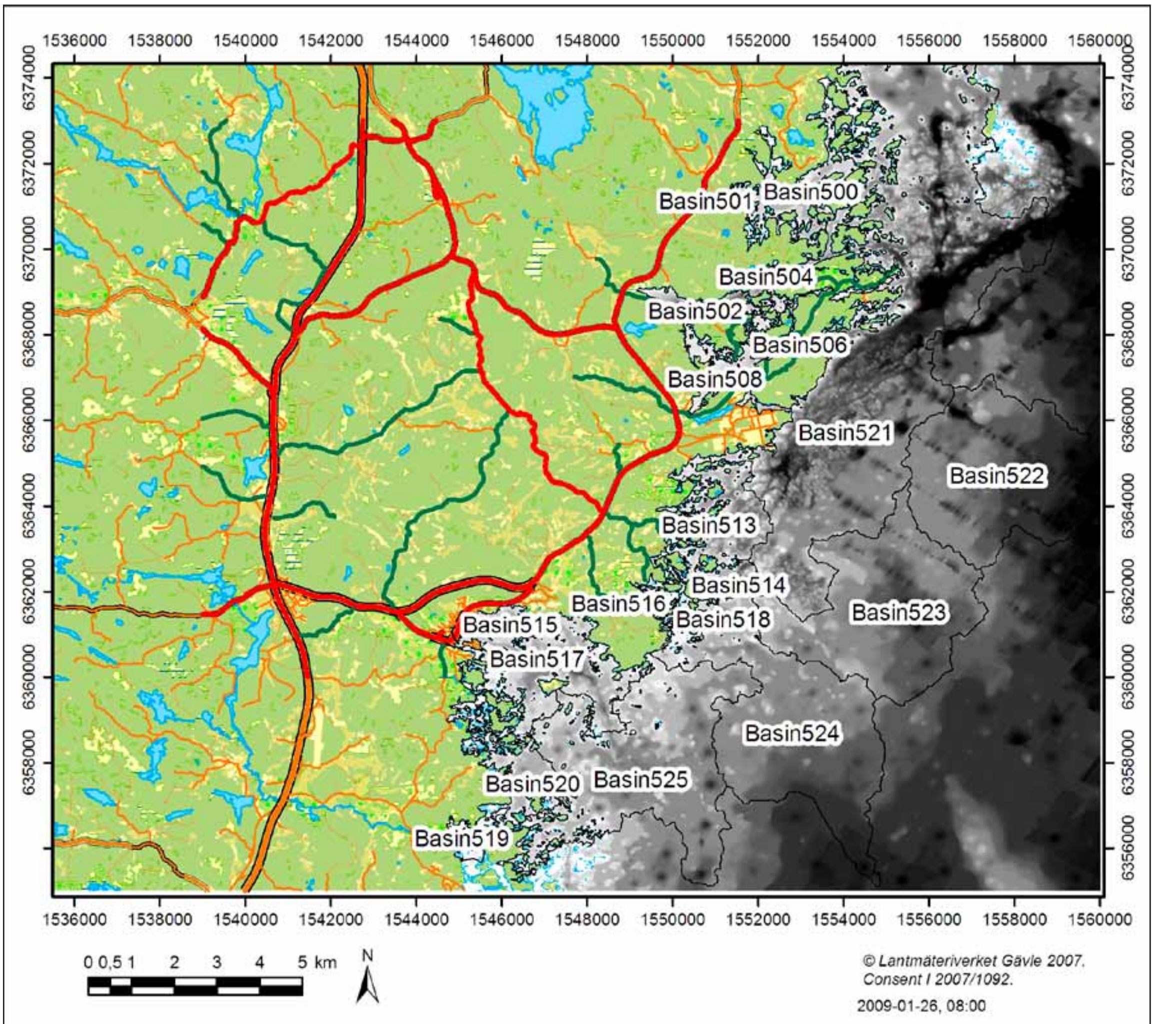


Figure 3-14. Marine basins and bathymetry in the coastal area of Laxemar-Simpevarp.

3.9.1 General description

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

3.9.2 Ecosystem model

The marine ecosystem and its characteristics were conceptualised in an ecosystem model for energy flow within the system (Figure 3-15). Based on site data, the ecosystem model was used for quantifying pools and fluxes of matter within the marine basins in the Laxemar-Simpevarp area, using carbon as a proxy. 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 (primary production, consumption, respiration, excretion, advection, burial and runoff) in the ecosystem. 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 determining which groups to use and how to divide the organisms among these groups was similar to the model structure used by /Kumblad et al. 2003/, but modified as shown in (Figure 3-15). The origin of data and (if any) further treatment of data regarding biomass and distribution of the biotic and abiotic pools used in the calculations, are extensively described in Chapter 4 in /Wijnbladh et al. 2008/.

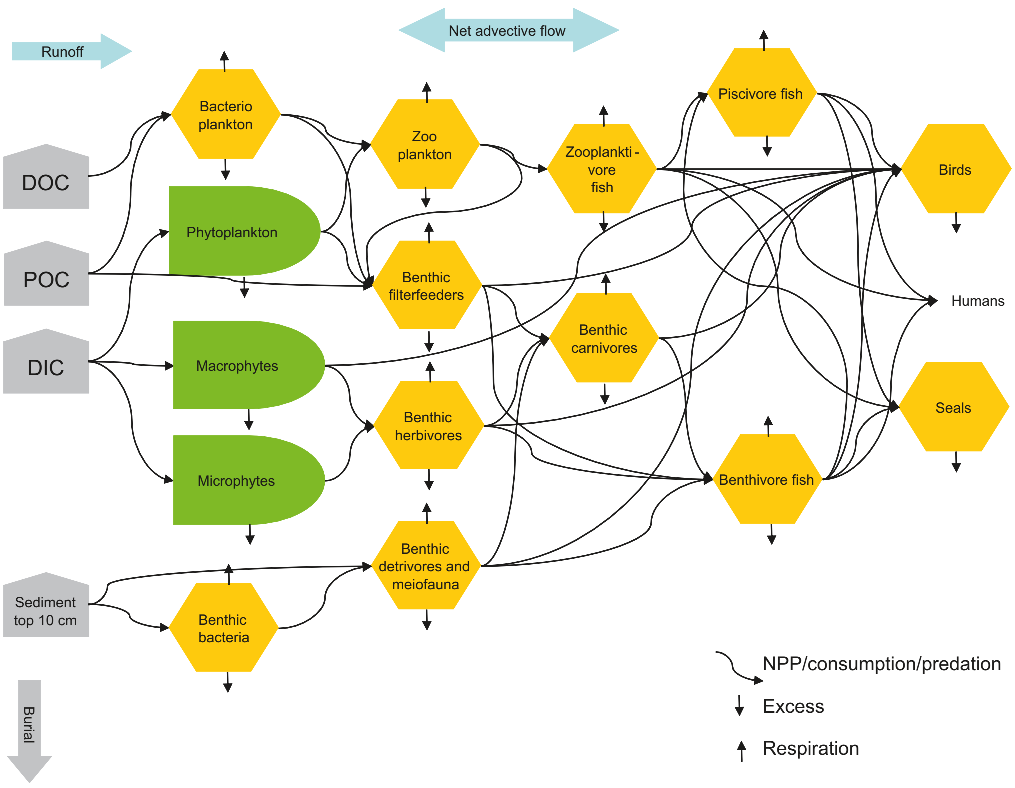


Figure 3-15. *Conceptual illustration of the food-web based ecosystem model for the marine ecosystem at Laxemar-Simpevarp. Boxes and arrows denote pools and fluxes of matter, respectively. Excretion and death of organisms is included in the "Excess".*

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

3.9.3 Mass-balance models

In addition to the marine ecosystem model, mass balances for each basin were calculated for carbon (C), nitrogen (N), phosphorus (P), iodine (I), thorium (Th) and uranium (U), to identify the major pools and fluxes. Primary production and respiration were included in the carbon balances, but these processes were not quantified for other elements and hence were not included in the mass balances. Fluxes and processes included in the calculations of mass balances for the marine ecosystem are shown in Table 3-9.

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 Simpevarp" /Miliander et al. 2004/. The Simpevarp area is defined in that report. Most of the data demonstrated in /Miliander et al. 2004/ were obtained from Statistics Sweden (Sw: SCB).

Other data sources such as the National Board of Fisheries (Sw: *Fiskeriverket*), the County Administrative Board of Kalmar (Sw: *Länsstyrelsen i Kalmar 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, data for a period of ten years were not available for all variables, so shorter time series were used as well. For more detailed information on issues relating to the collection and compilation of human population data, see /Miliander et al. 2004/.

Table 3-9. Pools and fluxes considered (marked with X) in the mass balance models for C, N, P, I, Th and U in the marine basins of Laxemar-Simpevarp.

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 C, N and P
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	X
Out to atmosphere	Respiration	X	Not applicable
Out to atmosphere	Evaporation/transpiration/volatilization	Not considered	Not considered
Diffusive outflow	E.g. Migration of organisms	Not considered	Not considered
Accumulation	Burial in sediment	X	X

3.10.1 Human consumption

The human consumption of crops (barley) and animal products (beef, milk, pork, mutton and game-meat) originating from different drainage areas in Laxemar-Simpevarp has been calculated. The figures represent input data for the terrestrial ecosystem carbon budget in /Löfgren (ed.) 2008/. Two different cases have been studied concerning production of meat and milk from domestic animals. First, a regional generic case based on the meat production in Laxemar-Simpevarp described in /Miliander et al. 2004/. Secondly, a potential self-sustainable case based on literature data regarding the maximum livestock an area intended for fodder production and grazing can support. In this report, we only present results from the regional generic case.

The production of animal products in Laxemar-Simpevarp is presented 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 in mammals is 11.7% of the total (live) weight (44.9% of the dry weight) according to site-specific analyses of the chemical composition of biota in Forsmark and Laxemar-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 taken from in the Nutrient Database from United States Department of Agriculture /USDA 2007/. The carbon content in milk (2% milkfat) is estimated as 5.1% and in eggs as 14% (egg 50 g, raw).

There are no site-specific yield statistics available for the crop production in Laxemar-Simpevarp. However, there are statistics available describing the standard yields for the yield survey districts (SKO-areas). Laxemar-Simpevarp is situated in SKO-area 0814 /SCB 2007/. The amount of carbon in barley, the most important crop in the area, is estimated to 0.46 gC gdw^{-1}, as for the green field layer, in /Fridriksson and Öhr 2003/. The dry weight is 86% of the fresh weight according to /SCB 2007/. Comprehensive descriptions and evaluations of the input data and the methods used for calculating human consumption are presented in /Löfgren (ed.) 2008/.

4 Resulting models

4.1 Historical development at Laxemar-Simpevarp

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 historical 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 Laxemar-Simpevarp 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 has been characterised by large, and sometimes rapid, changes in global temperature. The present period was preceded and will be followed by colder periods in which ice sheets cover larger areas than at present. The Laxemar-Simpevarp area has been covered by glacier ice at least three times during the Quaternary period. However, 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 characterised by a climate similar to the present. However, long ice-free periods have also occurred 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 areas for long periods. The latest glaciation (Weichselian) started c. 115,000 years ago, and there is geological evidence of at least two periods when a large part of Sweden was free of ice. However, the exact timing and duration of these ice-free periods are unknown. The onset of the latest glacial coverage in the area is not known, whereas the timing of the latest deglaciation along the Baltic basin coast is rather well established.

The present interglacial, the Holocene, started with the deglaciation of Mid-Sweden around 9,500 BC, when the ice margin had already retreated from Laxemar-Simpevarp. The climate during the deglaciation became successively warmer, although some periods with colder climate did occur. In southern Sweden, the warmer climate caused a gradual change from tundra vegetation to forest dominated by deciduous trees. The Mid-Holocene climate was characterised by average temperatures a few degrees higher than today. The forests in southern Sweden have subsequently been dominated by coniferous forest. The areas covered by forest began to decrease c. 3,000 BC due to the introduction of agriculture.

The development of the Baltic Sea after the latest deglaciation has been characterised by ongoing shoreline displacement (Figure 4-1). All parts of the Laxemar-Simpevarp regional model area are situated below the highest shoreline. During the deglaciation at c. 12 l00 BC, the area was, depending on the local topography, situated 50–100 m below the sea level, and the first parts of the regional model area emerged from the sea around 9,400 BC (Figure 4-1).

The interaction between isostatic rebound related to the removal of glacial ice and the associated unloading, 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 in turn has caused variable salinity throughout the Holocene. The estimated salinity variations in the open Baltic Sea during the last c. 9,000 years are shown in Figure 4-2. During the period 4,500–3,000 BC, the salinity was almost twice as high as it is today.

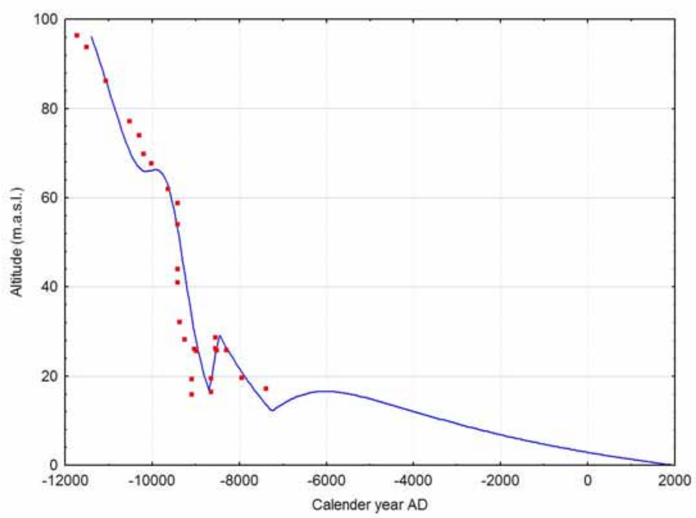


Figure 4-1. *Shoreline displacement in the Laxemar-Simpevarp area after the latest deglaciation. The red symbols show the results from dating of lake sediments in the region /Svensson 1989/. The blue curve was calculated using a mathematical model /Påsse 2001/. m.a.s.l.= metres above present sea level.*

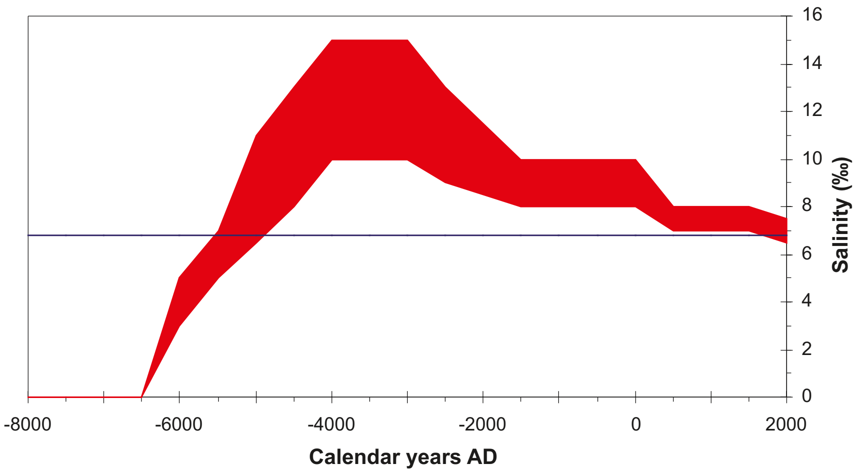


Figure 4-2. *Estimated range for the salinity of sea water in the open Baltic proper off Oskarshamn during the past 10,000 years. Maximum and minimum estimates are derived from /Westman et al. 1999/ and /Gustafsson 2004ab/. The present salinity in the area is shown by the horizontal reference line.*

The development of the Baltic Sea since the latest deglaciation can be divided into four main stages (Figure 4-3). Three of these stages; Yoldia, Ancylus and Littorina, are named after molluscs which reflect the ambient salinity of the stages.

It is suggested that all known unconsolidated deposits in the Laxemar-Simpevarp area were deposited during the last phase of the latest glaciation and after the subsequent deglaciation (see Chapter 4 in /Söderbäck (ed.) 2008/). However, the possibility of the occurrence of older deposits cannot be excluded and there are indications of older deposits in adjacent areas outside the regional model area.

Till and glaciofluvial material were deposited directly by the ice sheet and by glacial meltwater, respectively. During the deglaciation, glacial clay was deposited in the lowest topographical areas. In the terrestrial valleys, gyttja clay occurs, which was deposited when these areas were narrow bays. The subsequent shoreline displacement had a major impact on the distribution and relocation of fine-grained Quaternary deposits. The most exposed areas were strongly affected by wave washing

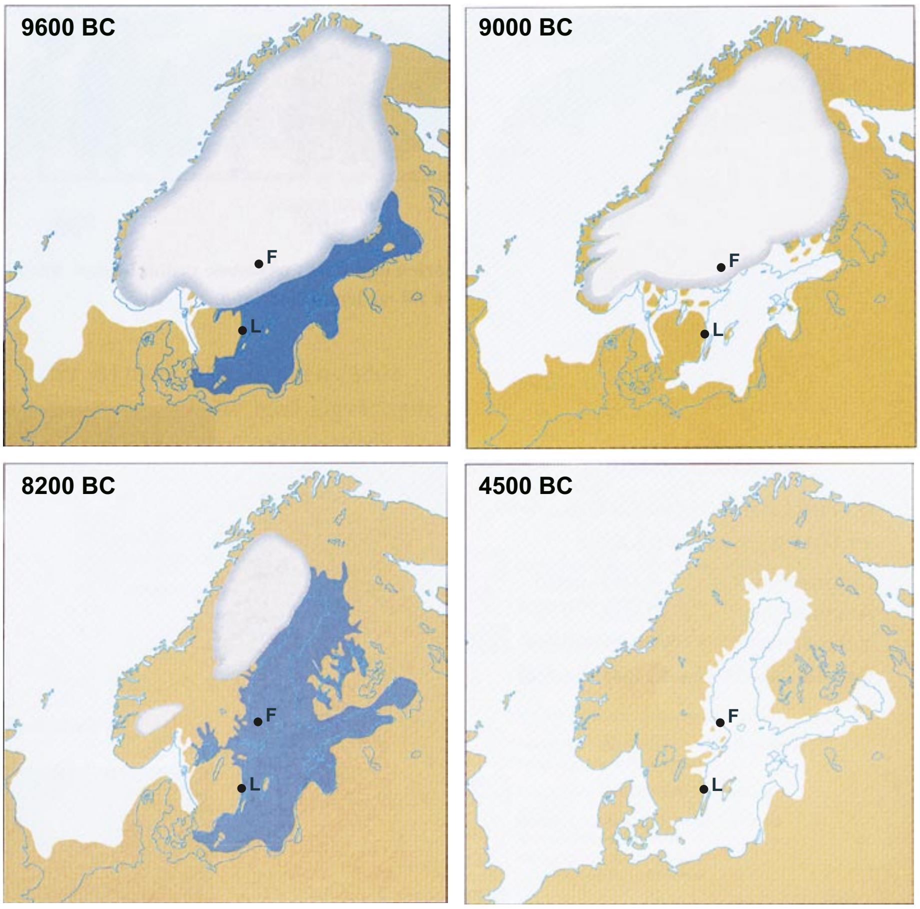


Figure 4-3. *Four main stages characterise the development of the Baltic Sea since the latest deglaciation: A) the Baltic Ice Lake (glacio-lacustrine, 13,000-9,500 BC), B) the Yoldia Sea (lacustrine/brackish/lacustrine, 9,500-8,800 BC), C) the Ancylus Lake (lacustrine, 8,800-7,500 BC) and D) the Littorina Sea (brackish, 7,500 BC-present). Fresh water is symbolised by dark blue and marine/brackish water by light blue, from /Fredén (ed.) 2002/. "F" and "L" indicate the location of Forsmark and Laxemar-Simpevarp, respectively.*

and bottom currents. Sand and gravel were consequently eroded from older deposits, transported and deposited at more sheltered locations. Periods of erosion also occurred at sheltered locations, which 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 elsewhere.

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 characterised as polar desert. Relatively soon after the deglaciation, the ice-free areas were colonised 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 the Younger Dryas (c 11,000–9,500 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 9,000 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 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 up of the landscape started c. 3,000 BC.

In coastal areas like Laxemar-Simpevarp, the shoreline displacement has strongly affected ecosystem development and is still causing a continuing change in the abiotic environment. As a result of an overall regressive shoreline displacement, the sea bottom is being uplifted and transformed into new terrestrial areas or to freshwater lakes (Figure 4-4). The initial conditions for ecosystem succession from the original near-shore sea bottom are strongly dependent on the topographical conditions, with sheltered bays 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 turn into a lake as the water becomes fresh, or it may remain as a bay until the shoreline displacement turns it into a wetland.

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. A usual pattern for the lake ontogeny is the sequential development of more and more eutrophic (nutrient-rich) conditions as the lake depth and volume

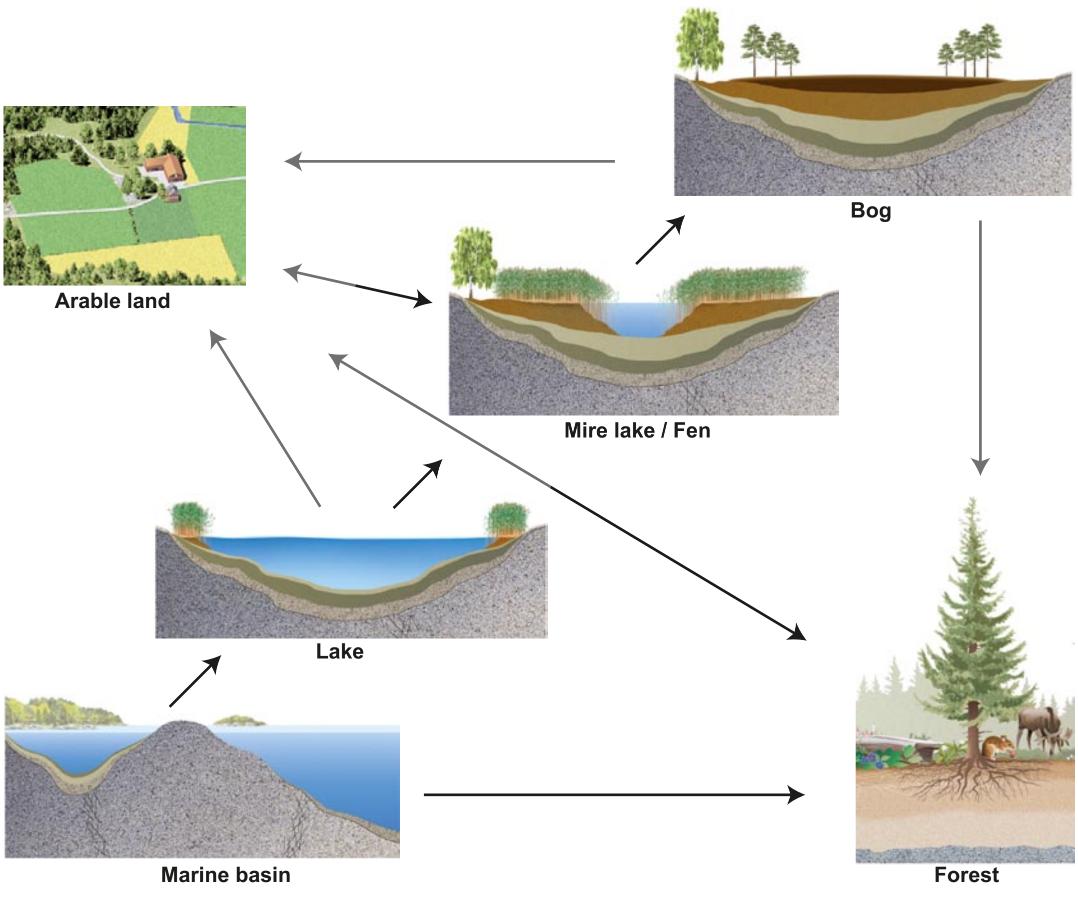


Figure 4-4. A schematic illustration of the major ecosystems that may be found at a location during temporal development in which the original sea bottom is slowly turned into an inland area due to shoreline displacement. Black arrows indicate natural succession, whereas grey arrows indicate human-induced 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.

decreases. There are, however, examples of lake ontogeny that include a transition to more oligotrophic (nutrient-poor), as well as to more dystrophic (low pH, brown-water) conditions. All lakes in the Laxemar-Simpevarp regional model area are characterised by more or less dystrophic conditions (cf. Section 4.7.1), and this is typical for small forest lakes in large areas of Sweden. Dystrophic lakes are characterised by high input of allochthonous carbon (i.e. transported from the surrounding catchment area) and often by short water turnover time /Brunberg and Blomqvist 2000/.

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 dominant process of mire formation in Sweden, is an ongoing water-logging of more or less water-permeable soils, mainly by expanding mires. Primary mire formation is when peat is developed directly on fresh soils after emergence from water or ice. All three processes are likely to occur in the Laxemar-Simpevarp area, but peat land filling in lakes (terrestrialisation) is probably the most common type of peat land development in the investigation area. Historically, mires have often been drained for forestry or to gain new agricultural areas, and in Sweden such activities peaked in the 1930s. In the Laxemar-Simpevarp area, a large part of today's agricultural land is characterised by a peat layer which was built up during a previous wetland phase.

4.1.3 Human population and land use

The coast of Småland became ice-free around 12,000 BC. At the time of the deglaciation, the whole Laxemar-Simpevarp region (an area which in this section refers to three parishes in the surroundings of Oskarshamn, that together constitute approximately 1,000 km^2 /cf. Söderbäck (ed.) 2008/) was situated below sea level. The oldest human remains in the region are found in the highest situated terrain, which is located in the western parts of the region 25–40 metres above sea level (which corresponds to emergence from the sea around 9400–8,300 BC). There is a rich occurrence of prehistoric remains in the region, some of them indicating that the area was exploited already during the Older Stone Age (9,000–4,000 BC). Following the arrival of the first humans to the region, it has been characterised by its forest- and archipelago settlements. The main occupation since the colonisation of the area has been a combination of agriculture, forestry and fishing activities /Lundqvist 2006/.

The settlement structure in the region during the medieval period (1,100–1,550 AD) was characterised by single farms, in contrast to for example Forsmark, where settlements were organised in small villages. The farms were subdivided into several smaller farms when the population increased. An unusually large proportion of farms in the Laxemar-Simpevarp region belonged to the crown, and the proportion of freeholders was correspondingly very small. The number of freehold farmers in the region increased during the 18th century, both due to the partitioning of farms and to the fact that farmers purchased farms that previously belonged to the nobility.

Following a nationwide decline in the population during the middle of the medieval period, there was a strong population expansion. The population in the region doubled or increased at an even faster rate between the 1570s and the 1750s, and the strong population growth continued until 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 has decreased during the 20th century, and instead, the number of people employed in industry and crafts has increased.

Woodland was and is dominant in the Laxemar-Simpevarp region. The forests in the region have been used for many different purposes; pastures, firewood, fencing material, subsistence needs, burn-beating (cutting and burning rough fallow on land to prepare for tillage), as well as production of charcoal, tar and potash. In addition to sawmill activities, the production of charcoal, tar and potash, were in many cases an important part of the economy of the individual household. Trading in timber was advantageous since the timber was easily transported in the coastal areas. In the Laxemar-Simpevarp region there was also a boat-building tradition, which grew during the 19th century to a minor shipbuilding industry /Lundqvist 2006/. The areal extent of arable land, and even more so of meadows, increased throughout the 18th and 19th centuries. Much of the new agricultural land was gained by ditching of wetlands. Some of these areas are still cultivated, whereas others are now deserted and, in some cases, have been turned into woodlands.

4.2 Geometric models

4.2.1 Digital elevation model (DEM)

As described in Section 3.3.1, a Digital Elevation Model (DEM) was constructed and used as a fundamental input to many of the other models of the surface system. The resulting DEM (see Figure 4-5) has a size of approximately 35×20 kilometres, a cell size of 20 metres, and a total number of 1,752,751 cells. The area is undulating with narrow valleys situated at bedrock deformation zones. The range in elevation is approximately 151 metres, with the highest point at 106 metres above sea level at the south-western part of the regional model area, and the deepest sea point at –45 metres in the south-eastern part of the area. The mean elevation in the model is 24 metres. The model area is covered by 73% land and 27% sea. The flat landscape is also reflected in the statistics of slope, where the mean slope is 2.52 degrees. 87.0% of the cells have a slope lower than 5 degrees and 11.7% have a slope between 5 and 10 degrees. As expected, almost all of the cells with a slope steeper than 10 degrees (2.5% of all cells) are situated along the earlier mentioned narrow valleys or along lake shores.

4.2.2 Regolith depth model and stratigraphy model (RDM)

Figure 4-6 shows the modelled distribution of total regolith depths in the Laxemar-Simpevarp regional model area. Figure 4-7 shows the distribution of regolith depths in the central part of the model area. The model includes the stratigraphical distribution of till, glaciofluvial sediments, glacial clay, post-glacial sand/gravel, clay gyttja, peat and artificial fill. Six Z-layers were used to describe the stratigraphical distribution of the regolith (Figure 3-4 and Table 3-1). A large proportion of the modelled area has a low data density and the area was therefore divided into nine domains (see Section 3.3.2). These domains were defined based on the geographical distribution of QD. The average regolith depth in each domain was calculated using the available data (Table 3-5 and Table 3-6). These average depths (Table 4-1) were used together with measured depths to interpolate the regolith depths in the model area.

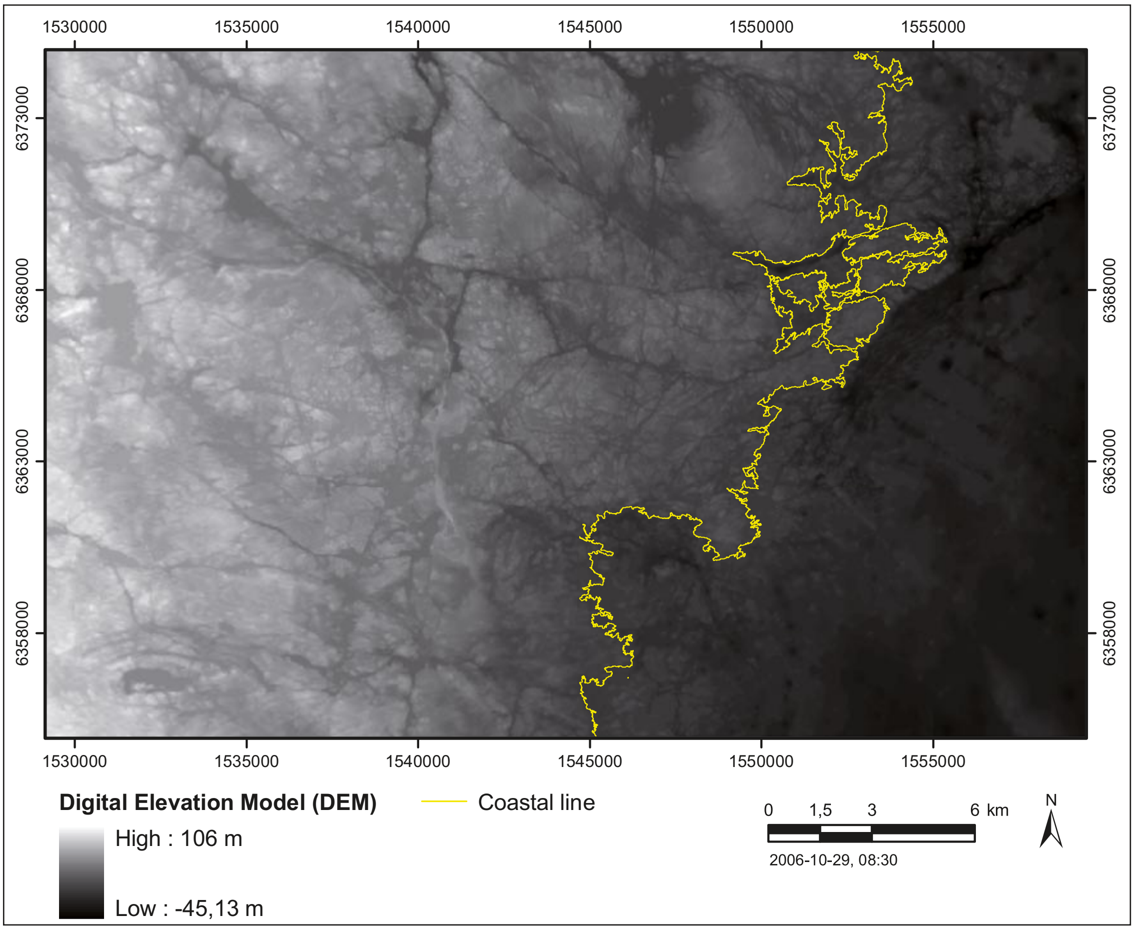


Figure 4-5. The 20-metre digital elevation model for the Laxemar-Simpevarp area, describing the land surface, lake bottoms, and sea bottom, with the coastal line indicated in yellow.

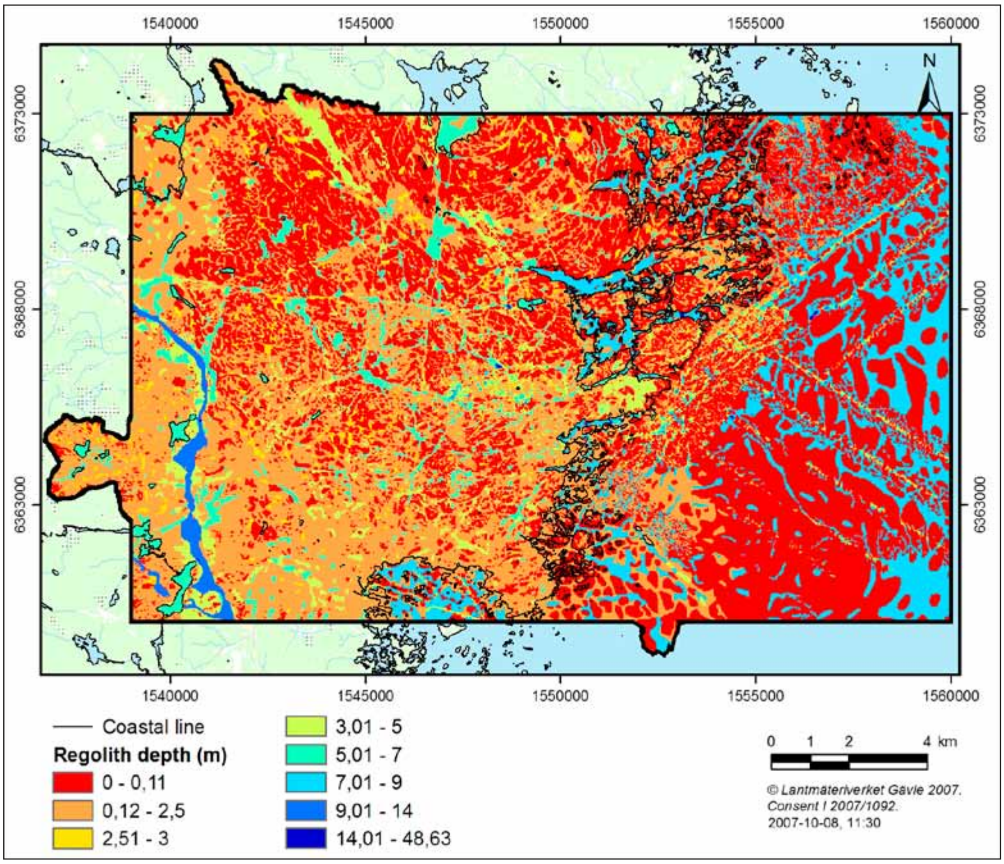


Figure 4-6. *The modelled distribution of total regolith depths in the Laxemar-Simpevarp area. Note the relatively thick glaciofluvial deposit (Tunåsen) in the western part of the area.*

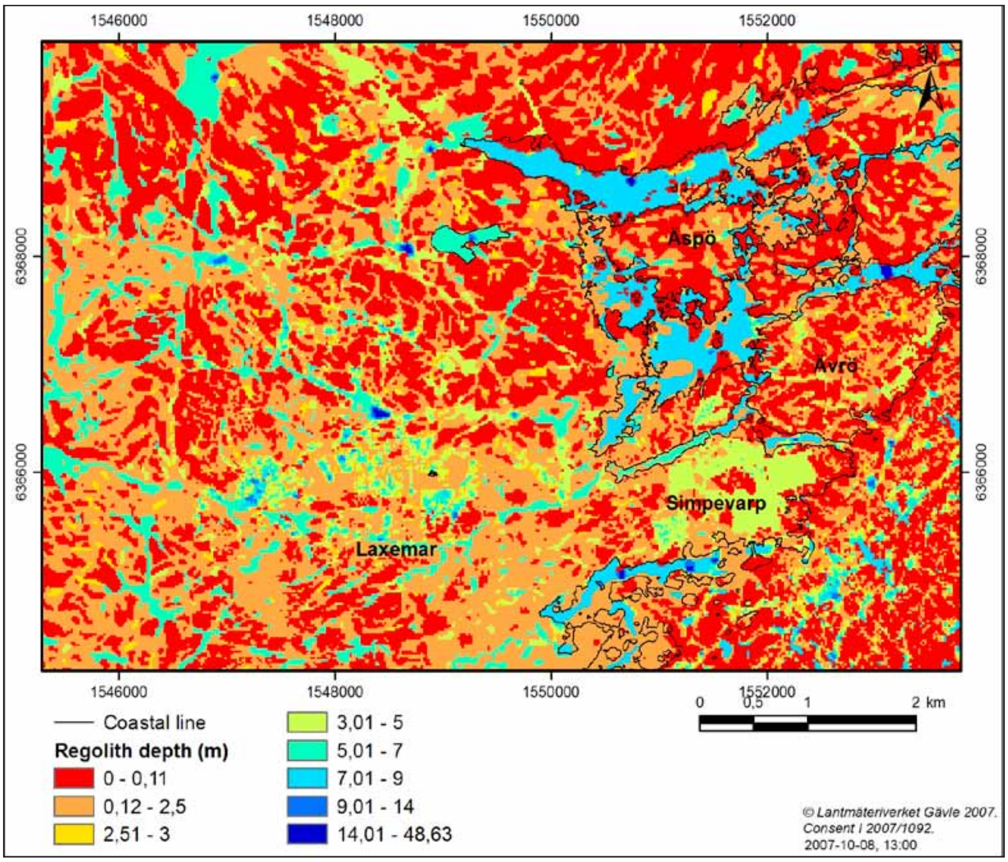


Figure 4-7. *The modelled distribution of total regolith depths in the central part of the Laxemar-Simpevarp regional model area.*

Table 4-1. The average depth and stratigraphy of QD in the domains used for the Regolith Depth Model. The average depths of the different types of QD are presented in Table 4-9 and Table 4-10. All bedrock outcrops and QD, except peat, have an uppermost Z1 layer (see Table 3-1), which is not shown in the present table.

Deposit on the QD map	Domain	Stratigraphy of the QD, from ground surface downwards	Average depth in the terrestrial areas (m)	Average depth in the marine areas (m)
Bedrock outcrops	1	No QD	0.1	0.1
Till	2	Till (Z6)	2.1	2.1
Clay gyttja	3	Clay gyttja (Z3), postglacial sand/gravel (Z4), glacial clay (Z5), till (Z6)	5.7	8.7
Peat	4	Peat (Z2),till (Z6)	3.0	Missing
Peat	5	Peat (Z2), clay gyttja (Z3), postglacial sand/gravel (Z4), glacial clay (Z5), till (Z6)	6.6	Missing
Glacial clay or postglacial sand/gravel	6	Postglacial sand/gravel (Z4), glacial clay (Z3), till (Z6)	4,1	7,1
The Tuna esker	7	Glaciofluvial sediments (Z4)	13.8	Missing
Other glaciofluvial deposits	8	Glaciofluvial sediments (Z4)	4.1	4.1
Artificial fill	9	Artificial fill (Z4)	5	5

The Regolith Depth Model clearly reflects the overall character of the area with thin layers of QD in the high topographical areas and thicker layers in the valleys (Figure 4-6 and Figure 4-7). The relatively thick regolith layers in areas covered by glaciofluvial sediment and artificial fill diverge from that pattern, however. The large Tuna esker in particular is clearly recognisable as a north-south zone with thick regolith in the western part of the modelled area (Figure 4-6). The average depths of regolith with and without outcrops are shown in Table 4-2. The largest regolith thickness (almost 50 metres) has been interpreted from refraction seismic in a bay north of Ävrö.

The regolith depth and stratigraphy model can be used for retrieving data from observation points, e.g. boreholes, and permits stratigraphical profiles to be extracted. The profiles also show all observation points that fall within 20 metres of the line. This means that observation points situated up to 10 metres from the line in either direction will be included. In some illustrated profiles, the elevations of observation points and depths of geological units may therefore differ from the modelled layers displayed in the profiles. The total regolith depth in the model is to a large extent produced from the average thicknesses of the different deposits. That is also reflected by the often smooth thickness of the Z-layers shown in the profiles (e.g. Figure 4-8). In most parts of the model area, the ground surface follows the underlying bedrock surface (e.g. Figure 4-8). However, certain areas have a relatively thick layer of till (see Section 4.4), which in many places forms hummocks

Table 4-2. Average and median regolith depths in the modelled area.

Type of data	Mean regolith depth (±SD) (m)	Median regolith depth (m)
Whole model (including bedrock outcrops)	2.2 (±2.6)	2.1
Whole model except bedrock outcrops	3.7 (±2.5)	2.1

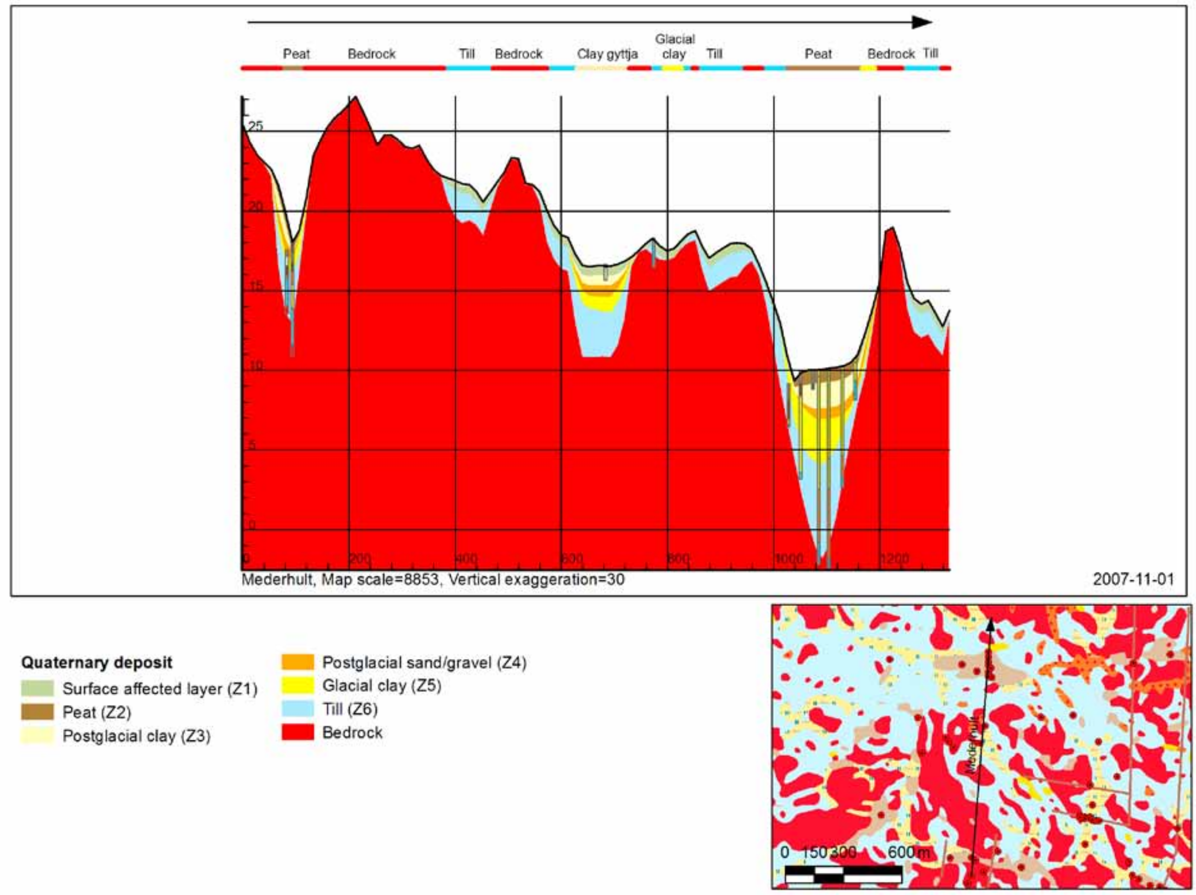


Figure 4-8. The profile shows the total depth and stratigraphy of the regolith in a north-south profile close to Mederhult. The valley in the right part of the profile is one of the largest lineaments in the model area.

with a ground surface morphology that differs from that of the underlying bedrock. One such area is situated east of "Lilla Laxemar" (Figure 4-9). The large glaciofluvial deposit in the western part of the model area, the Tuna esker, is an example of a deposit that has been modelled using a small data set. The thickness of the esker shown in the profile (Figure 4-10) is therefore the calculated average thickness of the Tuna esker (in the model area). As a consequence, the topography of the modelled bedrock surface follows that of the overlying ground surface. The true bedrock surface probably has a different morphology.

4.3 Surface hydrology and near-surface hydrogeology

The site investigations in Laxemar-Simpevarp included comprehensive investigations of meteorology, hydrology and near-surface hydrogeology: Monitoring is undertaken of meteorology (including "winter parameters" such as snow depth and ice freeze/breakup), surface-water levels in lakes and bays of the Baltic Sea, stream discharges, groundwater levels in the QD and point-water heads in the rock. Moreover, different types of field- and laboratory tests were conducted for hydrogeological characterisation of the QD and the interaction between groundwater in the QD and groundwater in the rock. A brief summary is given below of the conceptual and quantitative (MIKE SHE) modelling of hydrology and near-surface hydrogeology at Laxemar-Simpevarp. For more detailed information, see /Werner 2008, Werner et al. 2008, Bosson et al. 2008/.

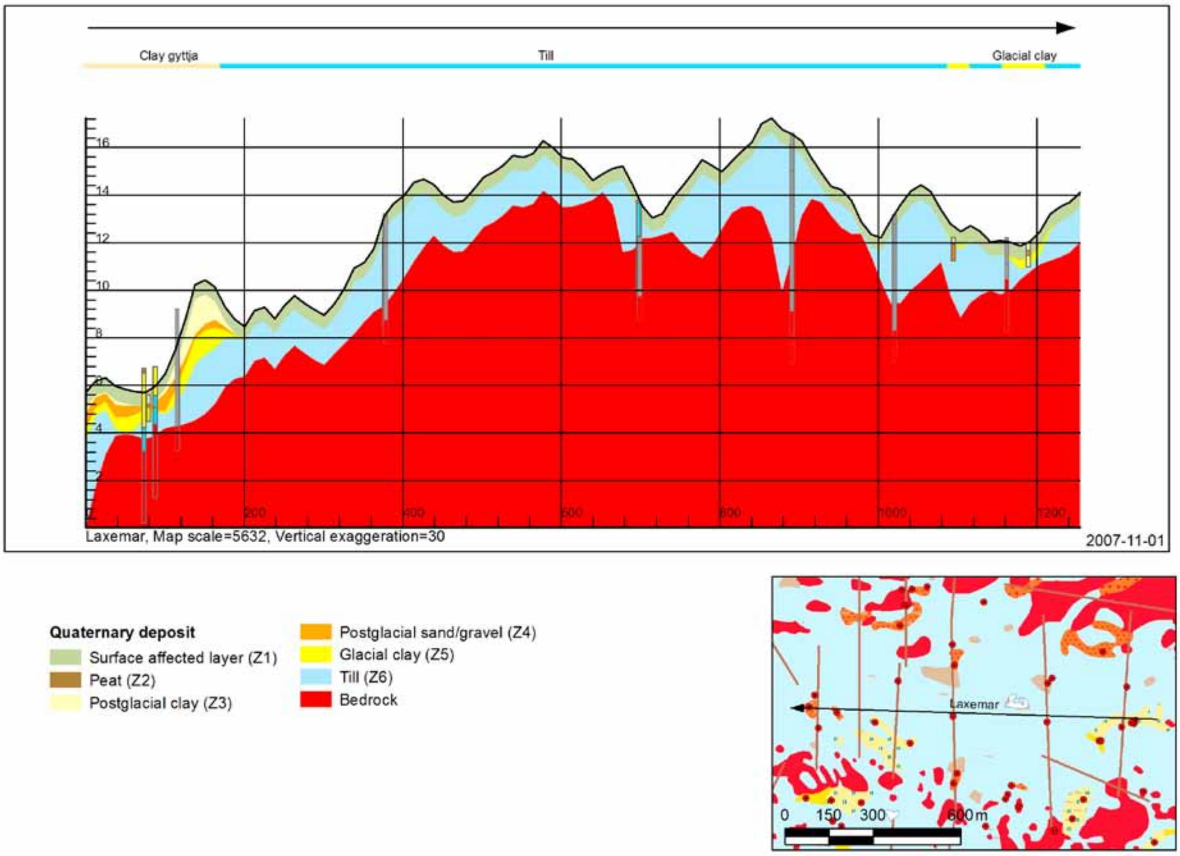


Figure 4-9. The profile shows the total depth and stratigraphy of the regolith east of "Lilla Laxemar". That area is characterised by a relatively thick till cover. Several refraction seismic profiles cross the stratigraphical profile. The results indicate that the morphology of the ground surface differs from that of the underlying bedrock.

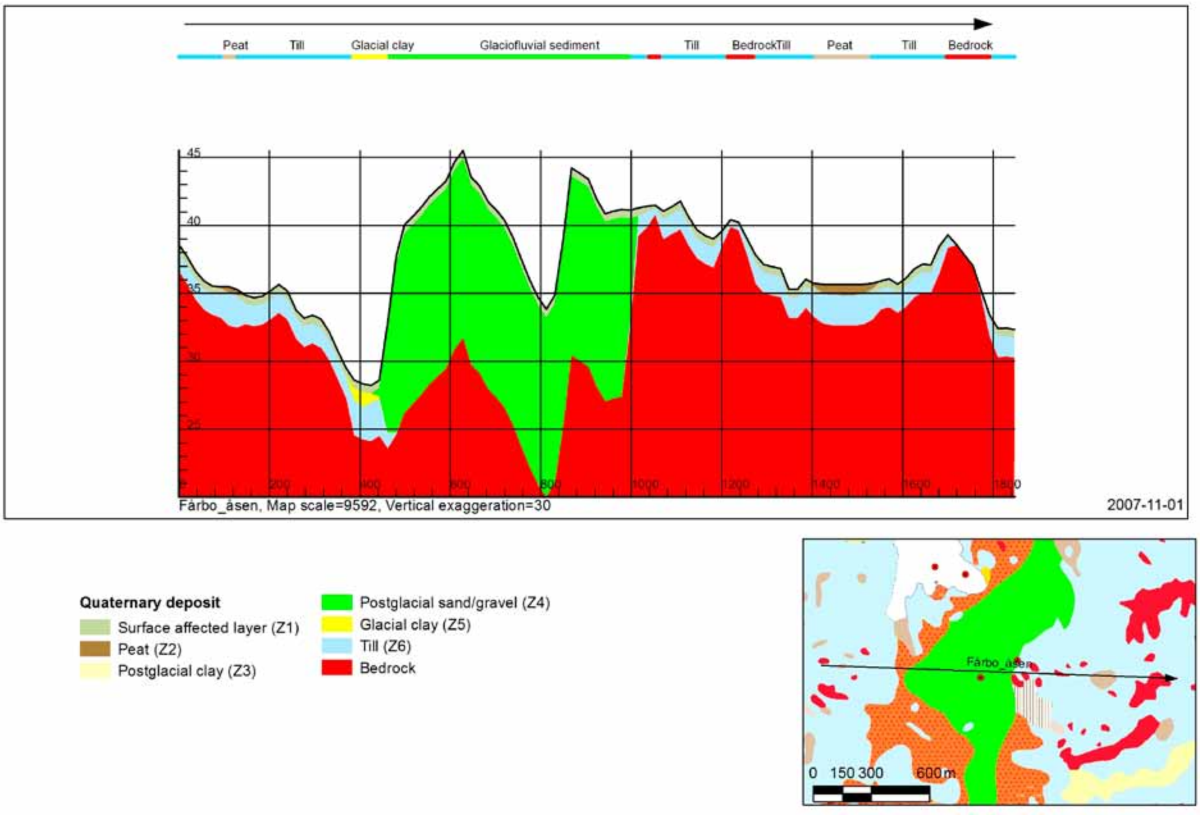


Figure 4-10. The profile shows the total depth and stratigraphy of the regolith across the glaciofluvial esker, Tunåsen, north of the village of Fårbo.

4.3.1 Hydrological and near-surface hydrogeological setting

As described in Section 4.2.1, the topography of the Laxemar-Simpevarp area is characterised by relatively distinct valleys, surrounded by higher-altitude areas dominated by exposed/shallow rock. The south-western and central parts of the Laxemar-Simpevarp regional model area are characterised by hummocky moraine and thereby small-scale topography. Almost the whole area is located below 50 m.a.s.l. Accordingly, the entire area is located below the highest coastline.

The precipitation demonstrates a near-coastal gradient, with less precipitation at the coast compared with areas further inland. Based on long-term meteorological data from surrounding stations, the Swedish Meteorological and Hydrological Institute (SMHI) has estimated the 30-year (1961–1990) annual average precipitation be to 553 mm for the Äspö station (on the coast) and 630 mm for the Plittorp station (further inland). For the three years 2005–2007, for which data are available from all discharge-gauging stations (at one station, monitoring commenced in Feb. 2005), the site-average specific discharge can be estimated to be c. 170 $mm \cdot y^{-1}$ (or c. 5.2 $L \cdot s^{-1} \cdot km^{-2}$), which is within the range of uncertainty of the regional long-term average estimated by /Larsson-McCann et al. 2002/. During the same period (2005–2007), the annual average precipitation was c. 580 mm on Äspö and c. 620 mm in Plittorp, whereas the potential evapotranspiration was c. 540 and 530 $mm \cdot y^{-1}$, respectively. Based on the available site investigation data, the site-average water balance for the years 2005–2007 can hence be estimated as P = 600 $mm \cdot y^{-1}$, ET (actual evapotranspiration) = 430 $mm \cdot y^{-1}$ and R (specific discharge) = 170 $mm \cdot y^{-1}$.

The main lakes are Jämsen (0.24 km^2), Frisksjön (0.13 km^2), Söråmagasinet (0.10 km^2), Plittorpsgöl (0.03 km^2), Fjällgöl (0.03 km^2) and Grangöl (no size data). These relatively small lakes are shallow, with average depths in the range 1–4 m and maximum depths in the range 2–11 m. It should be noted that all lakes are located above sea level, and hence no intrusion of sea water takes place. Wetlands covers in total c. 3% of the delineated catchment areas /Brunberg et al. 2004/. Most streams in the area are influenced by land improvement and drainage operations. The flow in the streams demonstrates seasonal variability. In particular, the smaller streams are dry during large parts of the year. Of the monitored streams, permanent waterflow occurs in the streams Laxemarån, Kåreviksån downstream from Lake Friskjön and Kärrviksån. The stream Ekerumsån is dry during the summer, whereas the other monitored streams are dry for approximately half of the year.

According to the conceptual description of the regolith, sandy-gravelly till overlies the rock in the whole area where significant depths of regolith are present, also in most areas with exposed/shallow rock (which may have a QD depth of up to c. 0.5 m). The exceptions are some of the exposed/shallow rock areas, in which organic soil and a relatively thin vegetation layer directly overlie the rock. The sandy-gravelly till is characterised by a relatively high hydraulic conductivity (estimated as c. $4 \cdot 10^{-5}$ $m \cdot s^{-1}$). Furthermore, as illustrated in the vertical N-S section in Figure 4-11, there are indications that the hydraulic conductivity of the QD overlying the rock in the deepest parts of the large (i.e. wide and deep) valleys is about one order of magnitude higher than that of till in other parts of the area. Permeameter tests on till indicate an anisotropic hydraulic conductivity, with an anisotropy ratio (K_h/K_v) that may be on the order of 15–30. However, it should be noted that permeameter tests are associated with a smaller tested volume than e.g. slug tests providing hydraulic conductivity data. Generic data are used to support the estimates of the hydrogeological properties for QD types other than till.

As part of the site-descriptive modelling of hydrology at Laxemar, four main hydrogeological type areas have been defined, which conform to the subdivision of the Quaternary deposits (cf. Section 4.4): High-altitude areas, large and small valleys, glaciofluvial deposits, and hummocky moraine areas. These type areas are mainly used as a framework for description of the overall patterns of groundwater recharge and discharge in the Laxemar-Simpevarp area, as described further below. Moreover, the conceptual modelling includes parameterizations of the overall hydrogeological flow domains (QD and rock). Further detailed parameterization of different types of QD has been done as part of the SurfaceNet project, whereas detailed descriptions and parameterization of the rock (including near-surface rock) were performed by the HydroNet modelling group.

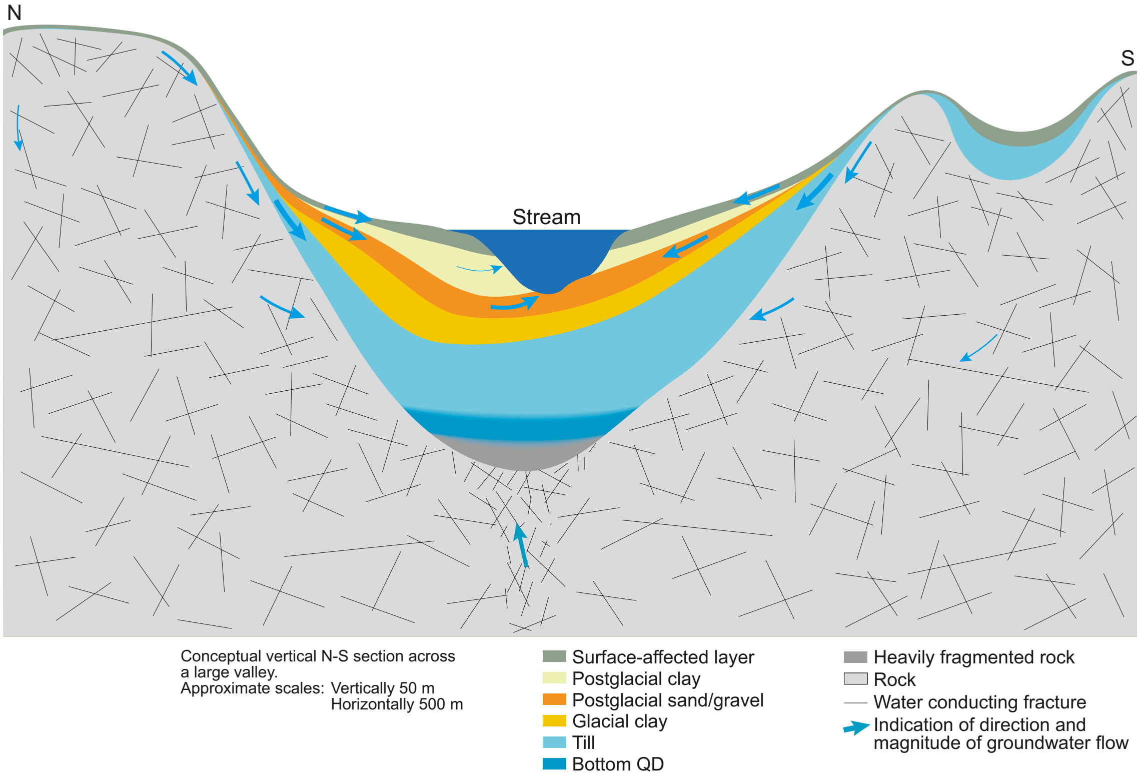


Figure 4-11. *Conceptual vertical N-S section across a large valley in Laxemar. Note the different horizontal (500 m) and vertical (50 m) scales, and that the size of the stream is exaggerated in the figure. "Bottom QD" represents more conductive QD that locally overlies the bedrock in the deepest parts of the large valleys.*

Table 4-3 provides a brief overview of the hydrogeological characteristics of the QD and the rock in Laxemar-Simpevarp, using rough estimates of the hydraulic conductivity (K) as a descriptive parameter. Site-specific data are used for till, whereas generic data are used to support the estimates for the other types of QD. The hydrogeological characteristics of the rock are further described in /Rhén et al. 2008, 2009/. A short summary of the bedrock hydrogeology description is given in Section 5.2.3 of the present report, where the division into the different depth intervals for which data are given in Table 4-3 is described and an illustration of the integrated surface-bedrock conceptual hydrogeological model is provided.

Except for some minor wetlands, the surface waters (lakes, streams and wetlands) are associated with low-altitude areas. These surface waters are mainly underlain by glacial and post-glacial sediments. Specifically, the general bottom-up QD stratigraphy below surface waters is till and glacial clay, overlain by postglacial sediments (sand/gravel, gyttja clay/clay gyttja, overlain by fen peat and bog peat in the wetlands). As illustrated in the conceptual section in Figure 4-12, groundwater-level measurements below lakes indicate that interaction between surface water in the lakes and the underlying QD is limited to near-shore areas. Some parts of the streams pass through areas where there are no layers of glacial clay and postglacial sediments, which is also the case for some near-shore areas of the lakes. The local conditions for surface water-groundwater interaction are also influenced by land improvement and drainage operations, which, for instance, imply that water flows in subsurface pipes along some parts of the streams. Interactions between groundwater in the QD, groundwater in the rock and surface water are further described and illustrated in Section 4.3.4.

Table 4-3. Characteristics of hydrogeological flow domains in Laxemar-Simpevarp. The hydraulic conductivity (K) is used as a descriptive parameter. Data for the rock are described in more detailed in /Rhén et al. 2008, 2009/ (m.a.s.l. = metres above sea level).

Flow domain	Description	K ($m \cdot s^{-1}$)
Surface layer	Surface-affected layer (general)	$4 \cdot 10^{-4}$
	Shingle	$1 \cdot 10^{-2}$
Postglacial QD	Bog peat	$4 \cdot 10^{-6}$
	Fen peat	$4 \cdot 10^{-6}$
	Gyttja	$1 \cdot 10^{-8}$
	Gyttja clay/clay gyttja	$1 \cdot 10^{-7}$
	Sand/gravel	$1 – 5 \cdot 10^{-3}/1 \cdot 10^{-2}$
Glacial QD	Glacial clay	$1 \cdot 10^{-8}$
	Till/artificial fill	$4 \cdot 10^{-5}$
	QD in deepest part of large valleys	$4 \cdot 10^{-4}$
Rock	Near–surface rock (depth 0–10 m)	No data, likely more conductive than deeper rock
	Rock (HRD and HCD, –10 – –150 m.a.s.l.)	$2 \cdot 10^{-7}$ (test scale 100 m)
	Rock mass (HRD, –10 – –150 m.a.s.l.)	$4.9 \cdot 10^{-9}$ (test scale 5 m)
	Rock (HRD and HCD, –150 – –400 m.a.s.l.)	$3.5 \cdot 10^{-8}$ (test scale 100 m)
	Rock mass (HRD, –150 – –400 m.a.s.l.)	$9.3 \cdot 10^{-11}$ (test scale 5 m) – $1.7 \cdot 10^{-8}$ (test scale 100 m)
	Deformation zones	c. 10 times more conductive than surrounding rock mass

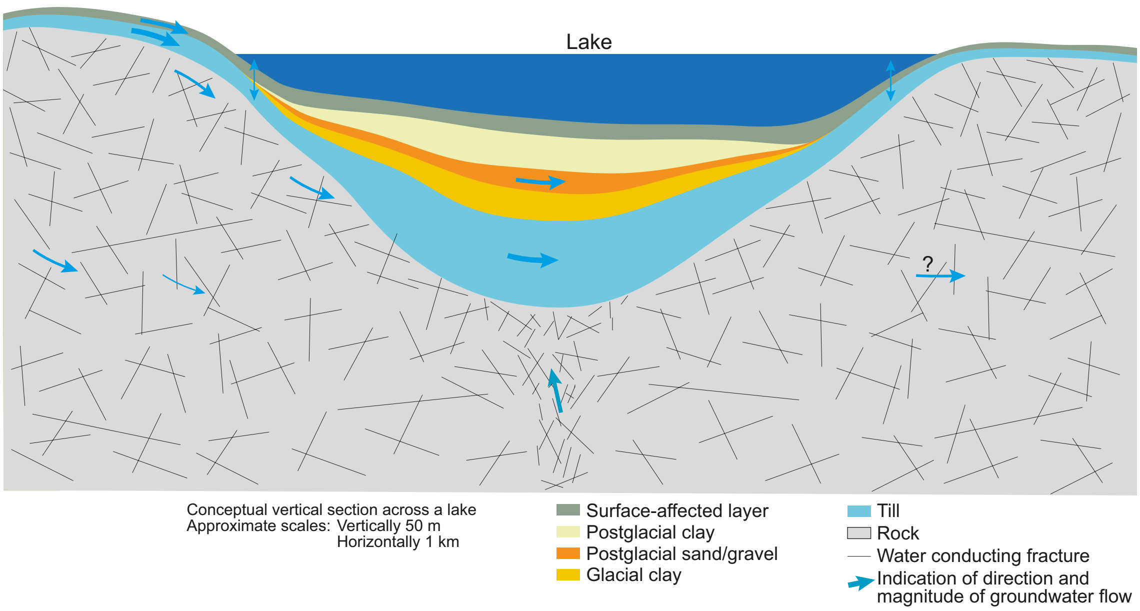


***Figure 4-12.** Conceptual vertical section across a lake in Laxemar, illustrating that interaction between surface water in the lakes and the underlying QD likely is limited to near-shore areas. Note the different horizontal (1 km) and vertical (50 m) scales in the figure.*

4.3.2 Boundary conditions

The meteorological conditions govern the upper (top) boundary conditions of the hydrological and hydrogeological system. Water is naturally added to this system by rainfall and snowmelt, and abstracted by evaporation, transpiration and run-off. This implies that the most important meteorological time-series data for a description of hydrology and hydrogeology include precipitation (P) and potential evapotranspiration (PET), since these parameters provide basic information on the site-specific driving forces of the hydrological cycle; for site averages of these parameters, see Section 4.3.1.

Average groundwater levels in the QD range from c. –0.8 to 26 m.a.s.l., whereas there is only a 4.5 m range in terms of groundwater levels below the ground surface. Figure 4-13 illustrates the observed strong correlation between groundwater levels in the QD and ground-surface elevations. Conceptually, the 3D ”groundwater surface” in the QD generally follows that of the ground surface, and it can be assumed that the identified surface-water divides /Brunberg et al. 2004/ coincide with the water divides for groundwater flow in the QD. The most pronounced outlier in Figure 4-13 (SSM000230, situated in the Gässhult esker close to Lilla Laxemar) is located in highly-conductive glaciofluvial material, a material which normally is characterised by a large depth to the groundwater level.

Concerning the sea as a hydraulic boundary, the average maximum and minimum sea levels during the period with available site-investigation data (May 2004–Dec. 2007) were –0.52 and 0.71 m.a.s.l., respectively, whereas the average sea level during this period was 0.03 m.a.s.l. The largest daily sea-level changes occurred on Nov. 1, 2006 (c. +0.26 m) and Dec. 22, 2004 (c. –0.23 m).

4.3.3 Infiltration and groundwater recharge

According to the conceptual hydrogeological model, groundwater recharge primarily takes place in high-altitude areas, dominated by outcrop rock or shallow regolith. Groundwater recharge also takes place within the ”hummocky moraine” and ”glaciofluvial deposits” type areas, characterised by smaller-scale topography and eskers, respectively. Precipitation and snowmelt are thought to be the dominant sources of groundwater recharge. Groundwater-level monitoring in the QD near the shore of Lake Jämsen and in the QD below Lake Frisksjön indicates that interactions between lake water and groundwater in the underlying QD are limited to near-shore areas. It should be noted that this observation is based on data from very few monitoring points. However, as explained in

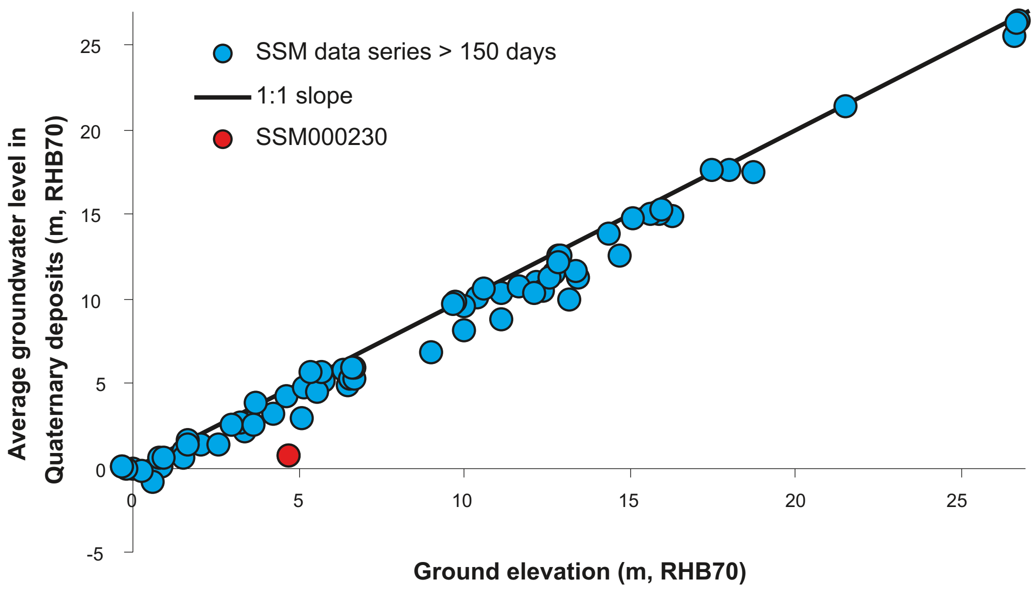


Figure 4-13. Cross plot of average groundwater levels in the QD versus ground-surface elevations. Data are from groundwater monitoring wells installed in the QD.

Section 5.2.3, it is supported by the numerical flow modelling results. In particular, the monitoring data indicate that near-shore areas of Lake Jämsen act as groundwater recharge areas during dry summer periods, whereas there is almost no vertical hydraulic gradient between Lake Frisksjön and the underlying QD.

The infiltration capacity of the QD at Laxemar-Simpevarp generally exceeds the rainfall and snowmelt intensity. The maximum recorded daily rainfall occurred on June 26, 2007, with 51 mm on Äspö and 44 mm at Plittorp (corresponding to c. $5–6·10^{–7}$ $m·s^{–1}$), whereas the maximum calculated daily snowmelt (22 mm) occurred on Dec. 5, 2004 (corresponding to c. $3·10^{–7}$ $m·s^{–1}$). These rainfall/snowmelt rates can be compared with the average saturated hydraulic conductivity obtained from permeameter tests on near-surface QD samples; for all samples from QD sampled <1 m below ground, the arithmetic mean of K is $1.54·10^{–5}$ $m·s^{–1}$ (geometric mean = $7.52·10^{–6}$ $m·s^{–1}$).

The high-altitude areas with shallow cover or exposed rock are difficult to parameterize in conceptual models and also to represent properly in quantitative water flow models. Conceptually, unsaturated (Hortonian) overland flow may appear on outcropping rock, but likely over short distances (say less than 10 m) before precipitation or snowmelt reaches open fractures or other cavities in the surface rock or a contact between rock and QD. In the MIKE SHE modelling, near-surface drains are activated in the high-altitude areas to represent this effect. Results of the MIKE SHE modelling /Bosson et al. 2008/ indicate that on the order of 10% of the annual precipitation enters the rock in areas with shallow cover or exposed rock. Hence, these results indicate that on an annual basis, most of the precipitation that falls in areas with shallow cover or exposed rock flows towards low-altitude areas in the form of surface/near-surface water flow.

4.3.4 Sub-flow systems and discharge

Groundwater discharge is conceptually interpreted to take place in the low-altitude areas, corresponding to the ”valley” type and near-coastal (bay) areas as defined in the conceptual hydrogeological model, cf. Figure 4-11. The characteristics of the hydrogeological flow domains, QD and rock (see Section 4.3.1) imply that one can identify two main sub-flow systems for groundwater flow in the discharge areas: one system localised to the upper part of the rock and the QD, which overlies a larger-scale flow system primarily associated with deformation zones (of different orientation) in the rock.

According to the conceptual model of the rock and the QD (see Section 4.4), most groundwater flow towards the discharge areas in the valleys takes place in the QD and in the upper c. 10 m of the rock, cf. Figure 4-11. Groundwater flow in the deeper parts of the rock primarily occurs in a system of connected deformation zones, and the associated groundwater discharge takes place at locations where this system connect to zones that outcrop in the valleys; groundwater discharge from the deep rock is less likely in areas where there are no outcropping deformation zones. For further discussion on interactions between the QD and the rock, see Chapter 5.

Figure 4-14 illustrates the MIKE SHE-calculated distribution of groundwater recharge and discharge areas in the QD /Bosson et al. 2008/. In this context, time-averaged groundwater-head differences between the two uppermost calculation layers of the MIKE SHE model are used to identify these areas. In the recharge areas (red in Figure 4-14), the hydraulic head is higher in the top calculation layer than in the underlying layer, and the opposite for the discharge areas (blue). According to Figure 4-14, the near-surface groundwater flow system is dominated by recharge areas, occupying c. 70% of the MIKE SHE model area. The groundwater discharge areas, hence occupying c. 30% of the model area, are located in low-lying areas such as stream valleys, Lake Frisksjön and the sea bays near the coast. MIKE SHE-analyses of seasonal variations /Bosson et al. 2008/ show that the overall near-surface groundwater recharge/discharge pattern is relatively stable during the year; for typical wet- and dry periods, the relative change of the sizes of recharge and discharge areas is on the order of 1–7%.

As exemplified in Figure 4-15, joint evaluations of stream discharges and groundwater levels in the QD in the vicinity of the streams indicate that there is an (unconfined) groundwater level ”threshold” for initiation of discharge, likely related to the local drainage depth (i.e. the depth to the bottom of the stream). Moreover, as mentioned in Section 4.3.3, monitoring of lake-water levels and groundwater levels near and below lakes indicates that interactions between lake water and groundwater in the underlying QD are limited to near-shore areas.

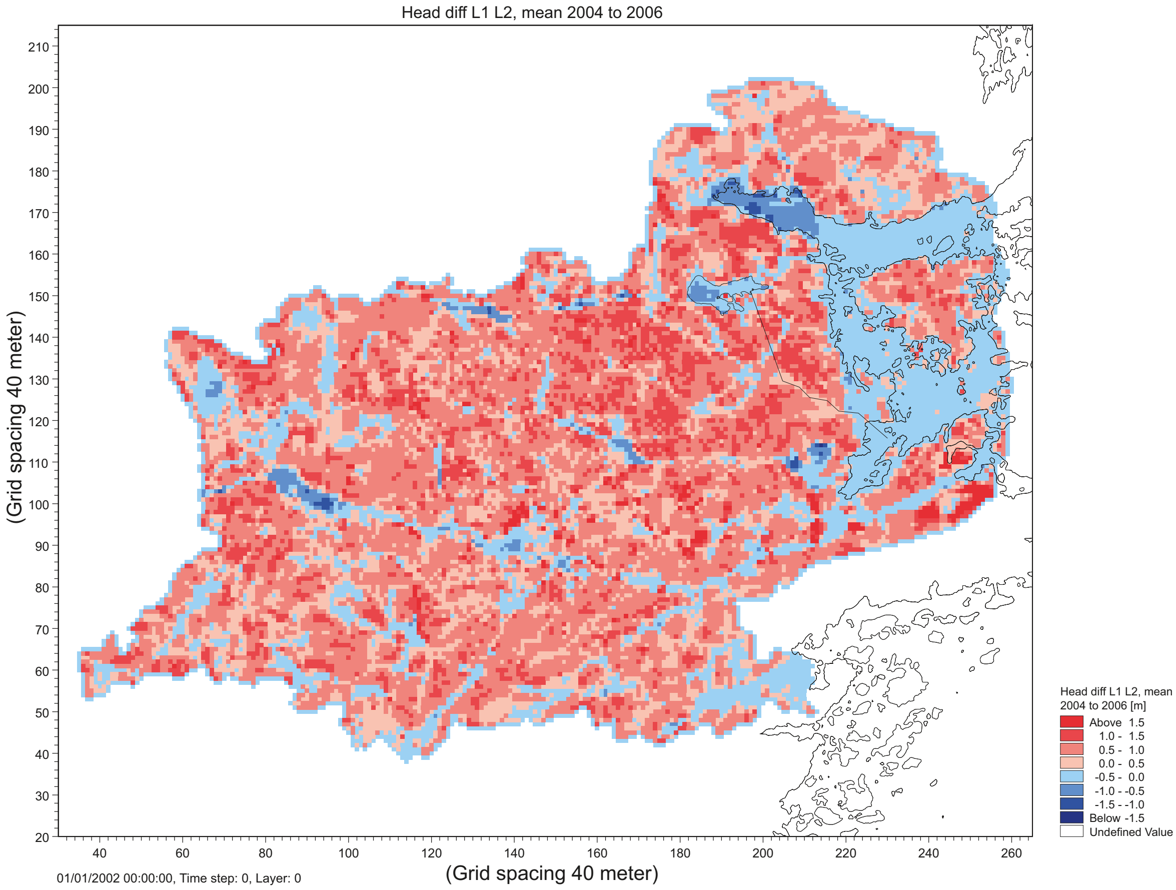


Figure 4-14. MIKE SHE-calculated distribution of groundwater recharge (red areas; corresponding to 74% of the model area) and discharge areas (blue areas; 26% of the model area) in the QD. Recharge and discharge areas are here identified based on time-averaged hydraulic-head differences between the two uppermost calculation layers of the model. The simulated time period is 2004-2006.

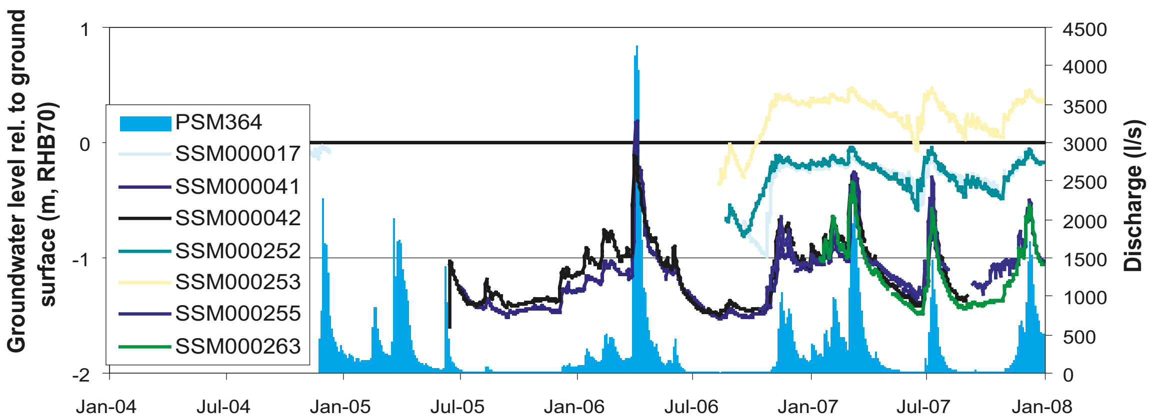


Figure 4-15. Time-series plots of groundwater levels (m.b.g.s.) in groundwater monitoring wells, installed within the catchment area of surface-water discharge gauging station PSM000364 (approximated by catchment subareas 10:1-32) in Laxemarån, co-plotted with the discharge ($L \cdot s^{-1}$) at PSM000364. The wells are located in the vicinity of Laxemarån or its tributaries.

Figure 4-16 presents the MIKE SHE-calculated annual average water balance for the period October 1, 2004–October 1, 2007, corresponding to three so-called hydrological years /Bosson et al. 2008/. For the same period, Figure 4-17 presents the model-calculated annual average water balance for each layer in the saturated zone. Note that the water balances in these figures are calculated for the terrestrial part of the model area.

On average per year for the considered time period, the area-averaged precipitation was 608 mm, whereas the model-calculated annual average of the actual evapotranspiration was 425 mm, i.e. the sum of different evaporation processes and transpiration from vegetation. The largest single component is transpiration from vegetation (on average 202 mm·y^{-1}), whereas the average calculated evaporation from soil is 88 mm·y^{-1} and evaporation from flooded areas 5 mm·y^{-1}. On average, interception by leaves is quantified as 124 mm·y^{-1} and evaporation from the saturated zone as 6 mm·y^{-1}. The model-calculated annual average specific discharge is 170 mm·y^{-1} (i.e. the sum of the discharges to surface water within the model area, 22+123 mm·y^{-1}, and the net boundary outflows, 8+17 mm·y^{-1}). It should be noted that there are relatively large inter-annual water balance differences. For instance, considering another 3-year period (October 15, 2003–October 15, 2006), the MIKE SHE-calculated annual average specific discharge is 199 mm·y^{-1}.

According to Figure 4-17, the net annual area-averaged groundwater recharge from the unsaturated zone to the uppermost calculation layer representing the Quaternary deposits is 226 mm, whereas the area-averaged groundwater recharge to the rock is 35 mm. The net annual average groundwater recharge from the Quaternary deposits to the rock, i.e. the net flow rate across the L2–L3 boundary in Figure 4-17, is 7 mm (calculated as 35 minus 28 mm·y^{-1}, cf. the flow rates between L2 and L3 in the figure). It can also be noted that the vertical groundwater flow at the level –150 m.a.s.l. in the rock is 10 mm downwards and 9 mm upwards, i.e. a small downward net flow.

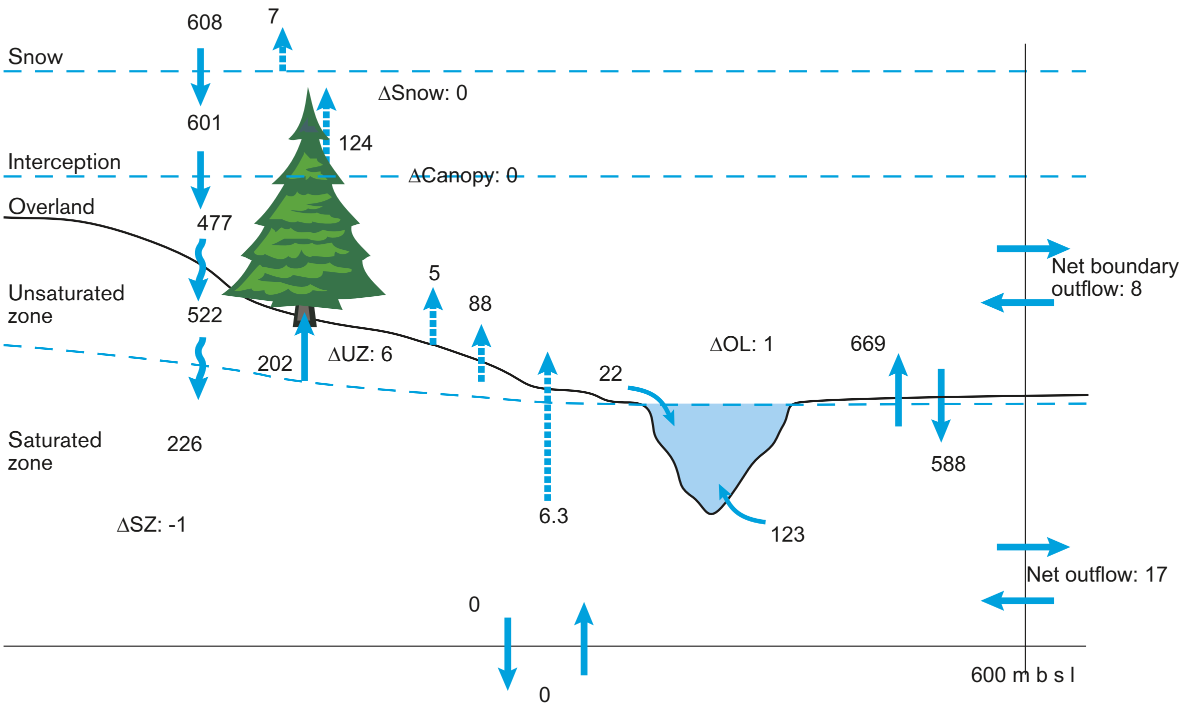


Figure 4-16. *MIKE SHE-calculated annual average water balance (mm·y^{-1}) for the time period October 1, 2003-October 1, 2007 /Bosson et al. 2008/; storage changes (Δ terms) are also given in mm·y^{-1}. Dotted arrows are evaporation components and arrows with wavy shafts indicate the vertical in- and outflow to and from the unsaturated zone. The discharge to the surface water system within the model area consists of 22 mm·y^{-1} from overland water and 123 mm·y^{-1} of groundwater from the saturated zone. Also shown are the flows across the vertical downstream model boundary (net overland outflow 8 mm·y^{-1}, net groundwater outflow 17 mm), and the direct exchanges between overland water and the saturated zone (669 and 588 mm·y^{-1}).*

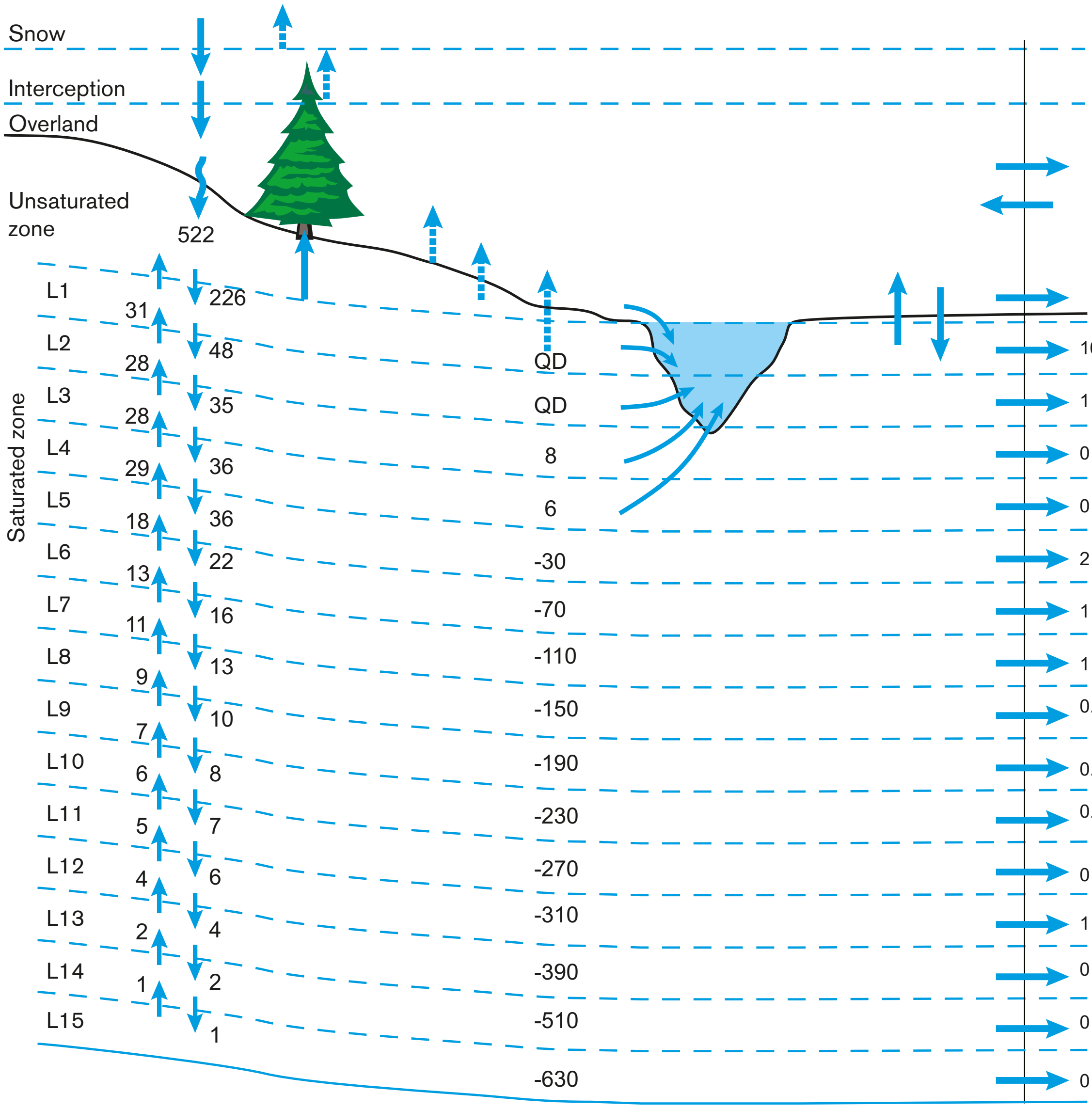


Figure 4-17. MIKE SHE-calculated annual water balance for each layer in the saturated zone in the terrestrial parts of the model area, including quantification of vertical flow components. The average level (m.a.s.l.) of the lower boundary of each calculation layer is shown in the middle of the figure; see Figure 4-16 for additional explanation of arrows and what they indicate, and /Bosson et al. 2008/ for details on the underlying calculations.

4.4 Regolith and Quaternary geology

This section summarises and evaluates the results from the investigations of Quaternary deposits (QD) and soils, i.e. the regolith. A regolith depth and stratigraphy model from /Nyman et al. 2008/ is described in Section 4.2.2 and compiles stratigraphical and surface data obtained from the regional model area. In /Sohlenius and Hedenström 2008/ a comprehensive description of the regolith in the Laxemar-Simpevarp model area is given.

Figure 4-18 shows the surface distribution of QD in the regional model area. The general stratigraphy of the area is summarised in Table 4-4. The known surface and stratigraphical distribution of QD in the regional model area are in agreement with the conceptual model for the distribution of QD below the highest shoreline in Sweden.

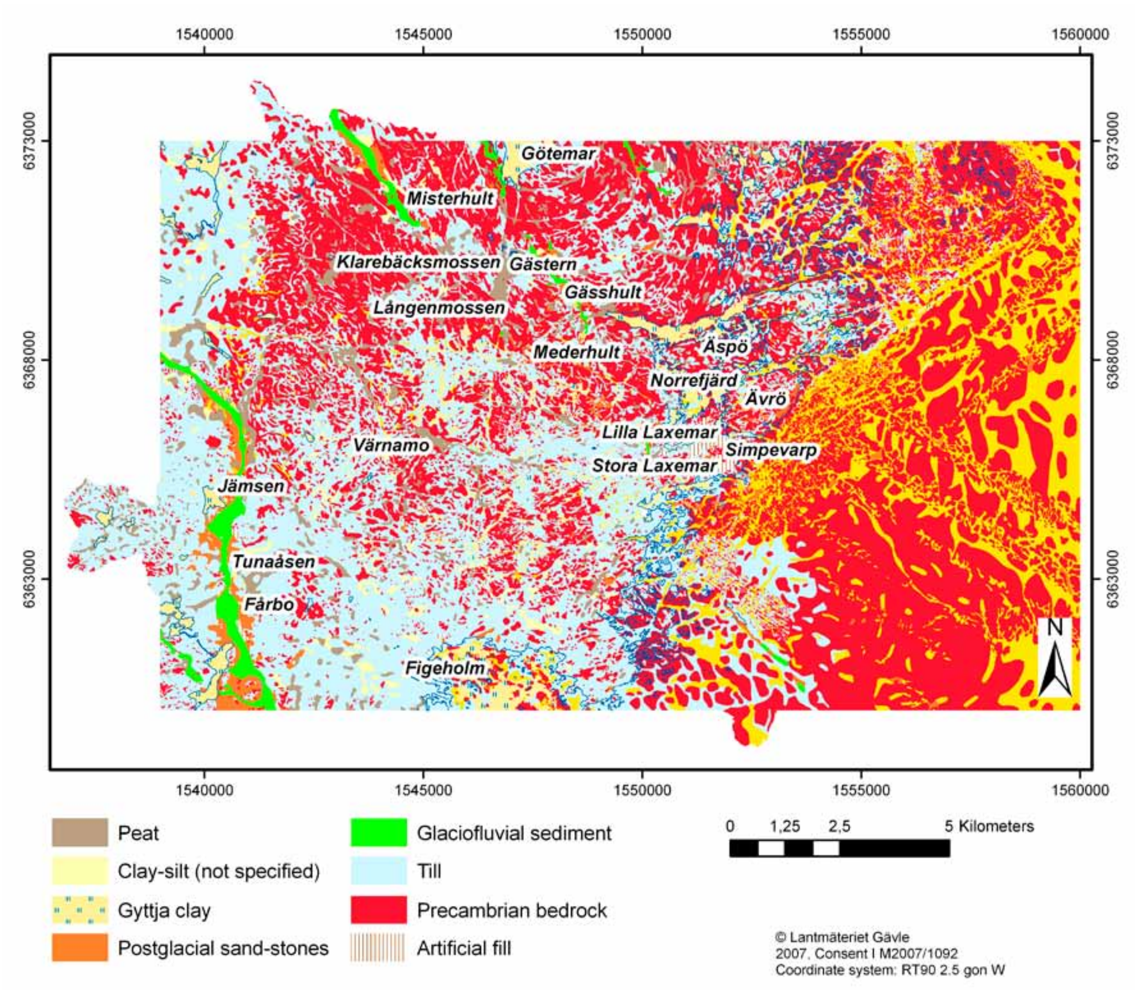


Figure 4-18. *The distribution of QD in the Laxemar-Simpevarp regional model area. The distribution of areas where different mapping methods were used is shown in Figure 3-8. The map presented here does not show all the different types of QD recognised during the mapping.*

Table 4-4. The stratigraphical distribution of QD in the Laxemar-Simpevarp regional model area.

Quaternary deposit	Relative age
Bog peat	Youngest
Fen peat	↑
Gyttja clay/clay gyttja	
Postglacial sand/gravel	↑
Glacial clay	
Till	↑
Bedrock	Oldest

There is no conclusive evidence of deposits older than the latest glaciation in the Laxemar-Simpevarp area, even though the existence of such deposits cannot be ruled out /cf. Lagerbäck et al. 2006/. The bedrock surface in the model area is often rough, indicating a low degree of glacial erosion. However, the absence of regolith predating the last glacial cycle indicates that the Quaternary ice sheets have eroded older loose deposits.

4.4.1 The geographical distribution of regolith

General description

Both the marine and terrestrial parts of the investigated area are characterised by a relatively flat bedrock surface with numerous fissure valleys, which, in many cases, can be followed for several kilometres. The geographical distribution and depth of the QD is largely determined by the topography of the underlying bedrock. The valleys represent zones where the frequency of bedrock fractures is denser than in the surroundings /SKB 2009/. The highest topographical areas have been subjected to erosion by waves and currents and are dominated by a relatively thin till coverage and bedrock outcrops. The distribution of fine-grained water-laid sediments is consequently mostly restricted to the long and narrow valleys. Periods of erosion have occurred in the valleys as well, but it is evident that there have been long periods of deposition of fine-grained material in these areas. The thickness of regolith is considerably larger in the valleys than in the topographically high areas.

Figure 4-19. *A valley that demonstrate the typical distribution of QD in the Laxemar-Simpevarp regional model area. The floors of the valleys are covered with postglacial clay gyttja, which is sometimes covered with a thin peat layer. The higher areas comprise bedrock exposures and glacial till. Many of these valleys are former fens, where the groundwater table has been artificially lowered for agricultural purposes. The Laxemar River can be seen in the floor of the valley (photo: Lars-Erik Olander SGU).*

Since the area is completely situated below the highest shoreline, water-laid deposits are found all over the model area. The shoreline displacement has had a great impact on the distribution and relocation of fine-grained Quaternary deposits. Clay sediments are currently being deposited in the lakes and in the bays along the present coast. Exposed areas have been, and still are at some sites, subjected to wave washing, which has caused erosion and redeposition of some of the regolith. Sand and gravel are currently being transported at the bottom of the most exposed parts of the sea. A sand and gravel layer therefore often covers the valleys on the sea floor. In the terrestrial part of the model area, the groundwater level in the valleys is situated close to the ground surface. There are consequently numerous wetlands at the floor of the valleys and a layer of peat often covers the clay. As land uplift proceeds, some new areas are being subjected to erosion at the same time as other new areas are becoming lakes and sheltered bays where fine-grained sediments can accumulate.

Forest covers the areas dominated by till and exposed bedrock, which constitute the main part of the investigated area. The clay and peat in the valleys are used as arable land in many places. Artificial ditches have lowered the groundwater level in these cultivated areas and the peat is consequently slowly oxidising.

In a regional perspective, the Laxemar-Simpevarp area is situated in a region with relatively thin QD cover. The frequency of exposed bedrock is relatively high compared with most other parts of Sweden (Table 4-5 and Table 4-6). There are, however, areas with a more coherent QD cover, mostly till, in the western and southern parts of the regional model area (Figure 4-18).

Table 4-5. The proportional distribution of QD in different parts of the Laxemar-Simpevarp regional model area. The extensions of the different areas referred to in the table are shown in Figure 3-8. LS=Laxemar subarea, SS=Simpevarp subarea, Area 2=the Laxemar river drainage area. Area 2 also includes LS and SS. The terrestrial areas were mapped by /Rudmark et al. 2005/. Areas 5, 7 and 9 refer to different parts of the marine area mapped by /Ingvarson et al. 2004/ and /Elhammer and Sandkvist 2005/.

Quaternary deposit Coverage (%)	LS	SS	Area 2	Area 5	Area 7	Area 9	Regional model area
Peat	5.3	1.9	8.0	–	–	–	4.5
Clay gyttja (postglacial clay)	5.8	0.1	3.4	0	44.0	0.7	–
Glacial clay	0.7	1.1	1.4	41.6	13.4	33.1	16.0**
Glaciofluvial sediments	0.1	0.0	3.0	0	0	0	1.2
Postglacial sand and gravel	4.8	5.8	4.3	3.3	2.1	0.3	1.8
Till	45.2	35.0	43.3	3.4	5.1	22.5	34.3
Precambrian bedrock*	38.2	38.2	34.5	51.6	35.4	43.4	41.9
Artificial fill	0	17.9	1.3	0.1	0	0	0.4

* Areas with bedrock outcrops
** Glacial and postglacial clays

Table 4-6. The distribution of QD in terrestrial areas covered by SGU local maps (scale 1:50,000). These maps cover c. 85,000 km^2 (2006) of the southern half of Sweden. The data represents QD from areas situated both above and below the highest shoreline. The area with a thin cover of QD represents areas with mainly till and bedrock exposures.

Quaternary deposit	Coverage (%)
Peat and gyttja	8.9
Clay and silt	19.7
Postglacial sand and gravel	6.4
Glaciofluvial sediments	5.6
Till	41.0
Thin coverage of QD	3.2
Bedrock outcrops	14.7
Artificial fill	0.2
Other deposits	0.1

Till

Glacial till is the most common QD and covers half of the terrestrial part of the regional model area (Table 4-5). Generally, till covers a much smaller proportion of the sea floor (Table 4-7), but there are locations with a high proportion of till also in the marine areas. The surface morphology of the till in general follows that of the bedrock. There are, however, some till areas where the frequency of bedrock outcrops is low and the till forms low-relief hummocks. One such area forms a c. 2 km long belt with an east-west direction east of Lilla Laxemar (Figure 4-20).

The frequency of boulders and stones at the till surface varies throughout the investigated area. In the Laxemar River drainage area, around half of the till areas have a normal surface frequency of boulders. Most of the remaining till area has a high frequency of boulders, but some small areas have a high surface frequency of large boulders. The uppermost till often has a relatively high content of coarse material compared with underlying till, probably as a consequence of wave washing. According to the composition of the matrix the till is sandy or gravelly (see Table 4-12). Most of the till has a normal to high degree of consolidation and is often rich in angular stones and small boulders. However, the till at one of the sites investigated during the studies in machine-cut trenches /Sohlenius et al. 2006/ is relatively well-sorted with respect to grain size and has a low degree of consolidation. Furthermore, data obtained from the drilling reported by /Morosini et al. 2007/ shows that the lowermost till at many sites in the clay-covered valleys is rather well-sorted with respect to grain size and almost lacks fine material (silt and clay). These well-sorted deposits have been classified as till in the field. However, the results of the grain-size analyses indicate deposition by water (see Table 4-12).

The characteristics of the till indicate a short transport distance. The petrographical and mineralogical composition of the till reflects that of the local bedrock even though the till has been transported from the north /Bergman and Sohlenius 2007/. There are, however, individual stones and boulders that have been transported several kilometres. Since the till has been subjected to chemical weathering, the chemical composition of the till differs slightly from that of the bedrock. The ice moved from the northwest during the last phase of the latest glaciation, which is indicated by the direction of striae on bedrock outcrops. There are also indications of older ice movements from the northeast. Material from the Baltic depression may consequently be incorporated in the till. Calcium carbonate has been recorded in some till samples, which supports that suggestion /Sohlenius et al. 2006/.

Table 4-7. The fraction (in %) of various types of QD on the sea floor. The areas in the table correspond to different methods of mapping which are shown in Figure 3-8 and in this table. The table shows the distribution of QD in the following areas: 1. The bay Granholmsfjärden, 2. The Simpevarp detailed area, 3. Areas interpreted by /Kjellin 2007/, 4. Areas mapped within SGU's regular mapping programme, 5. The Simpevarp local area, 6. Areas mapped by /Ingvarson et al. 2004/ and modified by /Kjellin 2007/, and 7. The total marine area.

	Area						
	1	**2**	**3**	**4**	**5**	**6**	**7**
(Area in Figure 3-8)	*(7)*	*(5)*	*(10)*	*(8)*	*(6)*	*(9)*	
Bedrock outcrops	35.4	51.6	52.1	80,6	63.4	43.4	53.6
Till	5.1	3.4	18.6	0	0.3	22.5	13.8
Glaciofluvial sediments	0	0	0.2	0	0	0	0.1
Glacial clay	13.4	41.6	24.7	16.9	31.0	33.1	28.1
Postglacial clay (clay gyttja)	44.0	0	4.2	0	4.3	0.7	3.9
Postglacial sand	2.1	3.3	0.2	2.5	1.0	0.3	0.7
Artificial fill	0	0.1	0	0	0	0	0

Table 4-8. Spatial coverage and carbon stock (kgC m⁻²) of the soil types in the terrestrial part of the Laxemar-Simpevarp regional model area. The geographical distribution of the soils is shown in Figure 4-21.

Soil class	Land class	GIS map soil class	Coverage (%)	C tot (kg/m²)
No soil	*Bedrock outcrops*	Bedrock	11.1	0.0
Leptosol	*Mostly rock outcrops and till with coniferous forest*	LP	23.6	2.8
Podsol/Regosol	*Mostly till in areas with coniferous forest*	PZ/RG	25.2	8.2
Podsol/Regosol	*Glaciofluvial sediments with coniferous forest*	PZ/RG-e	1.4	5.3
Umbrisol/Regosol	*Deciduous forest in till dominated areas*	UM/RG	15.7	9.5
Umbrisol/Gleysol	*Meadows*	UM/GL	10.9	39.4
Histosol	*Forested peatlands, artificially drained*	HI-d	3.7	44.2
Histosol	*Open wetlands*	HI-w	1.7	15.6
Histosol	*Arable land, artificially drained*	HI-a	1.7	41.5
Histosol	*Small peatlands*	HI-s	0.6	37.5
Regosol/Histosol	*Shoreline areas, dominated by till*	RG/HI	0.6	15.1
Umbrisol/Gleysol	*Arable land, mostly artificially drained*	UM/GL-a	2.8	20.5
No soil	*Artificial fill*	*Artificial fill*	0.6	–
No soil	Gravel pits	*Gravel pits*	0.4	–

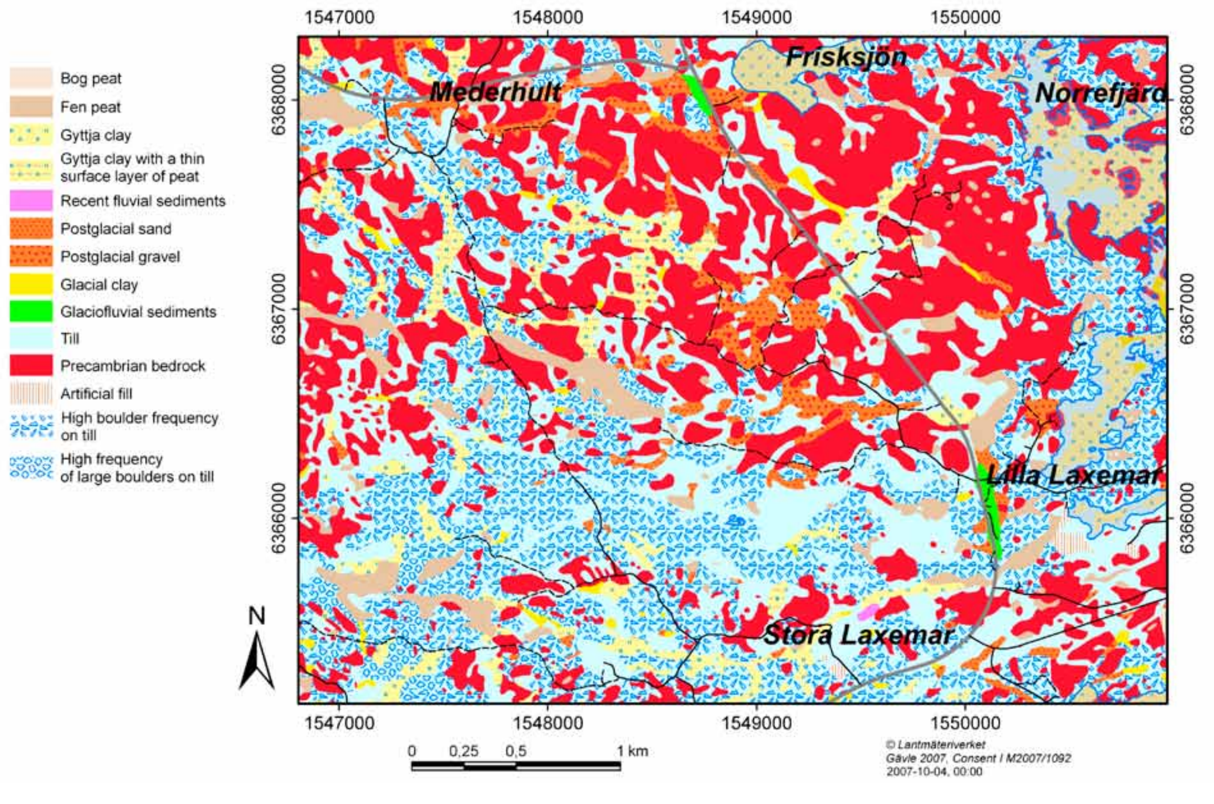


Figure 4-20. The distribution of QD and the surface frequency of till boulders in the central part of the Laxemar-Simpevarp area. Areas currently covered with water are shaded with grey.

Glaciofluvial deposits

In eastern Småland there are several large glaciofluvial deposits, mostly eskers, which have a northwesterly main direction. One of these deposits, the large Tuna esker, is situated in the western part of the Laxemar-Simpevarp regional model area (Figure 4-18). There are also three relatively small glaciofluvial eskers with a north-south direction in the northern part of the model area. The Tuna esker is by far the largest glaciofluvial deposit in the model area and has a north-south direction, which in the north changes to a northwest-southeast direction. This esker is, in a morphological sense, the most prominent QD in the regional model area. The three small eskers have a gentle morphology and are not prominent eskers in a morphological sense.

There is only one glaciofluvial deposit, the Gässhultsåsen esker, in the Laxemar subarea. That deposit can be followed from Gässhult in the north southwards along the eastern side of the Laxemar subarea to Lilla Laxemar (Figure 4-20). There is no direct observation of any glaciofluvial sediments on the sea floor. However, /Kjellin 2007/ suggests that there is a continuation of the Gässhult esker on the sea floor in the archipelago south of Simpevarp (Figure 4-18). Gravel and sand are the dominating grain sizes of the glaciofluvial deposits. The eskers have been affected by wave erosion, which is reflected by the occurrences of postglacial sand and gravel deposits along the sides of the eskers. It has sometimes been difficult to separate glaciofluvial sand/gravel from postglacial sand/gravel during the mapping of QD. Some of the deposits shown as postglacial sand/gravel may therefore be of glaciofluvial origin and vice versa. There are only a few stratigraphical observations from the eskers, which all suggest that the glaciofluvial material is resting directly upon the bedrock surface.

Clays and postglacial sand/gravel

Both glacial and postglacial clay were recognised during the QD mapping. The postglacial clay studied in the model area contains organic matter and is therefore referred to as clay gyttja. The oldest fine-grained deposit, glacial clay, was deposited during the latest deglaciation when the water was relatively deep. As the water depth decreased, currents and waves started to erode the uppermost clay and deposited a layer of sand and gravel on top of the clay. The lowest areas became sheltered bays as the water depth decreased and postglacial clay containing organic material (clay gyttja) started to accumulate. The processes of erosion and deposition are still active on the sea floor and along the present coast.

In the terrestrial part of the Laxemar-Simpevarp area the coverage of clay is relatively small compared with other areas of southern Sweden situated below the highest coastline. However, in the marine areas, glacial clay is the most common QD (Table 4-7), and in the area south of the Simpevarp Peninsula (Area 2 in Table 4-7) more than 40% of the sea floor is covered by glacial clay. A layer of gravel or sand a few decimetres thick almost always covers the glacial clay in the marine areas. The frequency of areas covered with glacial clay is very low in the terrestrial part of the model area. One reason for this is that a layer of postglacial clay gyttja or sand often covers the glacial clay in the terrestrial areas. The average thickness of the glacial clay is considerably greater in the marine areas compared with the terrestrial areas (Table 4-9 and Table 4-10). One reason for this is that waves and currents caused by land uplift have subjected the glacial clay in the terrestrial areas to erosion.

In the narrow bays along the coast and in the lakes, clay gyttja is currently being deposited. Gyttja clay is also common at the floor of the valleys in the terrestrial areas. A large proportion of the arable land in the terrestrial area is situated on clay gyttja. The thickness of clay gyttja is almost the same in the terrestrial and marine areas (Table 4-9 and Table 4-10). It has, however, been difficult to estimate the thickness of the clay gyttja in parts of the marine area due to the presence of gas in the sediment which makes it impossible to get reliable results with the geophysical methods /cf. Elhammer and Sandkvist 2005/. It is therefore possible that the average thickness of gyttja clay in the marine areas has been underestimated.

The effects of wave washing can be observed at many sites that have been or still are subjected to wave erosion. At some sites that have been exposed to extreme erosion, the uppermost QD consists of a stony layer, shingle. Such an enrichment of stones can also be seen at several places along the present shore, especially on the island of Ävrö. Currents on the sea floor (see below) have to a large

Table 4-9. The average depth of regolith in the marine areas mapped by SGU. Only sites with a thickness larger than 0.5 metre were used for the regolith depth and stratigraphy model /Nyman et al. 2008/ and Section 4.2.2 (RDM=Regolith Depth Model).

Quaternary deposit	RDM layer	N	Average depth (m)	Max (m)	Standard dev.
Till in the valleys*	Z6	4,575	3.6*	27.2	2.6
Glacial clay	Z5	14,886	2.6	25.7	2.3
Postglacial sand	Z4	2,405	0.8	2.9	0.3
Clay gyttja	Z3	2,359	1.7	4.7	0.8

* The average depth of till in the clay-covered valleys.

Table 4-10. The average depths of QD in the terrestrial areas. These data were used for the Regolith Depth Model presented in Section 4.2.2 (RDM=Regolith Depth Model).

Quaternary deposit	RDM layer	N	Average depth (m)	Max (m)	Standard dev.
Till obtained from refraction seismic*	Z6	343	2.3	10.2	2.4
Till in the valleys**	Z6	65	2.0	6.6	1.3
Till in areas shown as till on the QD map	Z6	35	2.1	7.0	1.7
The Tuna esker	Z4	8	13.8	20.0	4.1
Other glaciofluvial deposits	Z4	18	4.1	9.0	2.3
Glacial clay	Z5	54	1.3	8.4	1.3
Postglacial sand	Z4	96	0.7	4.9	0.8
Clay gyttja	Z3	110	1.6	10.1	2.0
Peat	Z2	83	0.85	3.8	0.7

*Areas shown as till on the QD map, corresponding to topographical high areas. Data from the southern parts of the Laxemar subarea were excluded due to a large till thickness. **Areas where other deposits, e.g. clay gyttja, covers the till.

extent deposited the QD mapped as postglacial gravel and sand. Flat areas with postglacial sand occur in many depressions, where the sand is often underlain by glacial clay. The largest areas with postglacial sand and gravel are found close to the glaciofluvial deposits. The reason for that is that there is a lot of sand and gravel available in the glaciofluvial deposits.

During periods with a high discharge, fine-grained sediments have been deposited along parts of the stream Laxemarån. These deposits are denoted “recent fluvial deposits” on the QD map.

Peat

In the local area (Areas 1 and 2 in Figure 3-8), the QD map shows two types of peatlands: bogs and fens. In the more generally mapped area (Areas 3 and 4 in Figure 3-8), peat and other deposits rich in organic matter (e.g. gyttja) are symbolised in the same way on the map. Many of the fens and bogs are small and situated in the areas dominated by bedrock outcrops, e.g. on the northern part of the island of Ävrö. The peat in these small depressions is not underlain by thick layers of clay, which is the case in the large valleys. The floors of many of the valleys are former or present wetlands where layers of peat have accumulated. The areas of wetlands have, however, decreased significantly due to artificial drainage. The peat in the drained areas is slowly oxidising and the underlying deposits, often clay gyttja, are slowly being exposed. A thin peat layer often overlies the clay gyttja in areas used as arable land. The thickest layers of peat are found in wetlands, which are more or less unaffected by ditching, for example the Klarebäcksmossen bog.

Soil types

The spatial coverage of the different soil types is summarised in Table 4-8. Figure 4-21 shows the geographical distribution of the same soil types. Different types of Histosol (peat) are the most frequently occurring soils at the sites investigated by /Lundin et al. 2005/. However, Histosol only occurs in c. 8% of the investigated area. Histosol is the most common soil type in the wetlands, which reflects that many of the wetlands in the area are covered with peat. Histosol is also common in many former wetlands, where ditches have lowered the groundwater level, e.g. in areas used as arable land. Podsol, Regosol and Leptosol are the most common types of soils and dominate areas covered by glacial till. Most of these till areas are covered by coniferous forest. However, a large part of the till areas are covered by deciduous forest. In these areas Umbrisol and Regosol are the most common soil types. The frequent occurrences of Regosol shows that the soil-forming processes have not been active long enough to form diagnostic soil horizons at all investigated sites. The area is completely situated below the highest shoreline, and many of the investigated sites have consequently only been subjected to soil-forming processes for a few thousand years. This may explain the high frequency of Regosol. For a definition of the soil types discussed in this section see /Lundin et al. 2005, Sohlenius and Hedenström 2008/.

In certain areas, the uppermost regolith consists of artificial fill. These areas are denoted artificial fill on both the QD map (Figure 4-18) and soil type map (Figure 4-21). The largest area with artificial fill is situated around the nuclear power plant. The artificial material is coarse grained and is composed of material from the local bedrock.

4.4.2 Stratigraphy and total depth of the regolith

The total depth and stratigraphy of regolith in the whole regional model area has been modelled. That model is presented in Section 4.2.2 and can be further studied in a report by /Nyman et al. 2008/. The stratigraphical distribution of QD in the terrestrial area has been obtained from drillings and excavations. Most data showing the total depth of regolith in the marine areas have

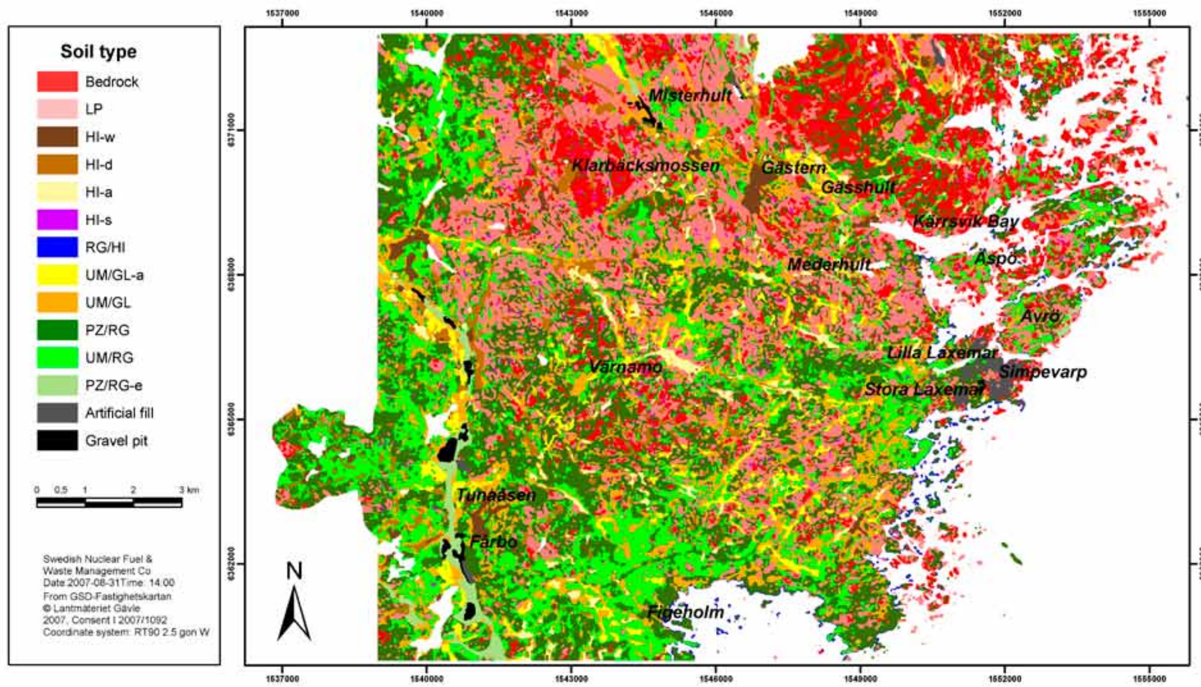


Figure 4-21. The distribution of soils in the terrestrial part of the Laxemar-Simpevarp regional model area /modified from: Lundin et al. 2005/. The map is based on field studies at 20 sites and interpretations of other geographical information such as maps of QD and vegetation. Since the most detailed mapping of QD took place in the Laxemar River drainage area, the soil type map is more reliable in that area. The abbreviations shown in the legend are explained in Table 4-8.

been obtained from geophysical investigations. Those data have also been used to determine the stratigraphy of regolith in the marine area. The stratigraphical data has been used to calculate the average thicknesses of the different QD in the terrestrial and marine areas (see Table 4-9 and Table 4-10, respectively). Results from stratigraphical investigations show that the stratigraphical distribution of QD in the investigated area is rather uniform (Table 4-1) and is similar in terrestrial areas to those covered by lakes or the sea /e.g. Sohlenius et al. 2006, Rudmark et al. 2005, Elhammer and Sandkvist 2005/. Till is the oldest QD in the area and consequently rests directly upon the bedrock surface. The till in the valleys is often overlain by glacial clay, which often is overlain by a layer of sand followed by clay gyttja and in the terrestrial areas by peat. The stratigraphy shown in (Table 4-1) is not always complete and stratigraphical units are consequently absent at some of the investigated sites. The average thicknesses of the stratigraphical units are generally larger in the marine area than in the terrestrial areas (compare Table 4-9 and Table 4-10).

Results obtained from studies in machine-cut trenches show that the uppermost bedrock at some places has a high frequency of open fractures. During these studies, /Sohlenius et al. 2006/ observed significant infiltration of water through the fractures in the uppermost bedrock in some of the valleys (Figure 4-22). Bedrock fractures may therefore be of importance for water transport in the transition zone between bedrock and QD.

4.4.3 Properties

The chemical and physical properties of the different stratigraphical layers used in the regolith depth and stratigraphy are described in detail in /Sohlenius and Hedenström 2008/. Below follows a summary of these properties.

Physical properties

The results from analyses of physical properties include grain-size distributions, bulk density, porosity, water content of the most common QD and soils. Some of the physical properties are summarised in Table 4-11. The organic content and water content of the top sediments in the archipelago were studied by /Fredriksson 2004/. The organic top sediments were sampled at sites where accumulation of sediment occurs. The inorganic sediments, mostly sand and gravel, represent bottoms dominated by erosion or transport of sediment. The till and glaciofluvial sediments has a high content of stone and gravel and it was therefore not possible to obtain undisturbed samples for volume determinations. There are unfortunately no data available showing the bulk density, porosity and water content of these deposits. The approximate porosity of these deposits has, however, been calculated from results obtained by /Lundin et al. 2005/. These measurements were made in the uppermost part of the QD and are presented in /Sohlenius and Hedenström 2008/. Values representing the deeper regolith of till and sand/gravel have been taken from the literature and are shown in Table 4-11. The literature values representing sand and gravel are assumed to be representative of the postglacial and glacial sand/gravel deposits in the model area.

The grain-size distribution of QD (material <20 mm) has been determined in several studies /e.g. Nilsson 2004, Rudmark et al. 2005/. The results of grain-size analyses of the most common QD are summarised in Table 4-12. Most till samples are totally dominated by sand and gravel and have clay contents lower than 5%. The coefficient d60/d10 (where d60 is the particle diameter corresponding to 60% finer on the grain-size curve, and d10 is the particle diameter corresponding to 10% finer on the grain-size curve) has been calculated to demonstrate the degree of sorting. The deposit is poorly sorted with respect to grain size if d60/d10 is above 15. Most of the till samples have a d60/d10 well above 15.

The grain-size distribution of glacial and postglacial sand is presented as one value in Table 4-12. There are too few samples to conclude whether there is any significant difference in grain-size distribution between glacial and postglacial sand/gravel.

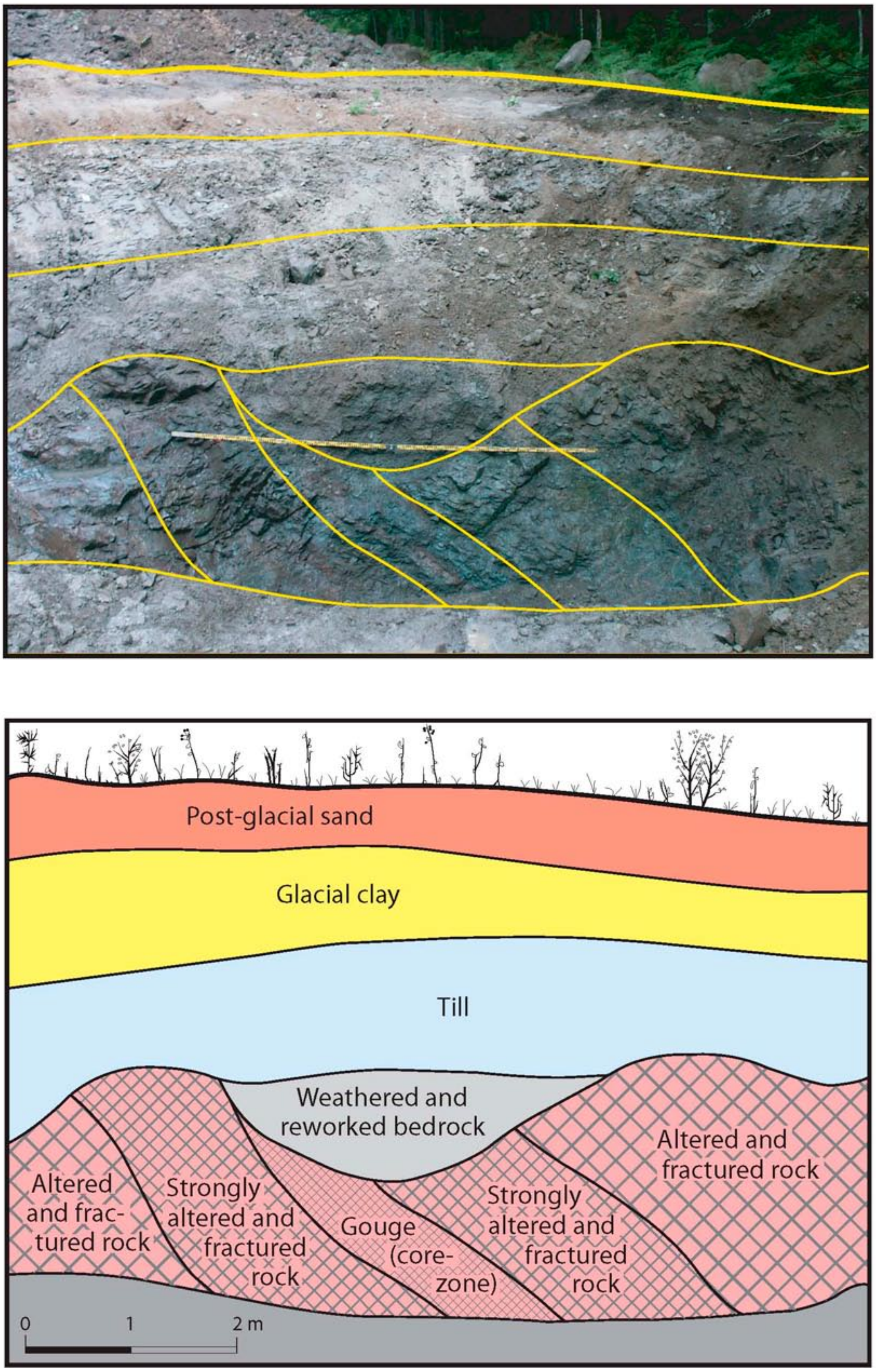


Figure 4-22. *The stratigraphical distribution of the QD overlying the bedrock in one machine-cut trenches (PSM007180) situated close to Ekerumsbäcken /from: Sohlenius et al. 2006/. The uppermost bedrock is rich in fractures and strongly altered. Inflow of groundwater was observed in the transition zone between bedrock and QD. The schematic illustration of the bedrock alteration is also shown in the picture. The photo was taken towards the north-west.*

Table 4-11. The average physical properties of the QD. The properties for till and sand/gravel were taken from the literature and were not obtained from the site investigation. The bulk density refers to the density of water-saturated material (RDM=Regolith Depth Model).

	N	Water content (% by weight)	Porosity (% by volume)	Bulk density (kg/m³)	RDM layer	Reference
Till			10–25	2,100–2,400	Z6	Almén and Talme 1975
Glacial clay	11	51.9±8.3	73.5±6.6	1,430±105	Z5	Nilsson 2004, Sohlenius et al. 2006
Clay gyttja	42	83.4±5.4	90.0±3.4	1,081±33	Z3	Nilsson 2004
Peat	18		92.6±3.0	100±57*	Z2	Lundin et al. 2005
Peat	2	91.5	92.0	1,005	Z2	Nilsson 2004
Top sediment (clay gyttja)	58	90.8±1.6	94.7±0.9	1,043±9	Z1**	Fredriksson 2004
Sand/gravel			15–50	1,800–2,300	Z4***	Almén and Talme 1975
Top sediment (sand and gravel)	22	24.8±14.7	43.4±17.3	1,914±293	Z1+	Fredriksson 2004

*Dry bulk density. **In areas with clay gyttja. ***In areas with peat, sand/gravel or clay. +At sea floor areas with sand/gravel.

Table 4-12. The average grain-size distribution of material <20 mm in QD. *The sand samples are of both glacial and postglacial origin. **Sand and gravel that were classified as till in the field but have a grain-size distribution equal to water-laid sediments. These well-sorted "till" samples were obtained from boreholes in the valleys. The values are presented as the percent by dry weight values (RDM=Regolith Depth Model).

Quaternary deposit	N	RDM layer	Gravel (%)	Sand (%)	Silt content (%)	Clay content (%)	d60/d10
Average gravelly till	31	Z6	47.7±10.5	40.1±10.4	9.4±3.6	2.8±1.2	102±134
Average sandy till	16	Z6	27.7±9.2	46.5±11.8	21.5±14.3	4.3±2.5	69.7±59.7
Average till	48	Z6	40.1±14.7	41.9±11.3	14.3±11.6	3.7±3.1	133±170
Average clay gyttja	61	Z3	0.0±0.1	20.9±11.6	46.4±11.6	32.7±12.5	–
Average glacial clay	18	Z5	0.5±1.2	9.0±7.6	31.1±9.0	59.4±12.3	–
*Average sand	9	Z4	17.4±22.1	79.5±22.0	2.3±1.5	0.8±1.1	–
**Sand and gravel	9	Z6	55.6±15.4	41.9±14.2	2.6±2.0	0	16.7±5.4

At several sites in the valleys the till below the clay is quite well-sorted /Morosini et al. 2007/. These well-sorted deposits have been classified as till in the field but are shown as sand and gravel in Table 4-12. The well-sorted till deposits almost completely lack silt and clay and thus probably have a considerably higher hydraulic conductivity than the till in general. The well-sorted till material is present in samples from several boreholes and it is therefore believed that the till deposits overlying the bedrock in the large valleys is often better sorted than the till in general.

There are no reports dealing with the properties of the artificial fill in the area. Most artificial fill is material from the building of the nuclear power plant. That material has probably a coarse grain-size distribution and a chemical and mineralogical composition similar to the local bedrock.

The results from measurements of the specific surface /Lundin et al. 2007/ show that the till and clay samples have a specific surface lower than the average Swedish values for these deposits /cf. Maxe 2003/. The till is rather coarse-grained in the investigated area, which may explain the relatively low specific surface of the till.

Mineralogy of Quaternary deposits

The mineralogical studies show that the till is dominated by silica-rich primary minerals, similar to these found in the bedrock /Sohlenius et al. 2006, Lundin et al. 2007/. Thus, the mineralogical composition of the till in the Laxemar-Simpevarp area probably reflects that of the local felsic bedrock /cf. Bergman and Sohlenius 2007/. The mineralogical studies also show that the till contains clay minerals that have been formed as a result of chemical weathering. All till samples contain a significant amount of vermiculite, indicating clay mineral alteration by chemical weathering. The formation of clay minerals may have taken place in the present till or before the latest ice age.

All but two till samples lack calcite. Two samples from one of the machine-dug trenches studied by /Sohlenius et al. 2006/ contain significant amounts of calcite. The bedrock in the Laxemar-Simpevarp area does not contain significant amounts of calcite. That mineral must therefore have been transported to the area from somewhere else. The sedimentary limestone at the bottom of the Baltic Sea east of the investigated area is a probable source.

/Lundin et al. 2007/ analysed the mineralogy of postglacial sand. The results indicate that the mineralogy of the sand resembles that of the local bedrock.

All but one sample from water-laid deposits lack or contain only traces of calcium carbonate. However, one gyttja sample from Långenmossen fen contains 12% $CaCO_3$, which is probably of biogenic origin, i.e. the calcite has precipitated at the site.

Sohlenius et al. /2006/ analysed the distribution of clay minerals (XRD) in four clay samples. The results show that illite is the dominant clay mineral, followed by chlorite and kaolinite. This agrees with other mineralogical studies of water-deposited clay from other parts of Sweden, e.g. Uppland /Snäll 2004/. The results imply that most of the clay has been affected only to a small degree by chemical weathering /cf. Snäll 2004/.

Chemical properties of soils

The carbon stocks for the sites, which were studied during the fieldwork, have been calculated. The average carbon stocks for the soil classes shown on the soil type map (Figure 4-21) are presented in Table 4-8. As expected, the largest carbon stocks are associated with areas classified as Histosol (peat). One exception is the class HI-w (Open wetland covered by peat), which has an unexpectedly low carbon stock.

The average pH and contents of carbon and nitrogen in soils from the Laxemar-Simpevarp regional model area /Lundin et al. 2005/ have been compared with the average values for forested areas in Sweden /Sohlenius and Hedenström 2008/. The results show that the pH values in the uppermost organic layer (the O horizon) of the soils are similar to the average Swedish values. The average pH in the uppermost mineral layer in the Laxemar-Simpevarp area is higher than the average for Sweden. This is due to the samples from arable land, which generally have a higher pH than equivalent samples from forested land.

The average pH value in the C horizon (55–65 cm) in the Laxemar-Simpevarp area did not differ much from that in the overlying layers. This deviates from the overall pattern for Swedish forest soils, where pH increased more with depth and also showed higher values as compared with the results from the Laxemar-Simpevarp area.

For a comprehensive description of the soil chemical investigation the reader is referred to /Sohlenius et al. 2006/ and /Lundin et al. 2007/.

Rates of sediment and peat accumulation

The recent and long-term rates of sediment and peat accumulation in the Laxemar-Simpevarp area have been determined by dating by radiometric methods (^{210}Pb and ^{14}C) by /Sternbeck et al. 2006/ (Table 4-13). The results were used to calculate the accumulation rates of carbon, nitrogen and phosphorus /see Sohlenius and Hedenström 2008/. The average long-term accumulation covers a period of several thousand years and the accumulation rates have probably varied considerably throughout that period.

Table 4-13. Average sediment mass accumulation rates (g m^{-2} y^{-1}). The ^{210}Pb record covers the 20th century and the ^{14}C dates have been used to calculate the long-term accumulation /from Sternbeck et al. 2006/ (S=sediment, P=peat).

Site	^{210}Pb, average (g m^{-2} yr^{-1})	^{210}Pb, range (g m^{-2} yr^{-1})	Average long term (^{14}C) (g m^{-2} yr^{-1})	Long term cal yrs ago
Lake Frisksjön (S)	410	300-600	400±30	2,600–4,060
Borholmsfjärden (S)	680	470–1,000	680±100	3,300–4,400
Norrefjärd (S)	740	200–1,100		
Granholmsfjärden (S)	380	200-650		
Klarebäcksmossen (P)	450	300-600	56±6	0-8,400

In the bays, the lowest accumulation rates were found in the bay of Granholmsfjärden. That sampling station is not situated in the deepest part of the basin, which may explain the low rate of accumulation. The long-term fluxes of carbon /see Sohlenius and Hedenström 2008/ in present and past bays (Borholmsfjärden and Lake Frisksjön) are considerably higher than in the open Baltic Sea /Emeis et al. 2003/. These two basins have, to a large extent, been surrounded by land for a long period of time and may therefore have had properties similar to lakes. That may explain the high accumulation rates of carbon in these basins. The recent accumulation rates of carbon are also generally higher than values calculated for the open Baltic Sea /Emeis et al. 2000/.

In the bog Klarebäcksmossen, the long-term accumulation of peat is similar to accumulation rates calculated for mires in Finland /Turunen et al. 2002/. The recent accumulation rate of peat in the bog Klarebäcksmossen is much higher than the long-term accumulation rate. Similar results have been obtained in other studies of peat accumulation in Sweden.

4.4.4 Resulting description

Based on the stratigraphical and geographical distribution of the QD, the area has been divided in three type areas (Figure 4-23, Table 4-14), which are presented below. Note that the type areas were defined based on the distribution of QD. This means that some areas classified as type area I (topographically high areas) may in fact be situated in valleys, since all till areas are classified as type area I (Table 4-14). Areas with artificial fill were not assigned to any type area.

Type area I, the topographically high areas

Most of the highest topographic areas are dominated by bedrock outcrops, till and numerous small peatlands (Type area Ia in Figure 4-23). The latter are classified as either bogs or fens. The regolith in the peat and till areas is generally one to a few metres thick. On land, this environment is completely dominated by forest. Areas with hummocky moraine and a low frequency of bedrock exposure occur in the southwestern part of the model area, but also in the central part of the Laxemar subarea (Type area Ib in Figure 4-23). The till in that environment is thicker than the till in general.

Type area II, the valleys

In the terrestrial area clay gyttja, peat and postglacial sand/gravel dominate the floors of the valleys. Glacial clay and till underlie these deposits. On the sea floor, the valleys close to the coast are dominated by clay gyttja, which is currently being deposited. In the marine areas outside the archipelago, the valleys are dominated by glacial clay covered with a thin layer of postglacial sand. The total thickness of the QD is often several metres in the valleys. Drilling results show a maximum regolith depth of more than 30 metres, while results of geophysical measurements indicate regolith depths of up to 50 metres. In the terrestrial areas, the groundwater table in the valleys has often been lowered and the former wetlands are used as arable land.

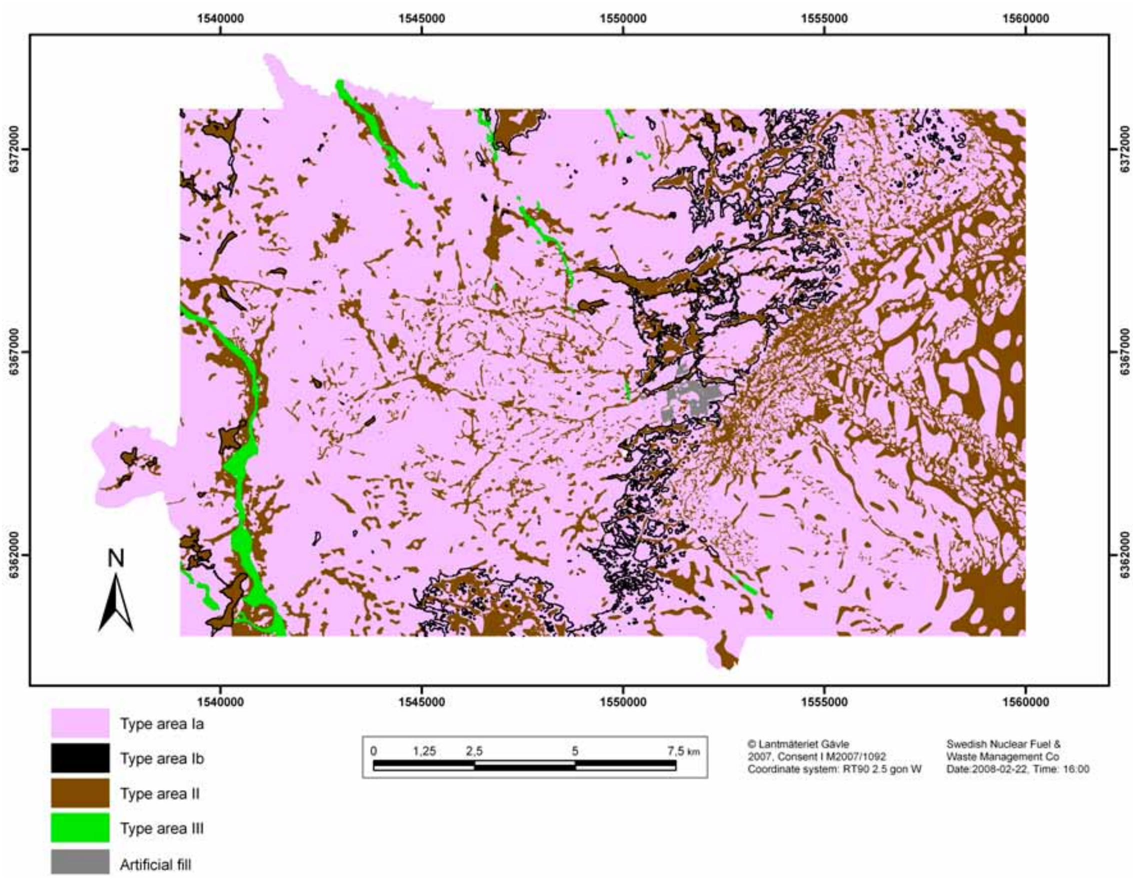


***Figure 4-23.** The distribution of the different type areas, defined based on the distribution of QD (cf. Table 4-14).*

Table 4-14. The type areas and corresponding Quaternary deposits.

Type area	QD
Type area I *(topographically high areas)*	Bedrock, outcrops, till, shingle, peat in till and outcrop-dominated areas
Type area II *(valleys)*	Glacial clay, postglacial sand-gravel, Clay gyttja, peat in the clay dominated valleys
Type area III *(glaciofluvial eskers)*	Glaciofluvial sediments

Type area III, the glaciofluvial eskers

There are three small and one large (the Tuna esker) glaciofluvial deposits in the regional model area. These deposits are well-sorted with respect to grain size and consist mainly of sand and gravel. In the Regolith Depth Model, the glaciofluvial sediments rest directly upon the bedrock surface. These deposits are well drained and the vegetation is therefore adapted to dry conditions.

4.5 Chemistry of water, regolith and biota

4.5.1 Hydrochemical characteristics of the surface system in the Laxemar-Simpevarp area

In general, fresh surface waters in the Laxemar-Simpevarp area are classified as mesotrophic brown water types. Most freshwaters are markedly coloured due to high contents of humic substances, leading to very high levels of total organic carbon (Figure 4-24). Both streams and lakes are also relatively rich in nitrogen and phosphorus, leading to high levels of chlorophyll, low visual depths and reduced oxygen conditions in the bottom waters of the lakes /Tröjbom and Söderbäck 2006/. Most fresh surface waters show 'moderately' to 'slightly acid' pH values and an alkalinity corresponding to 'good buffering capacity' according to the Swedish Environmental Quality Criteria /Naturvårdsverket 2000/. The electrical conductivity and the contents of dissolved ions are slightly elevated compared with most lakes and water courses in Sweden, due to influence from marine relics, anthropogenic sources such as road salt and the proximity to the Baltic Sea (Figure 4-24).

The shallow groundwater in the Laxemar-Simpevarp area is characterised by neutral or slightly acid pH values, a normal content of major constituents, and alkalinity ranging from 'high' to 'very low'. Iron and manganese show markedly elevated concentrations of about an order of magnitude if observations from the Laxemar-Simpevarp area are compared with normal Swedish conditions. Also, fluoride, iodide and strontium show higher concentrations in the area compared with Swedish reference data for shallow groundwater /Tröjbom and Söderbäck 2006/.

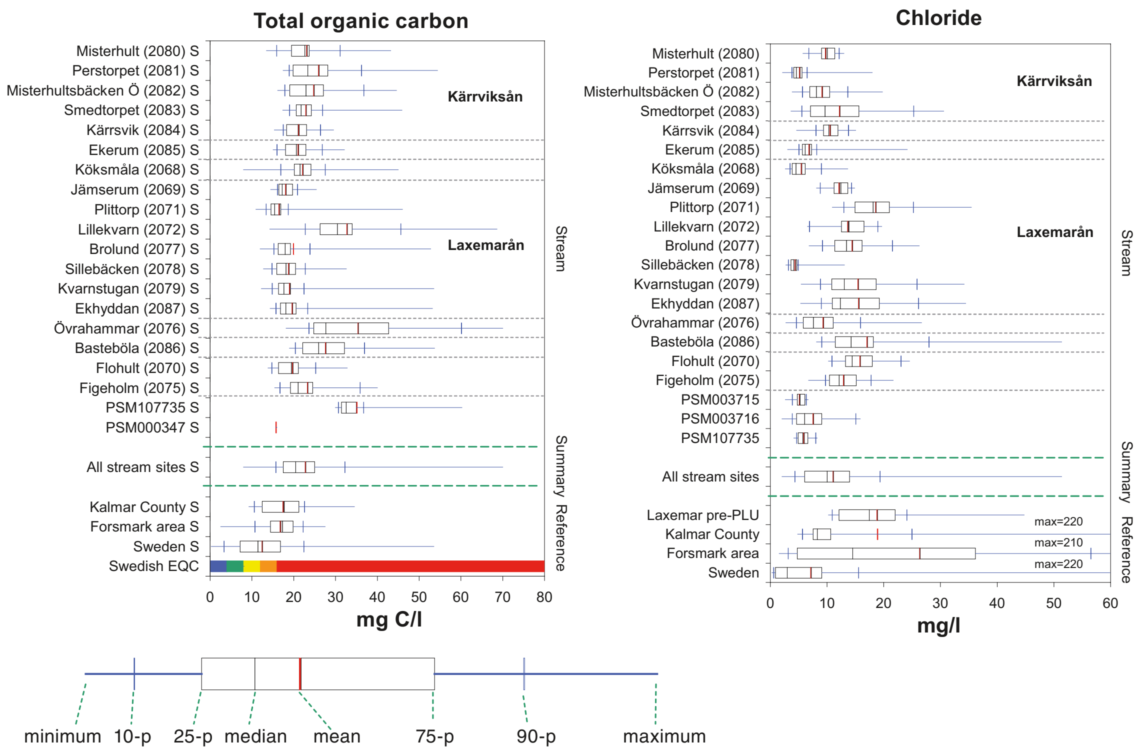


Figure 4-24. *Total organic carbon (left) and chloride (right) concentrations in streams in the Laxemar-Simpevarp area during the period Nov. 2002–Mar. 2005. Reference data from the Forsmark area and other parts of Sweden are also included in the figures together with the classification from the Swedish Environmental Quality Criteria /Naturvårdsverket 2000/. The lower panel explains symbols in the box-plots. Data from /Tröjbom and Söderbäck 2006a/.*

4.5.2 Important factors influencing the hydrochemistry of the surface systems

A historical perspective of factors governing the hydrogeochemistry is necessary in order to explain the hydrological patterns that are observed in the Laxemar-Simpevarp area today.

The topography in this region is characterised by elevated areas covered by thin or no regolith, intersected by deep fissure valleys filled with thick sediments. This topography, in combination with the withdrawal of the Baltic Sea due to isostatic land uplift, are two important factors determining the hydrochemistry of the Laxemar-Simpevarp area. Furthermore, marine remnants in the regolith influence the hydrochemistry in areas at low elevation close to the coast, whereas higher-lying areas are mostly influenced by atmospheric deposition and weathering processes.

Glacial residues in the form of till were deposited during the Weichselian glaciation and deglaciation. When the ice cover retreated about 12,000 BC, the whole area was covered by water and the deposits were exposed on the sea floor. The deep fissure valleys which overlay the major deformation zones in the bedrock are now filled with thick sediment layers of glacial and post-glacial origin. The gradual isolation of these former brackish bays has resulted in succession from brackish water to freshwater followed by formation of wetlands (in the Laxemar-Simpevarp area there was usually no lake stage). In modern times, fertile soils such as wetlands have often been converted into agricultural land by ditching and drainage, further altering the hydrochemical parameters in the area.

The formation of vegetation and a soil layer on the emerging land had a profound impact on the hydrochemistry of the surface system. Degradation of biogenic carbon generates large amounts of H^+ ions, which drive weathering processes in the regolith as well as in the bedrock. The distribution and fate of elements utilised by the biosphere, e.g. nutrients and essential trace elements, are significantly affected by biochemical cycles and retention processes.

In the Laxemar-Simpevarp area, the calcite content in the deposits is almost negligible, which results in a quite different hydrochemistry of the surface system than at the Forsmark site (which is characterised by very high alkalinity and Ca^{2+} concentrations in the surface system). In spite of the low calcite content, carbonates have nevertheless been found to play an important role in the cycling of Ca^{2+} and HCO_3^- in shallow groundwater, as well as in the upper parts of the bedrock /Gimeno et al. 2008/.

Road salt has a significant impact on the concentrations of major ions measured in the surface waters in the area. In the catchment of the Laxemarån River, winter road salt spread on the E22 motorway constitutes about 50% of the total Cl flux in this catchment. Summer road salt, spread on gravel roads for dust control, is also a potential source of Cl that has been shown to have significant influence in some areas. As much of 2/3 of the total Cl input in the Laxemar-Simpevarp area may be of anthropogenic origin.

4.5.3 Conceptual model for the hydrochemistry of the surface system

The present situation in the surface system is a consequence of the palaeohydrological past. In higher elevated areas, meteoric recharge has a great influence on the observed hydrochemistry, which is usually characterised by dilute fresh waters of low ionic strength. In lower areas close to the coast, there are indications of ongoing flushing of marine relicts since the area was covered by sea water. At most locations in the Laxemar-Simpevarp area, this flushing is more or less completed and concentrations of marine ions may be explained by deposition and anthropogenic sources such as road salt.

On a regional scale, meteoric recharge and subsequent flushing of ions results in the large-scale hydrochemistry according to the conceptual model illustrated in Figure 4-25. Marine relicts in combination with regional groundwater flow patterns may explain the anomalous composition at shallow groundwater sampling points in till below lake and sea sediments. These sites are predominantly located close to major facture zones, which are potential deep groundwater discharge locations. When all the pieces are put together, the following conceptual model can explain the hydrochemistry of the area on a regional scale:

- In the lower-lying areas close to the coast, relict marine water prevails in the deeper parts of the deposits and in the upper parts of the bedrock. The high salinity, compared with present Baltic Sea water, in combination with negative deuterium excess values indicates that this sea water is probably a remnant of the Littorina stage when sea water with a Cl concentration of approximately 6,500 mg L^{-1} infiltrated the deposits and the bedrock.
- In the deposits closer to the surface, intermediate Cl concentrations in combination with meteoric isotope signatures indicates ongoing flushing of relict marine remnants of Littorina or younger age.
- In slightly higher-lying areas, which should also have been covered by sea water after the latest glaciation, meteoric isotope signatures and low Cl concentrations indicate that marine influences have been washed out due to the meteoric recharge. This process has also affected the groundwater in the upper parts of the bedrock, resulting in signatures similar to the shallow groundwater at a few hundred metres depth.
- In areas located above the highest coastline of the Littorina Sea, relict marine remnants are probably almost absent. Cl concentrations in these areas can be fully explained by atmospheric deposition and point sources such as road salt.
- Deep saline signatures present in two soil tubes located in till below thick lake and sea sediments may indicate an influence of deep groundwater discharge. Both these sites are located in the vicinity of major fracture zones in the area, which have been proposed as potential areas for deep groundwater discharge. A differing water isotope signature between these two sites indicates, however, that SSM000241 in Granholmsfjärden is attributable also to regional or local meteoric discharge originating from the higher elevated area in the north, whereas SSM000242 in Lake Frisksjön probably reflects a more stagnant relict marine groundwater less influenced by ongoing meteoric recharge.

4.5.4 Surface – deep groundwater

To generalise, the three major ion sources affecting the groundwater in the Laxemar-Simpevarp area are A) deep saline groundwater, B) weathering of local minerals driven by H^+ of biogenic origin, and C) marine ions, either of modern or relict origin.

The Ion Source Model can also be interpreted in terms of water types, and four encircled groups can be identified in Figure 4-26. It should be noted, however, that any classification is artificial, as most observations belong to continuous gradients between theoretical end-members.

The most obvious 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 located along this gradient are groundwater samples from the bedrock (percussion boreholes, and cored boreholes). A few shallow observations in soil tubes also plot along this gradient.

The marine groundwater type contains all observations from the Baltic Sea and the brackish basins Granholmsfjärden and Borholmsfjärden (hidden under the black symbol for the Littorina Sea water end-member), as well as a few observations from the bedrock and deposits. Generally, there are rather few observations of groundwater and shallow groundwater that show significant marine influence (contrary to the Forsmark site where most samples from the bedrock show relict marine influence /Tröjbom et al. 2007/).

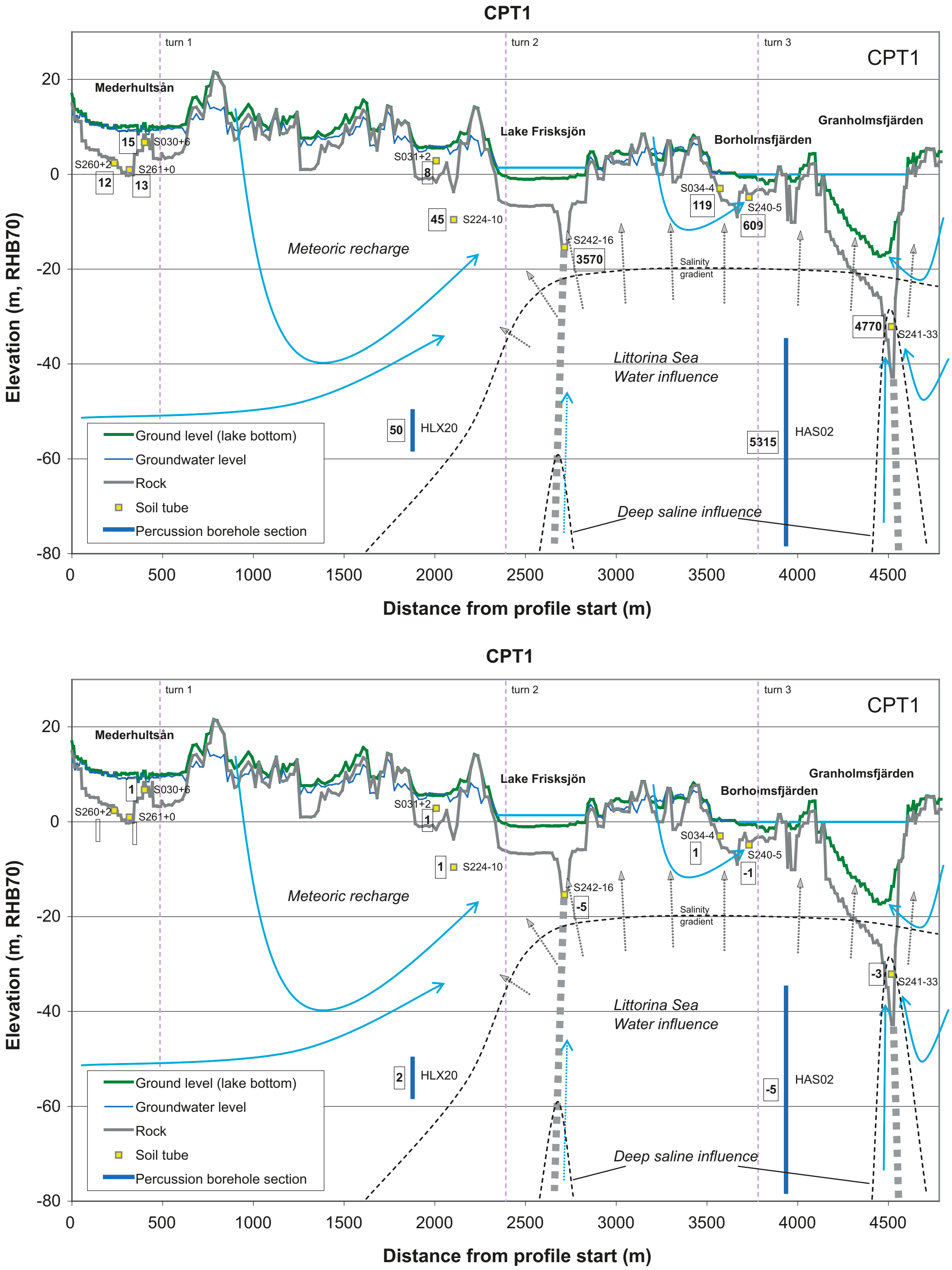


Figure 4-25. *A profile covering a W-E transect of the central parts of the Laxemar-Simpevarp regional model area. The figure shows the ground level and the upper part of the rock, soil tubes and percussion boreholes in the vicinity of the transect, and the average groundwater level. Thick dotted grey lines represent the approximate location of major fracture zones. A selection of hypothetical groundwater flow lines is shown by blue-green arrows. Figures within the boxes represent, in the* ***upper plot****, Cl concentrations (mg L*$^{-1}$*), whereas corresponding figures in the* ***lower plot*** *represent the deuterium excess (see Section 8.3 in /Tröjbom et al. 2008/ for more details).*

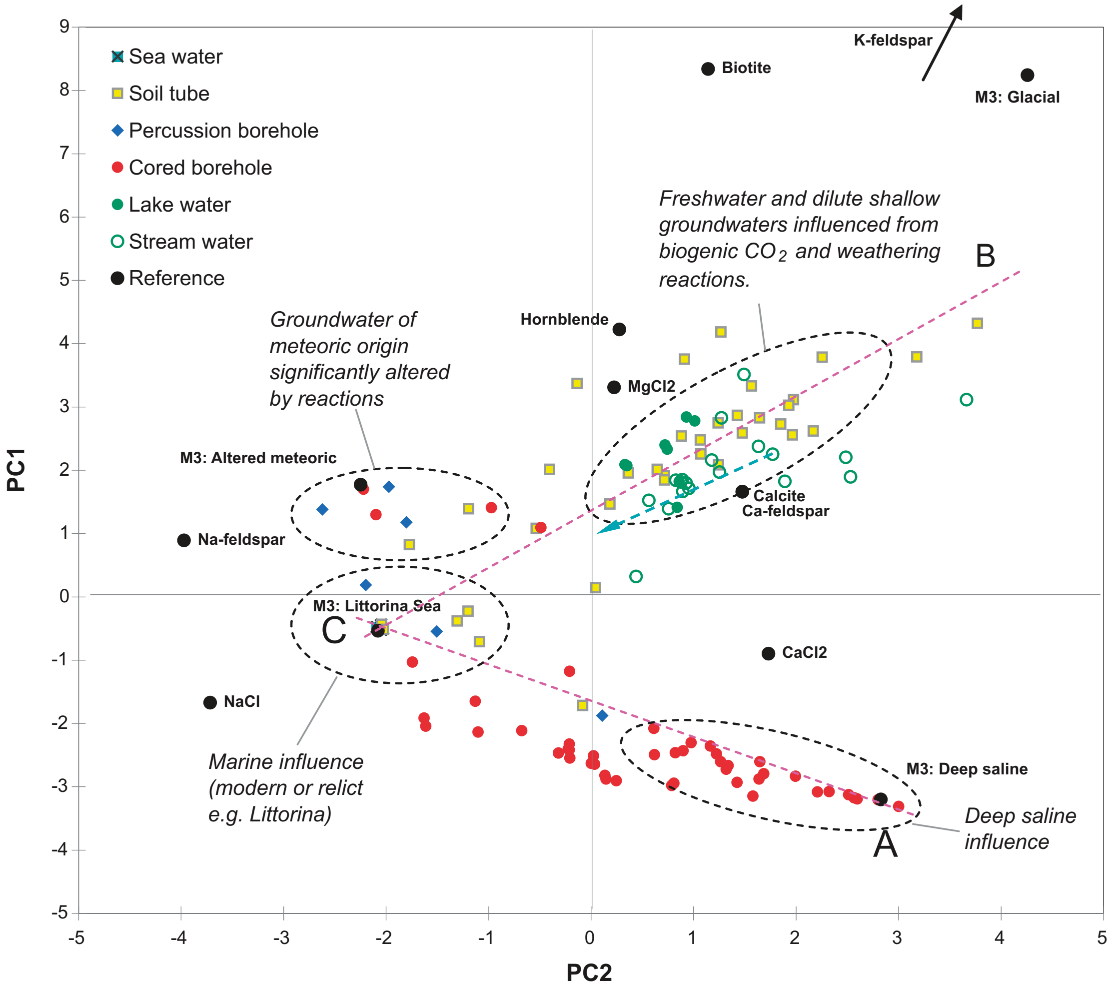


Figure 4-26. *The Ion Source Model, with different possible ion sources marked. The composition of M3 end-members constitute "wet" ion sources, whereas weathering products from selected minerals and from salts used for road maintenance are shown as theoretical compositions.*

The other marked trend connecting C and B contains almost all observations from fresh waters (lakes and streams) and shallow groundwater. These dilute waters have a meteoric origin and are mostly affected by biogenic CO_2 and weathering of minerals in the Quaternary deposits. Most theoretical signatures of the few selected minerals plot around this group, indicating possible mineral sources. A varying input of marine ions due to deposition and leaching of marine relicts in the deposits causes the trend towards modern sea water. Anthropogenic input of salts used for road maintenance may also contribute to this trend, for example winter road salt (NaCl), where the theoretical shift is marked as a blue-green arrow in the figure.

The group altered meteoric groundwater probably belongs to the sea water-meteoric water trend (C-B), significantly altered by reactions. Many percussion boreholes representing the upper parts of the bedrock plot in this group, along with a few shallow groundwater samples located in the deposits (e.g. SSM000022 located beneath thick sediments on Ävrö).

4.5.5 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. Results from a study by /Kumblad and Bradshaw 2008/ 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 primary consumers were generally more similar to other primary producers than to secondary consumers. There was a marked difference between different trophic levels in the concentrations of many elements. Most elements showed lower concentrations in fish compared with other organisms, with the exceptions of C, N, P and Se, and to a lesser extent also 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 2008/.

The results from a study of the chemical composition of different types of flora and fauna in the Laxemar-Simpevarp area are compiled in /Engdahl et al. 2006/. These results are also utilized in calculation of mass balances for different ecosystems in Section 4.6–4.8 below. As well as being of ecological interest, the data on chemical composition of biota 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.

4.5.6 Chemical properties of the regolith

The chemical composition of most QD roughly reflects the composition of the local or neighbouring bedrock. The primary rock composition may, however, be partly changed due to chemical processes taking place before and after the deposition of the QD. The chemical properties of the surface system have been discussed by /Tröjbom and Söderbäck 2006/. Results from chemical analyses of the most common QD obtained from the site investigation are shown in Table 4-15. The chemical composition of 20 till samples from the Laxemar-Simpevarp area was analysed within SGU's geochemical mapping programme /Andersson and Nilsson 1992/ before the start of the site investigation. The results were compared with the average Swedish chemical composition of till /see Sohlenius and Hedenström 2008/.

In the Laxemar-Simpevarp area, the chemical composition of the till is relatively normal in a Swedish context, and the contents of Si, Al, Fe, P, Mn, Mg and Na are close to the average contents of till in Sweden. The contents of some elements differ, however, from the average Swedish values. The content of potassium (K) is somewhat higher in the Laxemar-Simpevarp area than in other parts of Sweden. The reason for this is not understood, since the K content of the bedrock is not higher than in other areas. The potassium may originate from the Götemar granite north of the Laxemar-Simpevarp area. Ti is slightly enriched in till from the Laxemar-Simpevarp area. High contents of illmenite (Ti-Fe oxide) have been recorded in diabase from the Laxemar-Simpevarp area /Carl-Henrik Wahlgren SGU/. That may explain the high Ti content in some till samples. The contents of Cr and Ca in till are lower in the Laxemar-Simpevarp area than in the rest of Sweden.

/Lindroos 2004/ discussed the potential for ore industry in the Laxemar-Simpevarp area and concluded that it is highly unlikely that there will be any opening of mines in the Laxemar-Simpevarp area. However, some elements (Pb and Cu) show relatively high contents in parts of the local bedrock, which also is recorded in some till samples.

Table 4-15. The average contents (in %) of organic carbon, nitrogen (N) and sulphur (S) in clay gyttja, peat and glacial clay /from: Nilsson 2004 and Sternbeck et al. 2006/. The nitrogen content of the glacial clay was below the detection limit. The S content was not measured by /Sternbeck et al. 2006/.

	N (C,N)	N (S)	Org. C	Max C	Min C	Tot. S	Max S	Min S	Tot N	Max N	Min N
Peat	5	2	52.4±4.5	56.0	49.3	0.16			1.4±0.6	2.1	0.6
Clay gyttja in fens	13	13	15.3±8.1	34.6	3.6	1.5±1.1	3.9	0.24	1.3±0.6	2.0	0.3
Clay gyttja in fens	13	13	15.3±8.1	34.6	3.6	1.5±1.1	3.9	0.24	1.3±0.6	2.0	0.3
Clay gyttja in lakes	35	31	17.4±8.1	36.9	2.3	1.4±1.2	3.4	0.14	1.6±0.6	2.6	0.2
Clay gyttja in bays	26	14	13.4±1.1	16.7	11.9	2.2±0.5	3.1	1.6	1.7±0.2	2.3	1.4
Clay gyttja (total)	74	58	15.6±6.7	36.9	2.3	1.7±1.1	3.9	0.14	1.6±0.5	2.6	0.2
Clay gyttja in Lake Frisksjön	13	9	20.2±4.0	26.8	15.1	2.3±0.8	3.4	1.1	2.1±.3	2.6	1.6
Glacial clay	8	8	0.5±0.3	1.0	0.2	0.5±0.5	1.2	0	–	–	–

The chemical composition of sand was analysed in eight samples (Table 4-16). These samples were taken both from glacial (2 samples) and postglacial deposits. The composition of the sand is similar to that of the till and is therefore interpreted as reflecting the composition of the local bedrock. Too few samples were analysed to conclude if there is any significant difference between postglacial and glacial sand.

The chemical composition of the water-laid sediments may reflect the environmental conditions prevailing during sediment accumulation. However, diffusion, bioturbation and other processes taking place after accumulation may change the original composition of the sediments.

The content of Al is higher in glacial clay than in sand and till (Table 4-16). This probably reflects relatively high contents of Al-rich clay minerals in that clay. Weathering of primary bedrock minerals formed these minerals. The content of trace elements is generally higher in clay samples than in till and sand (Table 4-16). However, several of the trace elements were analysed after digestion with HNO_3. That method does not digest the samples completely, and the digestion is more effective in fine-grained deposits (e.g. clay) than in more coarse-grained deposits like sand. That may explain the relatively high trace element contents in the clays compared with the more coarse-grained deposits.

The clay gyttja has a relatively high content of silicon (SiO_2) compared with other elements, which occur in high contents in the other QD (e.g Al and Ti). That is probably an effect of high contents of biogenic silica in the clay gyttja. Also, the contents of Cl and Br (Bromine) are high in many of the clay gyttja samples. These sediments have partly been deposited in brackish water, which explains the high contents of these elements.

/Sohlenius and Hedenström 2008/ compared data from SGU's national mapping with data from the Laxemar-Simpevarp area. The glacial clay in Laxemar-Simpevarp generally has a higher content of trace elements compared with the SGU samples. The clay gyttja on the other hand has lower contents of many elements compared with the SGU samples. That may be explained by the high content of biogenic silica (diatoms) and organic material in the clay gyttja from Laxemar-Simpevarp diluting the contents of other elements.

In all investigated lakes and bays, organic carbon (C), nitrogen (N) and sulphur (S) show an increasing trend from the glacial clay to the overlying younger gyttja sediments (Table 4-15). The total contents of all these elements are relatively low in the glacial clay.

The low organic C and N contents in glacial clay can be explained by at least two factors: 1) The accumulation rate of minerogenic particles was high during the formation of the glacial clay; 2) The primary production of organic matter was low due to the cold climate and/or low concentrations of nutrients in the water.

High productivity of organic matter in the sheltered bays and lakes probably caused the relatively high N and organic C contents preserved in the clay gyttja deposited in these environments. The S contents are higher than 1% in most sediments overlying the glacial clay and the highest values, almost 4%, were recorded in the organic-rich gyttja sediments. Sulphur in the sediments may, in part, be associated with organic material, but most sulphur in postglacial organic-rich sediments is bound in iron sulphides /cf. Sternbeck and Sohlenius 1997/. These sulphides are formed as a consequence of reduction of ferric iron and sulphate during the anaerobic breakdown of organic matter. It is therefore likely that the postglacial gyttja sediments and clay in the Laxemar-Simpevarp area contain significant amounts of iron sulphides. Oxidation of iron sulphides may cause acid soil conditions and increased leaching of trace elements /e.g. Åström and Björklund 1995/. The hydrochemistry of the surface waters in the Laxemar area is probably affected by sulphide oxidation /cf. Tröjbom et al. 2008/.

Compared with the average Swedish peat, the peat samples in the present study have lower or similar elemental contents. However, all analysed peat samples were taken from the same wetland, the bog Klarebäcksmossen, and it is likely that the chemical composition of the peat varies within the model area.

Table 4-16. Analyses of QD from the Laxemar-Simpevarp regional model area. For analyses of As, Cd, Cu, Co, Ni, Pb, and S (marked with * in the table) the samples were digested in HNO_3 and subsequently analysed by ICP-MS. The other elements are presented as the total concentrations of each element. Elements with results below the detection limit are not presented. The values represent the concentration in samples dried at 105°C. ** Layer in the Regolith Depth Model (cf. Section 3.3.2).

Element	Analysed element or compound	Unit	Peat N=5 Z2**	Clay gyttja N=36 Z3**	Sand N=8 Z4**	Glacial clay N=9 Z5**	Till N=8 Z6**
Aluminium	Al_2O_3	%	0.52±0.31	5.41±2.37	13.0±2.7	16.3±1.2	14.0±0.59
Calcium	CaO	%	0.80±0.67	1.13±0.35	1.77±0.41	1.40±0.14	2.09±0.52
Iron	Fe_2O_3	%	0.51±0.35	3.83±2.11	3.56±1.24	7.65±2.06	4.79±1.64
Potassium	K_2O	%	0.018±0.018	1.12±0.71	3.75±0.71	4.33±0.25	4.15±0.46
Magnesium	MgO	%	0.064±0.015	1.03±0.45	0.93±0.55	2.50±0.48	1.28±0.49
Manganese	MnO	%	0.004±0.005	0.030±0.021	0.056±0.018	0.080±0.024	0.070±0.017
Sodium	Na_2O	%	0.018±0.018	1.25±1.03	3.40±0.53	1.87±0.23	3.58±0.20
Phosphorus	P_2O_5	%	0.064±0.027	0.29±0.17	0.14±0.05	0.19±0.02	0.174±0.049
Silicon	SiO_2	%	0.82±0.53	44.4±13.0	68.0±4.9	59.7±4.3	69.1±1.99
Titanium	TiO_2	%	0.012±0.008	0.20±0.10	0.38±0.12	0.70±0.05	0.474±0.112
Carbon	C	%	47.4±3.5	15.2±7.5	–	0.38±0.28	–
Organic carbon	Org.C	%	36.6±9.3	11.4±6.3	–	0.35±0.23	–
Nitrogen	N	g/kg	14.5±8.2	14.3±5.6	–	1.7±3.5	–
Organic nitrogen	Org. N	g/kg	13.4±8.1	13.1±5.3	–	1.3±2.9	–
Arsenic	As*	mg/kg	1.17±0.76	6.75±3.69	2.07±1.22	3.25±1.35	0.97±0.22
Barium	Ba	mg/kg	38.8±23.6	194±124	825±234	673±67	952±80
Beryllium	Be	mg/kg	0.23±0.15	3.29±2.82	1.78±1.22	2.95±0.72	1.80±1.03
Bromine	Br	mg/kg	0.66±1.56	70.7±74.5	13.2±34.8	5.77±13.5	0.91±0.36
Cadmium	Cd*	mg/kg	0.18±0.17	1.42±1.22	0.17±0.35	0.12±0.05	0.029±0.008
Cerium	Ce	mg/kg	20.6±17.8	125±79	65.5±33.1	95.8±16.7	67±19.6
Chlorine	Cl	g/kg	0.046±0.095	9.6±16.2	1.67±4.42	1.04±2.29	63.6±11.0
Cobalt	Co	mg/kg	0.96±0.32	910.0±7.0	5.69±1.95	17.4±2.95	7.29±2.16
Caesium	Cs	mg/kg	–	–	1.72±0.63	7.70±1.93	2.02±0.88
Chromium	Cr	mg/kg	3.9±2.2	42.1±28.3	41.5±17.0	94.9±23.8	51.1±21.6
Copper	Cu*	mg/kg	6.26±4.51	53.7±17.3	15.4±8.5	27.1±2.9	13.4±4.8
Dysprosium	Dy	mg/kg	1.05±0.89	6.56±3.47	2.58±1.05	5.50±1.14	2.50±0.81
Erbium	Er	mg/kg	0.62±0.51	3.92±2.06	1.50±0.77	3.17±0.74	1.44±0.44
Europium	Eu	mg/kg	0.3±0.3	1.78±1.18	0.66±0.33	1.11±0.30	0.77±0.29
Gallium	Ga	mg/kg	2.64±1.52	–	–	25.7±20.1	13.2±2.1
Gadolinium	Gd	mg/kg	1.4±1.2	8.46±5.16	2.90±0.94	5.6±1.3	2.59±1.00
Hafnium	Hf	mg/kg	0.11±0.06	-	4.08±1.31	5.01±1.28	5.1±1.6
Holmium	Ho	mg/kg	0.22±0.18	1.33±0.71	0.53±0.21	1.09±0.22	0.52±0.15
Lanthanum	La	mg/kg	11.4±10.0	61.4±38.8	24.1±7.0	44.5±9.1	31.8±8.4
Lithium	Li	mg/kg	0.42±0.22	18.0±9.0	18.5±6.5	47.9±13.1	21.2±7.5
Lutetium	Lu	mg/kg	0.08±0.07	0.58±0.30	0.25±0.11	0.44±0.10	0.25±0.07
Molybdenum	Mo	mg/kg	0.9±0.6	–	–	–	2.1±2.2
Niobium	Nb	mg/kg	0.28±0.13	–	9.4±3.2	15.3±1.44	9.7±1.92
Neodymium	Nd	mg/kg	9.9±8.6	34.0±40.8	23.9±7.6	42.1±7.9	28.3±6.37
Nickel	Ni*	mg/kg	2.74±1.92	35.1±13.0	13.4±6.7	32.1±6.6	16.6±11.6
Lead	Pb*	mg/kg	6.28±9.25	18.0±12.8	9.5±3.8	24.5±5.9	9.7±3.97
Praseodymium	Pr	mg/kg	2.7±2.3	16.4±10.5	6.49±2.68	11.0±2.1	7.09±1.83
Rubidium	Rb	mg/kg	1.1±0.6	47.2±27.2	118±25	166±38.0	116±16.1
Sulphur	S*	g/kg	2.4±1.1	21.5±12.6	2.6±4.7	2.96±5.10	167±135
Scandium	Sc	mg/kg	0.68±0.45	6.24±2.16	4.72±1.59	14.5±2.2	5.93±1.29
Samarium	Sm	mg/kg	1.7±1.4	10.2±6.6	3.62±1.27	7.00±1.42	4.2±1.0
Tin	Sn	mg/kg	–	–	–	–	2.1±2.2
Strontium	Sr	mg/kg	32±21	103.7±36.4	397±146	173±28	464±82
Tantalum	Ta	mg/kg	0.014±0.009	-	0.70±0.16	1.57±0.79	0.86±0.19
Terbium	Tb	mg/kg	0.18±0.18	-	0.44±0.18	0.81±0.16	0.49±0.11
Thorium	Th	mg/kg	0.69±0.48	7.74±2.56	8.40±2.28	17.7±1.6	10.9±2.92
Thallium	Tl	mg/kg	–	0.43±0.16	0.38±0.26	0.91±0.34	0.27±0.19
Thulium	Tm	mg/kg	0.09±0.08	–	0.27±0.13	0.49±0.13	0.22±0.07
Uranium	U	mg/kg	1.1±0.9	10.4±5.2	2.69±1.62	4.57±1.40	2.94±1.10
Vanadium	V	mg/kg	7.0±6.1	41.3±19.0	39.4±15.6	105±15	51.6±13.2
Tungsten	W	mg/kg	0.12±0.06	–	–	–	1.94±0.84
Yttrium	Y	mg/kg	6.9±5.9	45.2±24.7	18.3±6.2	34.1±7.4	17.6±2.91
Ytterbium	Yb	mg/kg	0.54±0.47	3.80±2.04	1.64±0.61	3.26±0.39	1.61±0.37
Zinc	Zn	mg/kg	7.8±9.8	109±72	44.9±26.3	101±15	51.9±14.2
Zirconium	Zr	mg/kg	3.8±1.6	59.5±21.3	196±90	219±36	201±37.3

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 area is young as an effect of the land uplift, and has a more pronounced topography than the Forsmark area. A number of crossing valleys are surrounded by higher-located till and bedrock outcrop, and agricultural land is located along the valleys. Most of the Laxemar-Simpevarp area is covered with coniferous forests, in which Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) dominate. Mires are common, but not to the same extent as in the Forsmark area. The spatial distribution of a number of different vegetation types was presented by /Boresjö Bronge and Wester 2003/ in a vegetation map. 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 86% of the land area in Laxemar-Simpevarp area and, as noted above, these 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, whereas deciduous tree species are more common near the coast, i.e. mainly *Quercus robur* but also *Corylus avelana*, *Sorbus aucuparia*, *S. intermedia* and *Acer platanoides*, making mixed forest the second most common forest type. *Q. robur* is often the dominant tree species where more or less pure deciduous forests are found (Figure 4-27). The character of these forests is a function of boulder frequency, nutrient availability and earlier history of management. The predominant humus form is Moder in Scots pine and Norway spruce forests, where Regosols dominate, but Podzol becomes more common where there is a deeper soil cover. The mull-like humus form is more dominant as deciduous trees becomes more prevalent /Lundin et al. 2005/ and here Regosols and Umbrisols are found. The Laxemar-Simpevarp 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 4-27. *Oak forest in the Laxemar-Simpevarp area.*

Wetlands cover only 3% of the area in the main catchments and poor fens are the dominant type of mires in the Laxemar-Simpevarp area /Rühling 1997/. Although not currently numerous, bogs are also present in the inland and are continuously created due to land rise and mineral- and nutrient-leaching processes. Coniferous forest swamps (with *Pinus sylvestris*) located in crevices are common in the northern, more bedrock-influenced areas /Rühling 1997/. 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. Such areas may be of importance for the retention of various substances that otherwise would be transported by the water to the sea.

Agricultural land covers approximately 8% of the Laxemar-Simpevarp area. It consists of arable land (Figure 4-29) and 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 classes 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 190±9 gC $m^{-2}y^{-1}$ (years 2000–2007).

Figure 4-28. *Wetland Gästern in Laxemar-Simpevarp, dominated by Reed (Phragmites australis).*

Figure 4-29. *Arable land in the Laxemar-Simpevarp 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 Laxemar-Simpevarp area. The mammals that have been included in the surveys are listed in Table 4-17. The mean densities of the monitored species set out in Table 4-17 have been used in the carbon budget calculations. In the Laxemar-Simpevarp area, 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. However, the population growth is more rapid than the average rate in the county /Truvé 2007/.

The most common bird species in the Laxemar-Simpevarp area according to the breeding bird counts between 2002 and 2004 are listed in Table 4-18.

4.6.2 Ecosystem models

Field-estimated local carbon balances for three ecosystems

Net Primary Production (NPP) in the three investigated localities (cf. Section 3.7.2) was between 360 and 736 gC $m^{-2}y^{-1}$ (Table 4-19). The net carbon balances for the alder shore forest and the oak forest were close to zero, whereas the Norway spruce forest on peat soil had a large net accumulation allocated to the growing vegetation. This large net accumulation was mainly an effect of a high NPP in the earlier drained soil. This investigation described the ecosystems more closely from a site-specific perspective and served as a baseline for comparison with the results of dynamic modelling (Section 4.1.3 and Chapter 7 in /Löfgren (ed.) 2008/) and to more general literature data that may be used to describe pools and fluxes in long term perspectives in the safety analysis.

Table 4-17. Mammal species that have been monitored at Laxemar-Simpevarp. 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 Laxemar-Simpevarp area
Herbivores (Eventoed ungulates)	Fallow deer (Sw: *Dovhjort*)	*Dama dama*	Pellet: 2007
	Moose (Sw: *Älg*)	*Alces alces*	Pellet: 2003,2007 Aerial: 2003,2007
	Red deer (Sw: *Kronhjort*)	*Cervus elaphus*	Pellet: 2003, 2007
	Roe deer (Sw: *Rådjur*)	*Capreolus capreolus*	Pellet: 2003, 2007
Herbivores (Lagomorphs)	European (common) hare (Sw: *Fälthare*)	*Lepus europaeus*	Pellet: 2003, 2007
	Mountain hare (Sw: *Skogshare*)	*Lepus timidus*	Pellet: 2003, 2007
Carnivores	Marten (Sw: *Mård*)	*Martes martes*	Snowtracking:2003
Omnivores	Wild boar (Sw: *Vildsvin*)	*Sus scrofa*	Snowtracking: 2003 Pellet: 2003, 2007
Rodents	Bank Vole (Sw: *Skogssork/ Ängssork*)	*Cletrionomus glareolus*	Trapping: spring and autumn 2003
	Field vole (Sw: *Åkersork*)	*Microtus agrestis*	Trapping: autumn 2003
	Water vole (Sw: *Vattensork*)	*Arvicola terrestris*	Trapping: spring and autumn 2003
	Wood mouse (Sw: *Mindre skogsmus*)	*Apodemus sylvaticus*	Trapping: spring[1] and autumn 2003
	Yellow-necked mouse (Sw: *Större skogsmus*)	*Apodemus flavicollis*	Trapping: spring[1] and autumn 2003
Insectivores	Common shrew (Sw: *Vanlig näbbmus*)	*Sorex araneus*	Trapping: spring and autumn 2003

[1] Spring trapping only included mice in forests, not in field.

Table 4-18. The fiftheen most common nesting bird species in the Laxemar-Simpevarp 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
Chaffinch (*Bofink*)	*Fringilla coelebs*	700	10.06	10.84	7.10
Willow Warbler (*Lövsångare*)	*Phylloscopus trochilus*	471	6.77	3.41	7.15
Robin (*Rödhake*)	*Erithacus rubecula*	388	5.57	7.42	2.22
Song Thrush (*Taltrast*)	*Turdus philomelos*	252	3.62	3.68	1.89
Blackbird (*Koltrast*)	*Turdus merula*	224	3.22	5.44	2.24
Great Tit (*Talgoxe*)	*Parus major*	192	2.76	7.77	1.55
Siskin (*Grönsiska*)	*Carduelis spinus*	170	2.44	1.89	0.81
Starling (*Stare*)	*Sturnus vulgaris*	163	2.34	0.40	0.49
Wood Pigeon (*Ringduva*)	*Columba palumbus*	157	2.26	2.62	1.63
Goldcrest (*Kungsfågel*)	*Regulus regulus*	131	1.88	1.44	0.38
Yellow hammer (*Gulsparv*)	*Emberiza citrinella*	106	1.52	1.59	0.87
Green finch (*Grönfink*)	*Carduelis chloris*	89	1.28	0.98	0.29
Blue tit (*Blåmes*)	*Parus caeruleus*	86	1.24	4.71	0.58
Tree pipit (*Trädpiplärka*)	*Anthus trivialis*	80	1.15	0.37	1.71
Wren (*Gärdsmyg*)	*Troglodytes troglodytes*	72	1.03	0.42	0.67

Table 4-19. Carbon pools and fluxes, distinguished into functional units, in the three investigated ecosystems at Laxemar-Simpevarp. See also Figure 3-12 for the conceptual ecosystem. Pools are in gC m^{-2} and fluxes are in gC m^{-2}y^{-1} (mean ± SD). NPP = Net Primary Production, NEP = Net Ecosystem Production.

Functional groups and properties			Vegetation types Oak forest	 Alder shore forest	 Norway spruce on peat
Tree layer	Biomass	Needles/leaves	233±87	97±56	421±116
		Wood	5,372±1,956	6,035±4,116	5,024±606
		Fine roots <2 mm	90±46	41±42	250±88
	Net accumulation	Branches	30±12	25±13	40±23
		Stems	129±52	107±57	172±100
		Coarse root	32±13	27±14	43±25
	Litterfall		136±33	115±42	184±65
	Root litter production <2 mm		183±76	90±49	41±42
Field and bottom layer	Biomass	Leaves	45±12	15±14	4±4
		Bryophytes	26±27	–	62±47
		Roots <10 mm	137±121	38±53	9±26
	Litter prod.		175±102	46±46	47±23
Soil Organic Carbon		Litter pool	294±79	507±116	746±507
		Humus	–	309,6[01)]	597,0[01)]
		Mineral soil	6,260	–	–
Heterotrophic respiration			290±125	395±620	590±490
Total	NPP		591±129	360±102	736±154
	Litter prod.		401±126	202±83	480±112
	Acc. in soil		–189±506	–163±321	55±415
	Acc. in veg		190±55	158±60	255±106
	NEP		1±507	–5±326	311±415

[1)] Peat soil

Generally, the estimated pools and fluxes for the three localities were in agreement with similar studies. The Norway spruce forest had a large NPP, which was explained by the fairly low age (≈60 y) and the drained peat soil. 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 data. The large variation found for a number of properties on this rather small spatial scale indicates that there are a number of factors that are affecting these properties on 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 on the scale measured.

Model-estimated carbon balances for a number of ecosystems

The spatial variation of NPP in the regional model area was studied by combining remote sensing and dynamic vegetation modelling for the most common vegetation types /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 4-30 showing the NPP for the most important tree species and the field layer separately. 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 420 and 591 gC m^{-2}y^{-1} for the forested vegetation types. All vegetation types were accumulating carbon in the SOC pool or were close to zero except for the previously mentioned clear-cut.

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 4-31. 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.

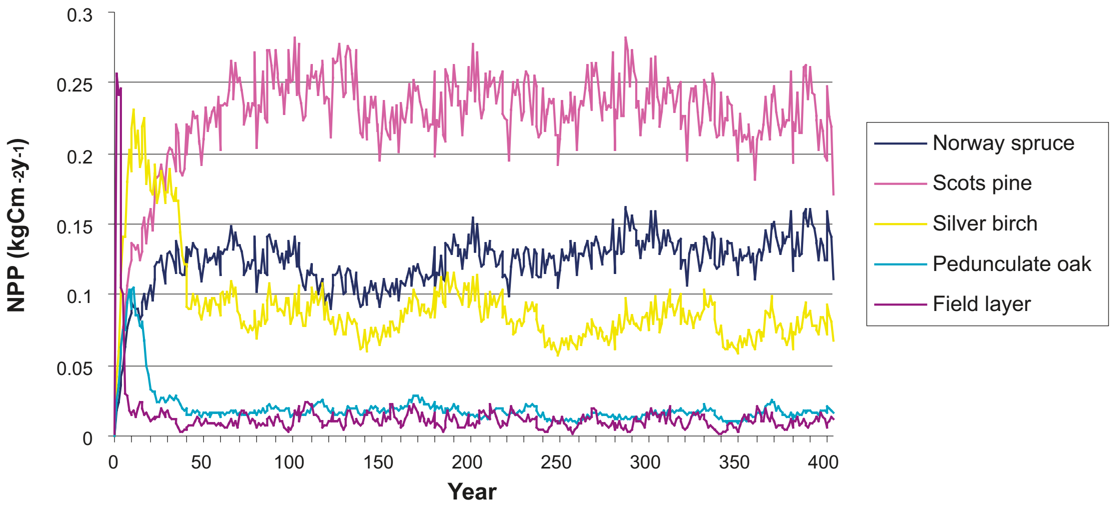


Figure 4-30. *Net primary production during a 400-y period of forest development starting after a clear-cut for Laxemar-Simpevarp showing performance of four different tree species and the field layer. The model was driven by climate data describing a 100-y period that was repeated. Values are given in kg C m*$^{-2}$*y*$^{-1}$.

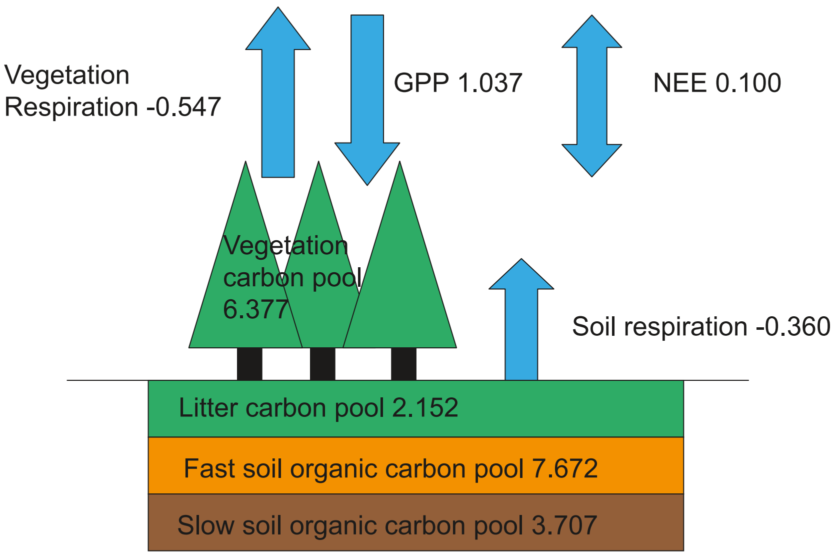


Figure 4-31. *A summary of mean carbon pools and fluxes for a 100-y forest cycle up until the final felling in Laxemar-Simpevarp. GPP (Gross Primary Production) represents the net carbon input to the ecosystem. The positive mean Net Ecosystem Emission (NEE) suggests an annual accumulation of carbon during the forest cycle. Values are given in kgC m*$^{-2}$ *for the carbon pools and kgC m*$^{-2}$*y*$^{-1}$ *for the carbon fluxes.*

Unlike 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 those for 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 estimated realistically in comparison with field estimates and literature values.

Food web

The estimations of biomass, production, consumption, egestion and respiration for mammals are presented in Table 4-20. Estimations for birds, amphibians and reptiles are presented in Section 4-2 and 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 below).

Table 4-20. General figures per unit area describing number densities, biomass, production, consumption, egestion and respiration for the mammals in the Laxemar-Simpevarp area.

Mammal species		Habitat	Density	Biomass (standing stock)		Production	Consumption	Egestion (Faeces)	Respiration
			Number per km^2	Body mass g·ind^{-1}	Biomass mgC m^{-2}	mgC m^{-2} y^{-1}			
Herbivores- (Even-toed ungulates)	Fallow deer	Forest+Field	0.04	70,000	0.3	0.1	5	2.4	3.0
	Moose	Forest+Field	1.07	300,000	37.5	7.3	415	182	226
	Red deer	Forest+Field	0.08	170,000	1.6	0.4	22	10	12
	Roe deer	Forest+Field	5.6	25,000	16.5	7.8	439	193	239
Herbivores (Lago-morphs)	European hare	Field	2.4	3,800	1.1	1.0	56	24	30
	Mountain hare	Forest	0.84	3,000	0.3	0.3	17	7	9
Herbivores- (Domestic)	Cattle	Field area (grain area excluded)	62	527,000/ 200,000	3,125	1,084	186,811	80,142	99,558
	Cattle (milk prod.)					6,027			
	Sheep	Field area (grain area excluded)	7	66,000/ 46,000	43.4	17	1,815	778	1,019
	Pigs	Field area (grain area excluded)	36	114,000	483	827	17,713	7,599	9,287
Carnivores	Marten	Forest	0.13	1,250	0.02	0.03	1.3	0.28	1.0
	Red fox	Forest+Field	0.20	6,000	0.14	0.18	7.4	1.7	5.6
Omnivorous	Wild boar	Forest+Field	0.21	60,000	1.5	0.56	22	5	17
Rodents	Field vole	Field	420	30	1.5	3.1	368	161	203
	Mouse	Field	640	23	1.7	3.9	464	203	257
	Field vole	Forest	30	30	0.11	0.22	26	11.5	15
	Mouse	Forest	685	23	1.8	4.2	496	218	275
	Bank Vole	Forest	445	23	1.2	2.7	323	141	178
	Water vole	around water[1]	570	74	4.9	10	1,183	518	655
Insectivores	Common shrew	Forest+Field	100	8.5	0.10	0.17	24	4.1	20

[1] A habitat zone of 10 m along each side of streams and lakes has been assumed.

Regional carbon balances for catchments

An ecosystem model describing pools and fluxes of carbon for the catchment area of Lake Frisksjön is illustrated in Figure 4-32. The NPP is allocated among the different functional components of the autotrophic organisms, with a minor amount incorporated into perennial woody tissues, such as the stems of trees, and a large part of the annual production enters the soil organic matter pool as litter. However, during the modelled year 2005, there was a net loss of biomass and a net accumulation of carbon in the SOC pool (Figure 4-32). Litterfall may be highly variable between years /e.g. Bray and Gorham 1964/ and a similar large amount of litter production was recorded in Laxemar-Simpevarp during the storm "Gudrun" in 2005 /Mjöfors et al 2007/. The largest part of the carbon entering the soil will be respired by soil fauna and microbes. The net ecosystem production is positive, with the loss of carbon from the vegetation biomass balanced by accumulation in the soil organic carbon pool. The largest flux of carbon to animals goes to the livestock. However, this flux includes fodder imported from outside the catchment. The flux to herbivores represented by both small animals such as rodents and larger animals like roe deer and moose is the second largest flux in the food web.

Human hunting in the area is today one order of magnitude lower than the fluxes to carnivores. The largest potential human intake of carbon in this catchment comes from crops, followed by meat and milk from livestock. Horizontal transport is relatively small compared with the major internal carbon fluxes. For the Frisksjön catchment, the accumulation of carbon in the vegetation pool was negative and the accumulation in the soil organic carbon pool was approximately 383 tonnes, making the total net ecosystem production 229 tonnes of carbon. Approximately, 4% of the terrestrial net ecosystem production is transported into the aquatic ecosystems (Figure 4-32).

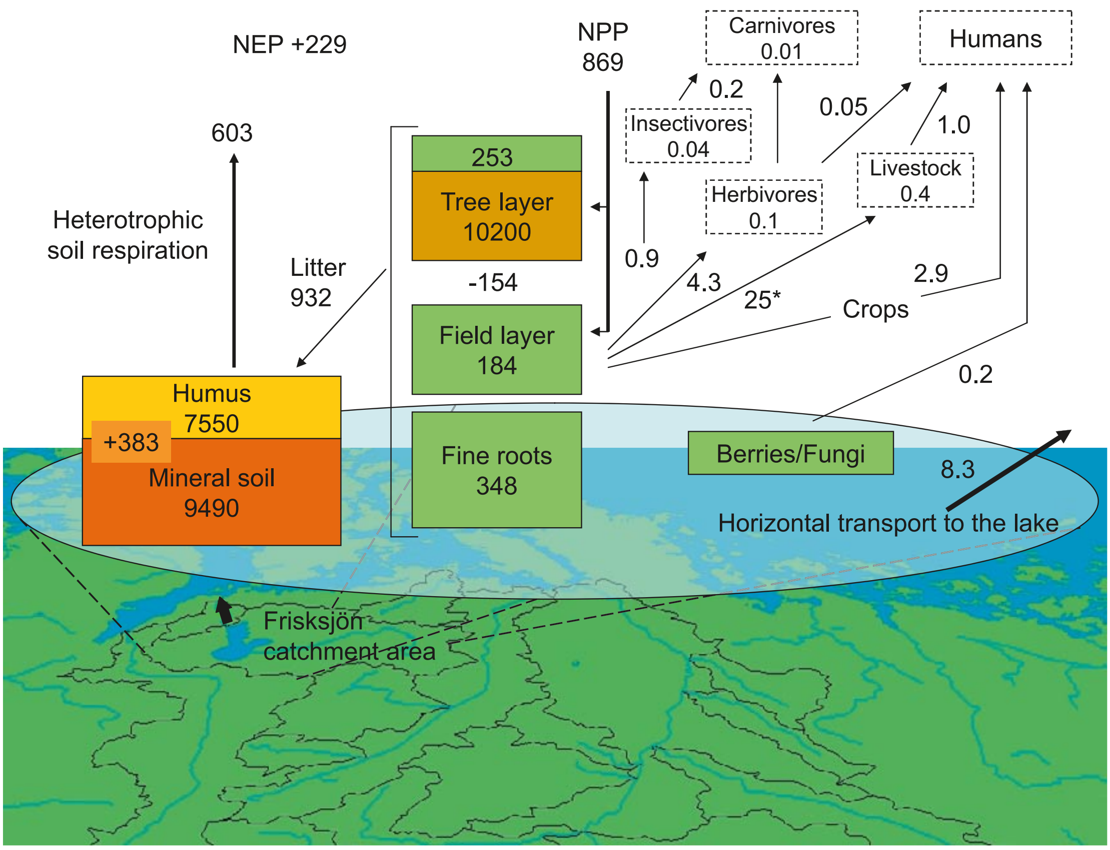


*Figure 4-32. A description of the carbon balance for the catchment of Lake Frisksjön, where modelled pools and fluxes for all vegetation types in the catchment have been summed. The production of berries/fungi is the potential harvest available to biota. The black arrow on the map denotes the discharge out of the catchment. All figures within boxes are in 1×10^6 gC and fluxes are in 1×10^6 gC y^{-1}. Changes in the soil organic carbon pool and the vegetation pool are denoted with a +/- before the figure. Vegetation dynamics and animal consumption have been modelled separately, which means that fluxes to the food web are not subtracted from the NPP. *Livestock consumption is generally divided between locally produced fodder and imported, and this figure includes both.*

4.6.3 Mass balances

Mass balances were calculated for iodine, thorium, uranium and phosphorus. These are presented and discussed in more detail using the catchment areas as units of study in Chapter 9 in /Löfgren (ed.) 2008/. Figure 4-33 illustrates the mass balance of phosphorus for the investigated catchments. The calculation suggests a net accumulation of phosphorus within the area. Wet deposition and weathering adds phosphorus, whereas horizontal transport and removes phosphorus. This results in a net accumulation of 717 kg phosphorus in the catchments. One potential sink is accumulation in wetlands. Long-term accumulation in wetlands was estimated as 0.02 g P $m^{-2}y^{-1}$ in Laxemar-Simpevarp /Sternbeck et al. 2006/, suggesting that only 3 kg would be accumulated (all wetlands included). By using the information from the ecosystem model describing carbon pools and fluxes at the regional level for the same area, it was estimated that approximately 1,550 kg P y^{-1} was needed to sustain the NPP. Substracting the phosphorus accumulated in vegetation and wetlands from this amount suggests that a source of 836 kg is unaccounted for. Most of this phosphorus originates from the decomposition of litter, where phosphorus is released. Moreover, the estimated atmospheric deposition included only wet deposition, which suggests that the input of phosphorus would be somewhat higher.

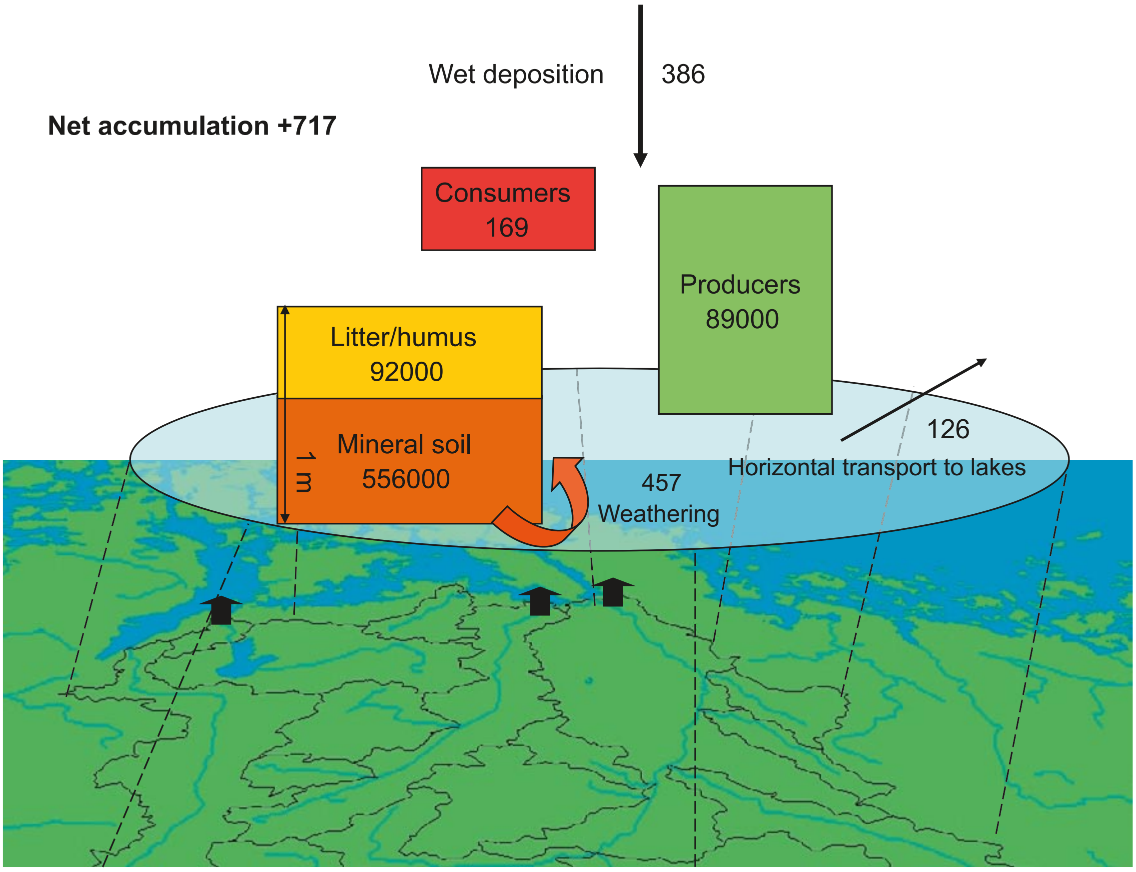


Figure 4-33. *Mass balance of phosphorus for the 14 modelled catchments in Laxemar-Simpevarp area. The black arrow on the map denotes the discharge into the sea. Pools are in kgP and fluxes are in kgP* y^{-1}.

4.6.4 Conclusions

The detailed site investigations have provided an extensive database that has been combined with dynamic modelling in order to characterise 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 can be found in /Löfgren (ed.) 2008/.

The field- and model-estimated carbon pools and fluxes for a large number of vegetation types 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 dominated by accumulation in the soil organic carbon pool. The total biomass experienced a net loss during the modelled year (2005). Export of carbon was low in comparison with the internal fluxes in the terrestrial ecosystems. This also was the case for fluxes to higher trophic levels in the food web, 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. The comparative approach revealed that the studied ecosystems varied in their emission or accumulation of material. For example, a clear-cut initates increased soil respiration and a release of organically bound elements, whereas some wetland types show long-term accumulation of organic matter. Especially, wetlands dominated by reed in close association with lakes had both high production and high accumulation of organic matter.

The mass balances of thorium, uranium, iodine and phosphorus illustrated some different behavioural patterns, where the water-soluble highly mobile iodine to a large extent seemed to be incorporated into the vegetation and also transported further downstream into the lakes. Phosphorus was found in the vegetation to a higher degree 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. They showed a less mobile pattern with low amounts found in the vegetation or transported downstream.

4.7 Limnic ecosystems

4.7.1 General description

The Laxemar-Simpevarp regional model area contains 26 catchments, 5 lakes and a number of streams. In addition, a couple of lakes are situated partly within the regional model area, and there are also some minor, but permanent pools. One of the lakes, Frisksjön (Figure 4-34 and Figure 4-35), is situated within the Laxemar local model area.

The lakes are small with relatively shallow depths. They are characterised as mesotrophic brownwater lakes, i.e. with moderate nutrient concentrations and with brown water colour. The water colour is caused by high influx of organic matter from the surrounding catchment, and the concentration of organic carbon is very high in comparison with the majority of Swedish lakes. Phosphorus concentrations are moderate whereas nitrogen concentrations tend to be high.

Because of the brownish water, light penetration is poor and the depth of the photic zone is generally small. In accord with this, macrophyte coverage is small in the lakes and the biota is dominated by heterotrophic organisms, particularly bacteria. European perch (*Perca fluviatilis*) is the dominant fish species, in numbers as well as in weight, in the lakes in the area.

Most lakes in the area are affected by human activities. One of the lakes, Söråmagasinet was originally a sea bay, but was dammed in order to ensure freshwater reserves to the nuclear power plant. At a few occasions each or every second year, water is pumped from Laxemarån to Söråmagasinet in order to maintain the available water storage in the lake. The naming of some wetlands and minor fields in the area indicate that a number of previous lakes have disappeared during the last few centuries due to human activities, probably with the intent to increase farming areas. There are also indications that the water level of several of the remaining lakes has been lowered by man.

Figure 4-34. *Lake Frisksjön (left) is a typical mesotrophic brown-water lake in the Laxemar-Simpevarp area. The right picture shows the small outlet from Lake Frisksjön.*

Figure 4-35. *Perspective view due west of Lake Frisksjön in the Laxemar-Simpevarp area.*

Most of the streams in Laxemar-Simpevarp area are small with mostly calm or slowly flowing water. Like the lakes, the streams are characterised as mesotrophic brown-water systems. Some of the streams are dry during summer. The largest stream in the area is Laxemarån. Five fish species have been noted in Laxemarån; ide (*Leuciscus idus*), roach (*Rutlius rutilus*), burbot (*Lota lota*), pike (*Esox lucius*) and ruffe (*Gymnocephalus cernua*), and there are indications that the stream is an important spawning site for both ide and roach. The streams are to a great extent influenced by human activities that have altered the channels by various technical encroachments.

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

4.7.2 Ecosystem models

Carbon ecosystem model for Frisksjön

Frisksjön (Figure 4-35) is shallow and of medium size compared with other lakes in the region. It is situated 1.37 m.a.s.l. and is humic-rich with highly coloured water.

The annual mean biomass in Frisksjön is estimated as 750 kg C and is clearly concentrated in the littoral habitat. Benthic bacteria make up the majority of the total biomass in the lake (73% of the total biomass). Phytoplankton makes up 12%, and fish and benthic fauna 7–8% each of the total biomass, whereas each of the other functional groups makes up 3% or less of the total biomass.

According to the model, the primary production rate is 4,300 kg C y^{-1} and is totally concentrated in the pelagic habitat. Benthic primary production accounts for less than 1% of the total primary production. The respiration rate is 12,600 kg C y^{-1} and thus much higher than primary production. This indicates that the lake is a net heterotrophic system with a negative net ecosystem production (NEP) of 8,300 kg C y^{-1}. Despite the low biomass in the pelagic habitat (20% of total biomass), a large share of total respiration occurs there (46% of total respiration). Benthic bacteria and bacterioplankton dominate respiration, together making up 78% of total respiration. Another important functional group in terms of respiration is mixotrophic phytoplankton, making up 12% of total respiration. The other functional groups make up at most 5% of the total respiration.

With the food web structure and feeding rates assumed in the conceptual model, a relatively large part (c. 34%) of the carbon fixed through primary production is directly consumed by higher organisms. The rest of the primary produced carbon is incorporated into the DOC and POC pools. Bacterioplankton and benthic bacteria, the two functional groups that consume most DOC and POC, make up 67% of the total carbon consumption in the lake (Figure 4-36). The DOC and POC consumption by bacteria is higher than the primary production, and thus the lake is dependent on allochtonous carbon entering it from the catchment. The largest carbon flow to the top predator fish goes from benthic bacteria via benthic fauna to fish (Figure 4-36).

Theoretically, the carbon incorporated into primary and secondary producers that is 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 of carbon through the outlet.

4.7.3 Mass balances

Carbon mass balance for Frisksjön

The inflow of carbon to Frisksjön is dominated by the inflow from the catchment (8,300 kg TOC y^{-1} and 1,100 kg DIC $year^{-1}$, cf. Figure 4-37). The atmospheric deposition of organic carbon (200 kg C y^{-1}) makes only a minor contribution to the carbon influx to the lake. According to the mass balance model, the most important carbon export from Frisksjön is burial in the sediments (8,000 kg C y^{-1}). Other important exports are the emission of carbon dioxide to the atmosphere (4,500 kg C y^{-1}), followed by the downstream export of TOC and DIC (4,300 kg C y^{-1} and 800 kg C y^{-1}, respectively). Other carbon fluxes, such as atmospheric wet deposition and bird consumption in the lake are of minor importance. There is a flux of carbon dioxide from the lake to the atmosphere of 4,500 kg C y^{-1}, indicating net heterotrophic metabolism. This is in agreement with the result of the carbon ecosystem model of Frisksjön, which shows much higher respiration than primary production.

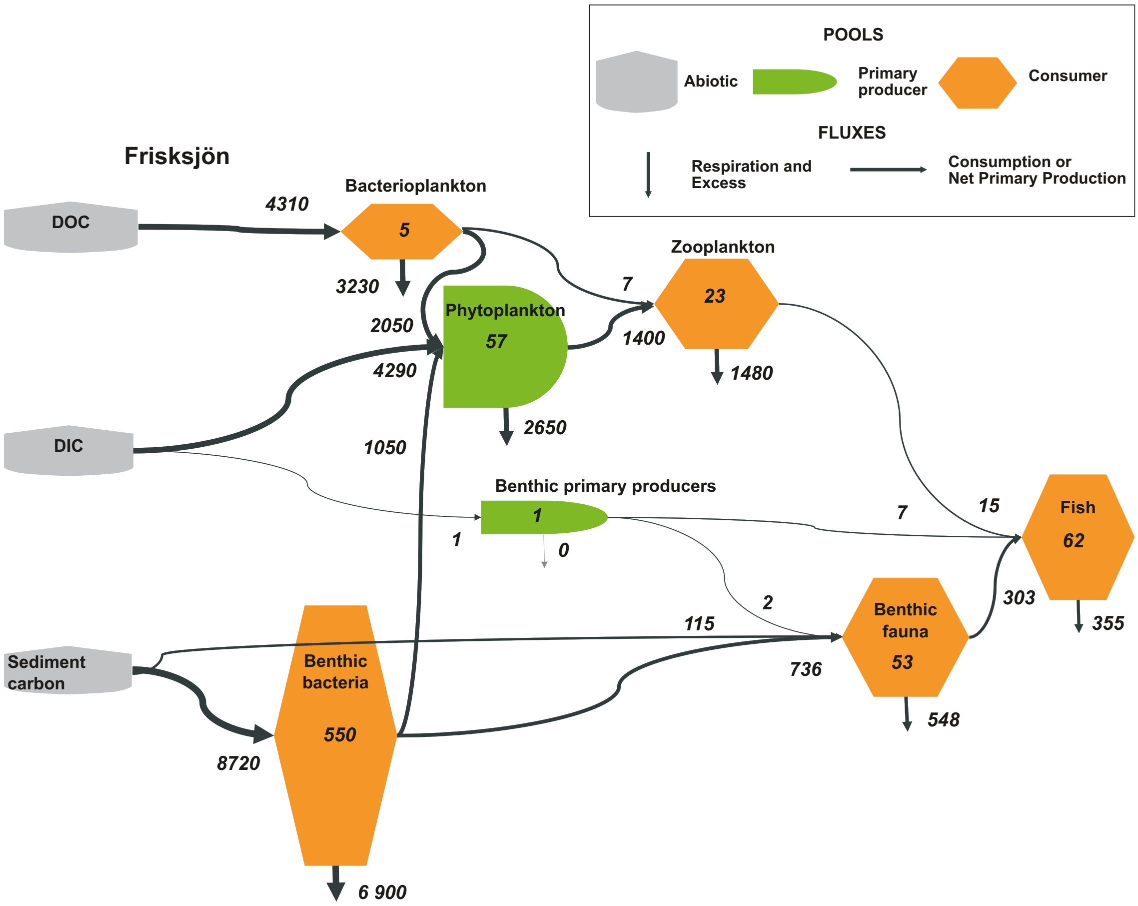


__Figure 4-36.__ Carbon fluxes (kg C year^{-1}) in the ecosystem model for Frisksjön. Sizes of arrows and boxes for biota are scaled relative to each other. The consumption of phyto-, zoo- and bacterioplankton by benthic fauna is included in the consumption of sediment carbon in the figure. Note that consumption within the same functional group is not shown, e.g. the consumption of fish by carnivorous fish.

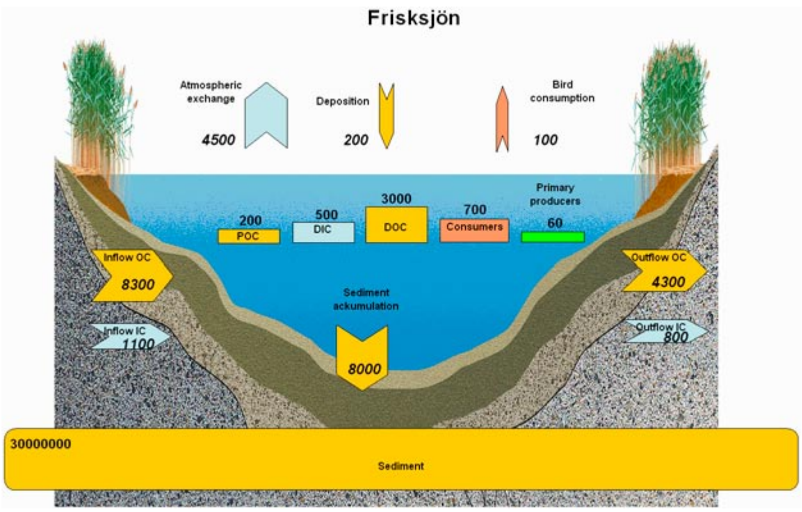


__Figure 4-37.__ Carbon mass balance for Frisksjön (components in kg C and fluxes in (kgC y^{-1}).

The influxes and outfluxes of carbon to/from the lake is in the same order of magnitude as 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 equally influenced by internal processes as by carbon entering the lake from the surroundings. The mass balance is heavily unbalanced with 8,100 kg C y^{-1} lower influx than outflux of carbon.

There is a large uncertainty in some of the flows, especially of the larger flows; carbon inflow and outflow via water, CO_2-emission and sediment accumulation. By using values in the higher range of TOC inflow from catchment, and values in the lower range of sedimentation and CO_2-emission, the mass balance would give higher inflow than outflow of carbon. Thus the large span in estimations of different parameters leads to uncertainties in the mass balance, and the calculated flows should be seen as indicators of magnitude rather than absolute numbers.

Phosphorus mass balance for Frisksjön

The estimated pools and fluxes of phosphorus in Frisksjön are presented in Figure 4-38. The sediment layer contains by far the largest phosphorus pool and almost 100% of the total amount of phosphorus is allocated there. This is as expected, considering the large amounts of sediments. However, excluding the deeper sediment and including only the top centimetre of sediments, there is still a strong allocation of phosphorus to the sediment component (c 90%). Next to sediment, the largest pool of phosphorus is found in the consumers, followed by the dissolved and particulate pools in lake water. Bacteria make up the major part of the biomass of biota in the lake and the concentration of biotic phosphorus in consumers is as expected, considering a high phosphorus content of bacteria. The phosphorus pool in the primary producers is small.

According to the mass balance model, the influx of phosphorus into Frisksjön is dominated by the inflow via water, which is about one magnitude larger than the influx via wet deposition (Figure 4-38). Outfluxes of phosphorus are clearly dominated by sediment accumulation, which is one order of magnitude higher than the outflow via water. The inflow via water is somewhat higher than the outflow via water, but the difference is not enough to balance the high sediment accumulation. There is a shortage of 85 kg P y^{-1}, which corresponds to over 400% of the total influx and to 81% of the total outflux. Thus, there are large uncertainties in the mass balance. The sediment

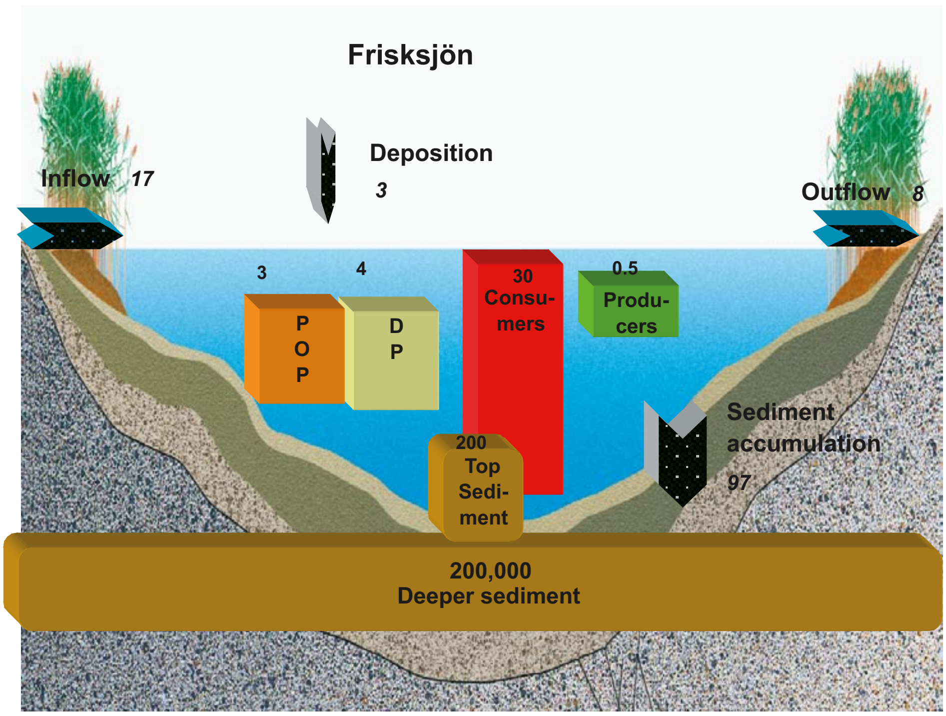


Figure 4-38. Phosphorus pools (kg P) and fluxes (kg P per year) in Frisksjön. Note that the sediment pools are scaled differently than the other pools in order to fit all pools in the same figure.

accumulation is rather uncertain as it is based on a few sediment cores in the deepest part of the lake. Calculating the accumulation rate as the difference between the other influxes and outfluxes in the mass balance indicates an accumulation rate of c. 12 kg P y^{-1}, which is about 10% of our estimate using phosphorus data from lake sediments.

Sediment accumulation is an estimate of long-term accumulation and the accumulation rate varies over time, it is evident that our estimate is somewhat high. In addition, also the estimates of inflow and outflow via water are rather uncertain. The inflow of P is calculated from the average area-specific transport in all modelled catchments in the area and so, although based on site-specific measurements is not determined for Frisksjön directly. The facts that the P accumulation rates are based on data from sediment cores in the lake, and that fluxes via water are calculated from site-specific data, give some confidence in the estimates. However, the calculated flows should be seen as indicators of magnitude rather than absolute numbers.

Overall, sedimentation appears to be an important process in the phosphorus dynamics, and the sediments contain by far the largest phosphorus pool 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 4-39. As expected, the outflow via water is much more important for the mobile iodine than for uranium (intermediate) and thorium (lowest flows). For uranium and thorium, the outflux via sediment accumulation is the largest outflux. Uranium accumulation in sediment is c. 3 times larger than uranium outflow via water and for the very immobile thorium sediment accumulation is c. 17 times larger than outflow via water. The reasons for the different flows of iodine, uranium and thorium are further discussed in /Nordén et al. 2008/.

For 16 elements for which all fluxes were estimated, inflow via water was the largest influx and atmospheric deposition was always small (max 14% of total influx, mean 3% of total influx). Outflux was dominated by sediment accumulation for most elements; this is particularly true for lanthanides where between 75 and 99% of total outflux was due to sediment accumulation. Some ions (which had a large part of their pools present in the dissolved component of lake water) had outflow via water as the dominating outflux.

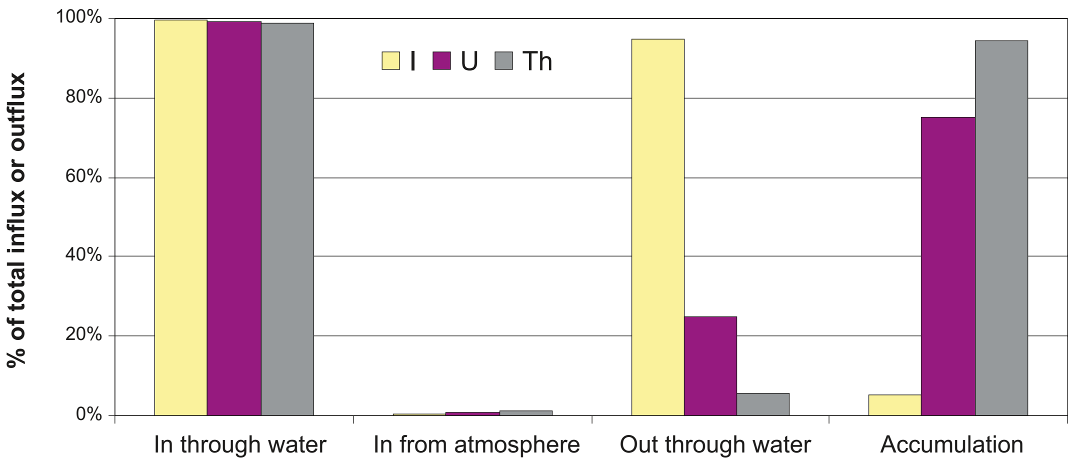


Figure 4-39. *Fluxes of iodine, uranium and thorium into and out of Frisksjön (% of total influx and % of outflux, respectively).*

In terms of mass, different elements dominate the fluxes to and from the lake. The largest contributions to sediment accumulation are from silicon, carbon, iron, aluminium, sulphur and nitrogen. Silicon, carbon and nitrogen are common elements in biota, whereas iron is common in humic substances. Some metalloids and metals, i.e. silver, mercury, tantalum and thallium have the lowest accumulation rate in sediment in accordance with their uncommonness in nature. Among the 16 elements for which atmospheric deposition has been measured some ions; Cl, Na and Ca, as well as carbon, dominate. The inflow as well as the outflow via water is dominated by carbon, sulphur and calcium. The fourth most important element in the inflow in mass terms is silicon, but this element is the sixth most important outflow. This can be explained by high sediment accumulation of silicon and the lakes can be considered a sink for this element. Mercury is the smallest contributor to inflow as well as to outflow via water.

The mass fluxes are not balanced, and outfluxes exceed the influxes for most elements; this is especially true for the mass fluxes of lanthanides which appear to be very unbalanced. 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 elements. A large degree of 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 time independent and the present sediment accumulation seems to somewhat overestimate the mass fluxes of elements to the sediment. This may also be the case with the estimates of lanthanide sedimentation. Thus, there is a degree of uncertainty in the mass balances, which is further discussed in /Nordén et al. 2008/.

Chemical composition of biotic and abiotic pools

The most common elements in Frisksjön (including all components: dissolved in water, particulate matter in water, biota and sediment) are silicon (38% of total mass of investigated elements) and carbon (37% of total). Other elements with substantial contributions to total mass are sulphur (5%), nitrogen (5%), aluminium (4%), iron (4%), and calcium (2%), whereas all other elements make up 1% or less of the total mass of investigated elements in the lake (hydrogen and oxygen, the elements of water are not included in the analysis).

The abiotic component (sediment, dissolved in water, and particulate matter in water) makes up 99.998% of the total mass of investigated elements and, accordingly, this component has the same distribution of elements as the total lake ecosystem. All elements are strongly concentrated in the sediment component (97 to 100% of total element pools).

A major part of the deeper sediment can be assumed to be unavailable for the biotic processes in the lake, and it is therefore of interest to evaluate the distribution of elements in the ecosystem when excluding the deeper sediments (i.e. sediments below 1 cm depth, and thereby only including the aerobic part of the sediment). After excluding the deeper sediment, many elements are still strongly concentrated to the sediment, but there are also some elements (Sb, Ca, Na, Mg, I, Cl, Br, F) that occur mainly in the dissolved phase of water. There is also a considerable amount of some elements in the biotic component, i.e. zinc, phosphorus and nitrogen. In the abiotic component in lake water, most elements mainly occur in the dissolved component, and amounts in the particulate component are considerably smaller.

The biotic component, which only makes up 0.002% of total mass in Frisksjön, is dominated by carbon followed by nitrogen (64% and 12% of total biotic component, respectively). Calcium, silica, phosphorus, sodium, chlorine and zinc each make up 2% or more of the total mass of investigated elements in the biotic components, whereas each of all other elements makes up 1% or less of the biotic components. Within the biotic components, there is a clear difference in distribution of elements among different functional groups (Figure 4-40). Metals have a higher share present in primary producers than lanthanides that are strongly associated with consumers. In total, most elements are more associated with the consumers and on average 66% of elements in the biotic component are present in consumers.

Mercury is an element known to show biomagnification in nature and thus one would expect to find a high share of this element in the top predator fish. This is the case; 75% of biotic mercury is present in fish (the true percentage is probably somewhat lower as data for bacteria are missing).

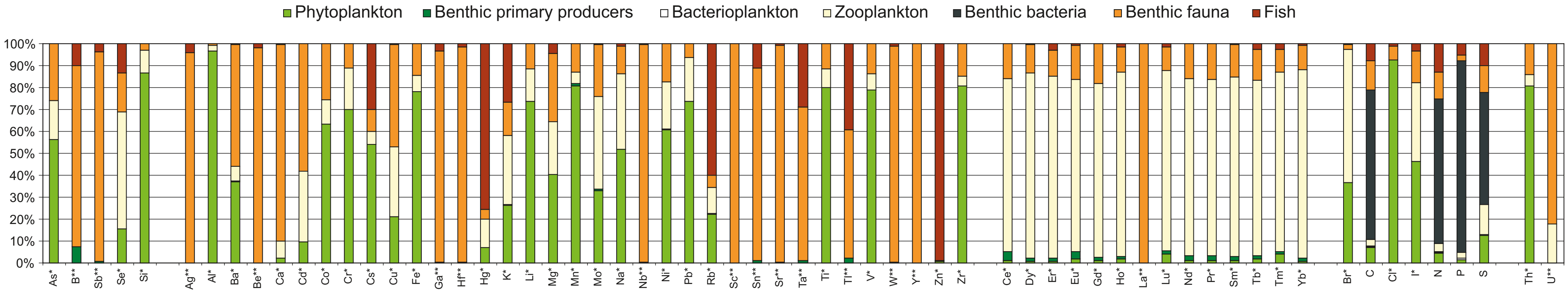


Figure 4-40. *Distribution of a number of elements among the biotic components of the ecosystem in Frisksjön. * indicates missing data for bacterioplankton and benthic bacteria. ** indicates missing data for at least one more functional group in addition to bacterioplankton and benthic bacteria. (From Chapter 7 in /Nordén et al. 2008/).*

Likewise, zinc and rubidium are strongly associated with fish (99% and 60%, respectively of total biotic pools). Lanthanides have a strong association with zooplankton, whereas most metals have a higher occurrence in benthic fauna. In addition to the lanthanides, bromine is also strongly associated with zooplankton. The reason for the association of bromine and lanthanides with zooplankton is unknown but this association of bromine is seen also in Forsmark lakes and in the marine areas /Wijnbladh et al. 2008/. For all elements except carbon, phosphorus, nitrogen and sulfur, data on the chemical composition of bacteria is missing. A large part of the biotic C, N, P and S is present within bacteria (69, 67, 88, and 57% of total biotic mass of each element, respectively) and thus, the association of elements with the consumer component of the biota may be even larger than suggested by Figure 4-40.

4.7.4 Conclusions

Both the carbon ecosystem model and mass balance for Lake Frisksjön indicate negative net ecosystem production, i.e. higher respiration than primary production. The carbon mass balance shows that the lake receives large influxes of organic matter from the catchment and that these influxes are to a large extent mineralised to CO_2 and emitted to the atmosphere. A large part of the carbon influx is also contributing to the sediment accumulation in the lake. Thereby, the lake may significantly alter the terrestrial export of organic carbon to the sea. The inflow of carbon is in the same order as the internal processes primary production and consumption, and there is a large probability of carbon entering the lake being incorporated into the lake food web. A relatively large part of the primary produced carbon (34%) is transported upwards in the food web. Thus, there is a large probability for any element incorporated into organic matter by primary production to be further transported upward in the food web. The major pathway to the top predator fish goes from benthic bacteria, via benthic fauna to fish. Thus, pollutants settling on the sediment could easily be reincorporated into the food web.

Mass balances for a number of elements indicate that generally, the most important influx is via water and the most important outflux is via sediment accumulation. This indicates that the lakes may be important sinks of elements in the catchment, as elements are bound into the sediments. However, most mass fluxes of elements in Frisksjön are unbalanced and the sediment accumulation is probably somewhat overestimated.

Overall, the main conclusion from the mass balances for all elements and from the carbon ecosystem model is that Frisksjön has a negative net ecosystem production and processes large amounts of organic carbon and thereby may be an important site for biogeochemical processes in the landscape.

4.8 Marine ecosystems

4.8.1 General description

As described above, the marine ecosystem in Laxemar-Simpevarp includes 19 marine basins (see Figure 3-14, Section 3.9), which together cover a total area of 119 km^2. Most of the area consists of shallow coastal bays. The mean depth in the area is 5.1 m and the annual mean water temperature is 7.2°C. The annual mean salinity for the area varies from 5.5 to 6.7 psu, with slightly higher salinity in the more offshore sampling areas, and lower salinity in the bays due to freshwater influence from land. The nitrogen and phosphorus levels are low to moderately high, and the chlorophyll concentrations are high, compared with national environmental monitoring data from the area. Phosphorus seems to be the limiting nutrient in the coastal bays in the area, whereas nitrogen is limiting in the more offshore areas, similar to the general conditions in the Baltic proper.

The distribution of post-glacial sediments in the area is typical of that in a coastal landscape characterised by fissure valleys, showing sediment accumulation in the sheltered bays, and bare bedrock, till and boulders along the exposed coast. The benthic area can be divided into three categories with more or less distinct characteristics with regard to factors like wave exposure, light penetration and substrate type. These categories are; secluded bays, shallow exposed archipelago and deep exposed areas. The bays are characterised by soft bottoms, low water transparency depth (annual mean 2–3 m) and low degree of wave exposure, whereas the archipelago and the outer exposed areas have an annual visibility of 4–7 m and 12 m, respectively, and are dominated by hard bottom substrates.

The vegetation on inner soft-bottom parts is dominated by *Chara sp*. and vascular plants. On the outer, more exposed areas with hard bottom substrate, red algae dominate. The benthic fauna in the secluded bays with soft bottoms is dominated by the bivalve baltic mussel (*Macoma baltica*). In the more exposed hard bottom areas, the blue mussel (*Mytilus edulis*) is completely dominating both in terms of abundance and biomass. Perch (*Perca fluviatilis*) dominates the fish community in the bays, whereas herring (*Clupea harengus*) is most common in the more exposed archipelago.

4.8.2 Ecosystem model

Total biomass in the area is unevenly distributed, and is mainly focused to the shallow areas along the coast. It varies from just over 2 gC m^{-2} to 450 gC m^{-2} in the various basins. The mean biomass in the whole area is 91 gC m^{-2}, resulting in an estimated total of 10,430 tonnes of carbon fixed in biota in all basins. The biomass in most basins is dominated by macrophytes, comprising between 26 and 80% of total biomass in the various basins. In the more off-shore, exposed basins, benthic filter feeders (blue mussels) dominate the biomass, but for the whole area they constitute 28% of the biomass. Organisms other than macrophytes and blue mussels contribute, with a few exceptions, less than 10% each to the total biomass in the area (see Figure 4-41 and Table 4-21).

Net Primary Production (NPP) is highest along the shoreline, but is also relatively high in the off-shore areas where larger depths and higher water transparency permit high phytoplankton production (Figure 4-42). The annual mean for NPP in the whole area is 170 gC m^{-2} y^{-1}.

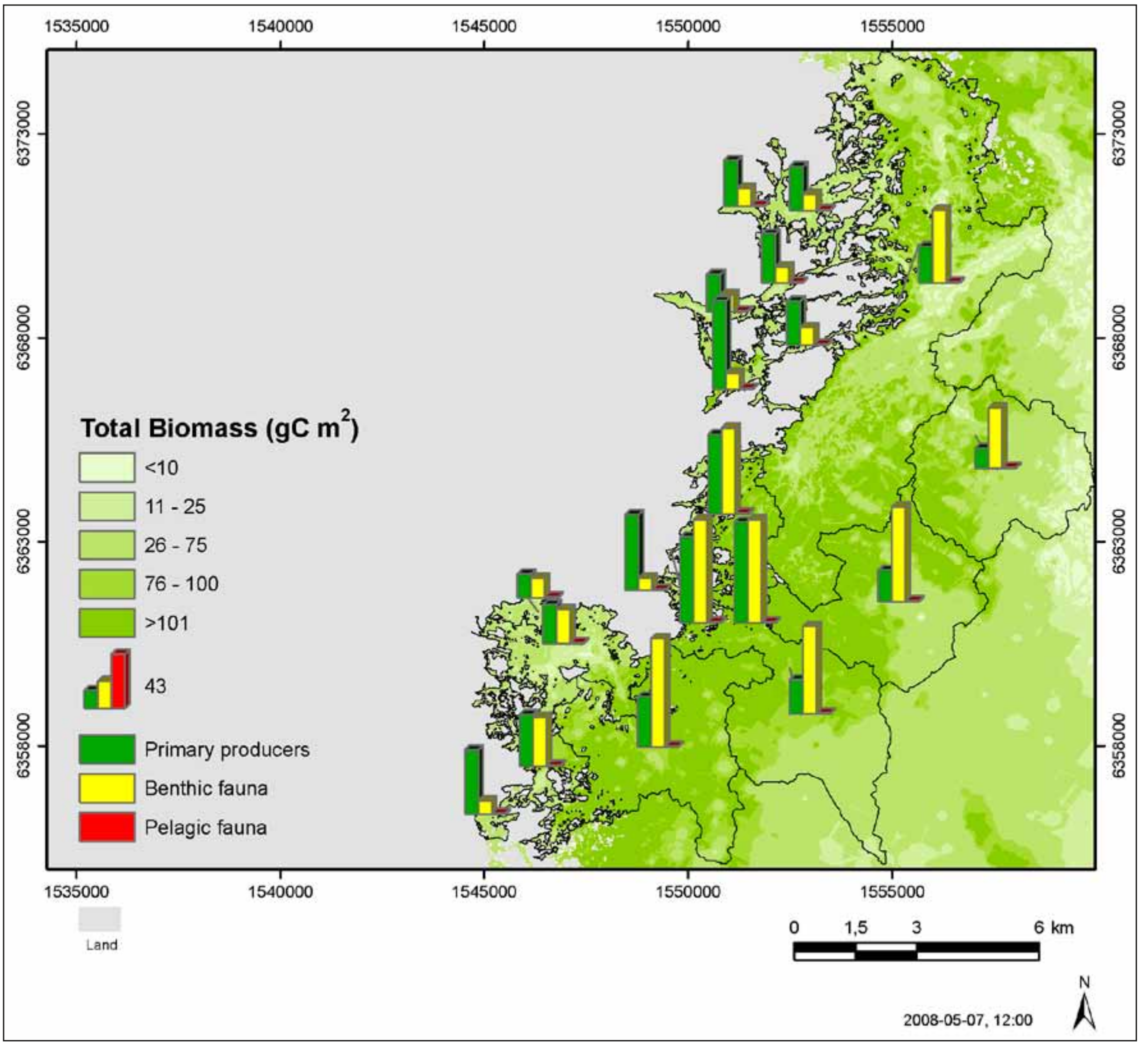


Figure 4-41. *Total biomass (green shading) and biomass of different functional groups in each of the basins (bars) in the marine parts of the Laxemar-Simpevarp area (annual averages, gC m*$^{-2}$*).*

Table 4-21. Annual average biomass of different functional groups in the marine ecosystem in Laxemar-Simpevarp (gC m^{-2}).

Basin	Macro-phytes	Micro-phytes	Phyto-plankton	Bacterio-plankton	Benthic bacteria	Benthic carnivores	Benthic detrivores	Benthic filter-feeders	Benthic herbi-vores	Benthi-vorous fish	Pisci-vorous fish	Plankti-vorous fish	Zoo-plankton	Seal	Bird	Total
Basin 524	26	1.2	0.2	0.3	1.7	0.3	11	52	4.2	0.2	0.02	0.4	0.08	0.005	0.002	**98**
Basin 525	38	2.2	0.1	0.2	0.7	0.3	10	69	5.5	0.2	0.03	0.4	0.05	0.005	0.01	**127**
Basin 522	15	0.6	0.4	0.4	1.1	0.2	7.2	37	2.8	0.2	0.01	0.4	0.1	0.005	0.0001	**65**
Basin 523	24	1.1	0.2	0.3	0.6	0.2	8.8	61	4.4	0.2	0.01	0.4	0.08	0.005	0.001	**101**
Basin 521	27	1.3	0.3	0.3	1.1	0.3	7.8	45	3.6	0.2	0.04	0.4	0.09	0.005	0.004	**87**
Basin 501	35	1.3	0.1	0.1	4.2	0.7	2	5	1.7	0.4	0.3	0.1	0.05	0.005	0.01	**51**
Basin 500	32	2.6	0.1	0.05	3.1	0.7	2.2	5	2.1	0.3	0.3	0.1	0.03	0.005	0.02	**49**
Basin 504	37	1.6	0.2	0.1	4.3	0.7	2.3	4	1.7	0.3	0.3	0.1	0.06	0.005	0.01	**53**
Basin 502	29	1.0	0.2	0.1	5.7	0.7	2.4	4	1.5	0.3	0.3	0.1	0.08	0.005	0.01	**45**
Basin 506	33	1.1	0.2	0.1	4.6	0.7	2.2	5	1.7	0.4	0.3	0.1	0.05	0.005	0.01	**49**
Basin 508	68	1.7	0.1	0.04	5.0	0.9	2.3	4	1.5	0.4	0.3	0.1	0.05	0.005	0.02	**84**
Basin 513	60	2.9	0.1	0.1	1.3	0.5	8.2	53	5.3	0.3	0.1	0.3	0.03	0.005	0.01	**132**
Basin 514	77	3.2	0.1	0.1	0.9	0.5	9.8	65	6.4	0.3	0.0	0.4	0.03	0.005	0.01	**164**
Basin 516	55	5.2	0.01	0.004	0.7	0.9	1.7	4	3.4	0.3	0.3	0.1	0.00	0.005	0.02	**72**
Basin 518	64	3.4	0.1	0.1	1.1	0.5	10	63	6.2	0.3	0.0	0.4	0.02	0.005	0.01	**149**
Basin 515	17	1.6	0.1	0.1	4.2	0.5	2.7	7	1.6	0.2	0.3	0.1	0.04	0.005	0.02	**35**
Basin 517	28	2.7	0.1	0.1	2.4	0.5	3.4	18	2.6	0.2	0.2	0.2	0.04	0.005	0.01	**58**
Basin 520	37	3.6	0.1	0.1	0.5	0.5	3.8	30	3.5	0.3	0.1	0.3	0.03	0.005	0.01	**80**
Basin 519	46	5.2	0.01	0.01	0.7	0.9	1.8	4	3.3	0.3	0.3	0.1	0.00	0.005	0.01	**63**

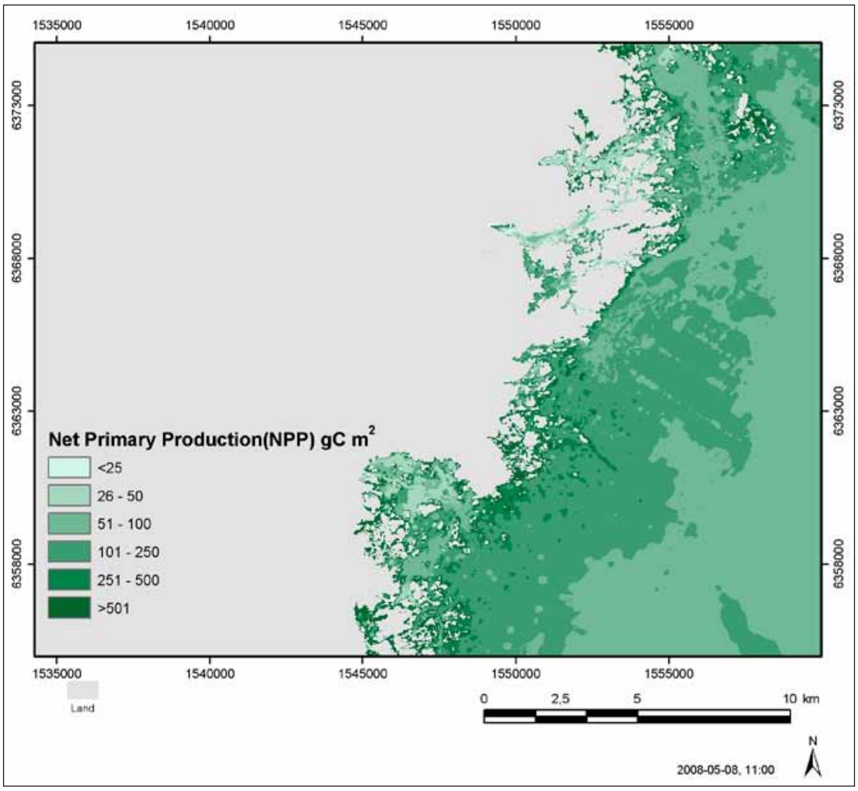


Figure 4-42. *Net Primary Production (NPP, gC m^{-2} y^{-1}) in marine parts of the Laxemar-Simpevarp area. Higher NPP is indicated by darker green colour.*

Due to the high biomass and the corresponding high respiration rate of blue mussels in the more exposed basins, the respiration (R) is largest in these more offshore areas. The second largest contribution to the respiration comes from benthic bacteria, mainly on soft bottoms in secluded bays, which can be seen in Figure 4-43.

The marine area as a whole is heterotrophic, i.e. more carbon is released than is fixed in biomass. This means that Net Ecosystem Production (NEP=NPP-R) is negative, which is the case for most of the basins (see Figure 4-44). Generally, all basins located in the more exposed areas are heterotrophic, whereas some basins with high macrophyte biomass, mainly inner bays, tend to be autotrophic.

4.8.3 Mass balances

Pools and fluxes of carbon were calculated for individual basins, as well as for the whole marine area. The major carbon pool in the marine area as a whole is contained in the water, in the form of dissolved inorganic or organic carbon (DIC and DOC). Dissolved carbon constitutes 54% of the carbon pool in the marine part of the regional model area, followed by sediment (21%), consumers (16%), and producers (9%). However, in some individual basins, mainly secluded inner bays, the sediment constitutes the major carbon pool. The major flux of carbon in the area is the advective flux; all other fluxes, including burial, are small in comparison. As an example of mass balance calculations, pools and fluxes of carbon in the autotrophic Basin 508 (see Figure 3-14 for location) are presented in Figure 4-45.

The relative abundance of different elements (based on masses and besides H and O) in all ecosystem components (i.e. biota, dissolved in water, particulate matter and top 10 cm of sediment) for the whole model area is presented in Figure 4-46. The most abundant elements are the major constituents of sea water (Cl, Na, Mg and Ca). The marine model area at Laxemar-Simpevarp contains on average 32 kg m^{-2} of the most abundant element, Cl, whereas the total amount of carbon is 0.4 kg m^{-2} on average (Table 4-22).

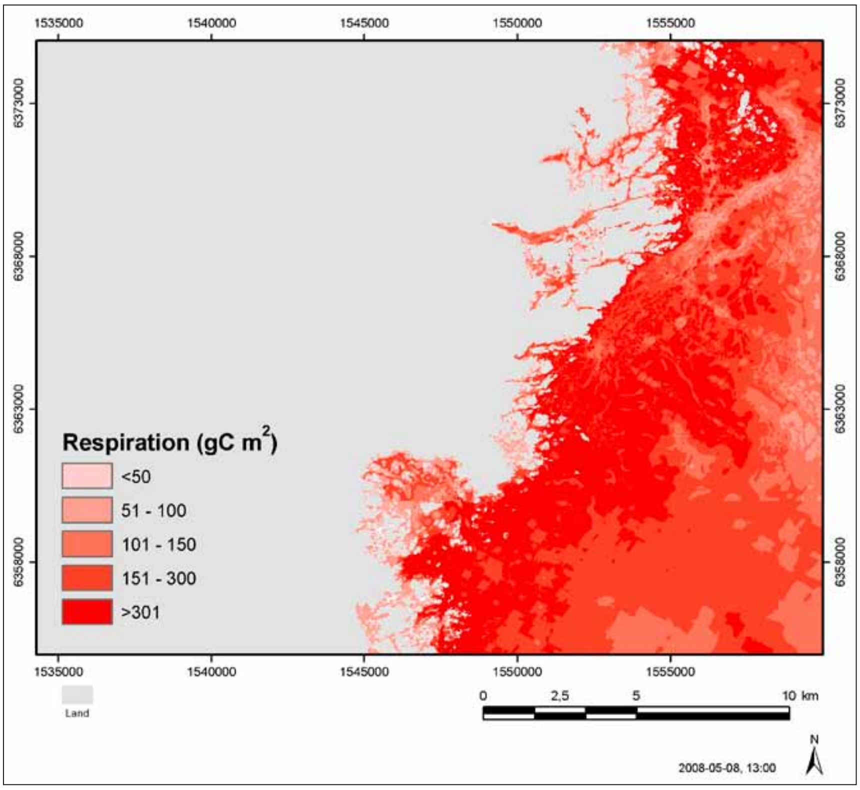


Figure 4-43. *The sum of consumer respiration (gC m^{-2} y^{-1}) in the Laxemar-Simpevarp area. Higher respiration is indicated by darker red colour.*

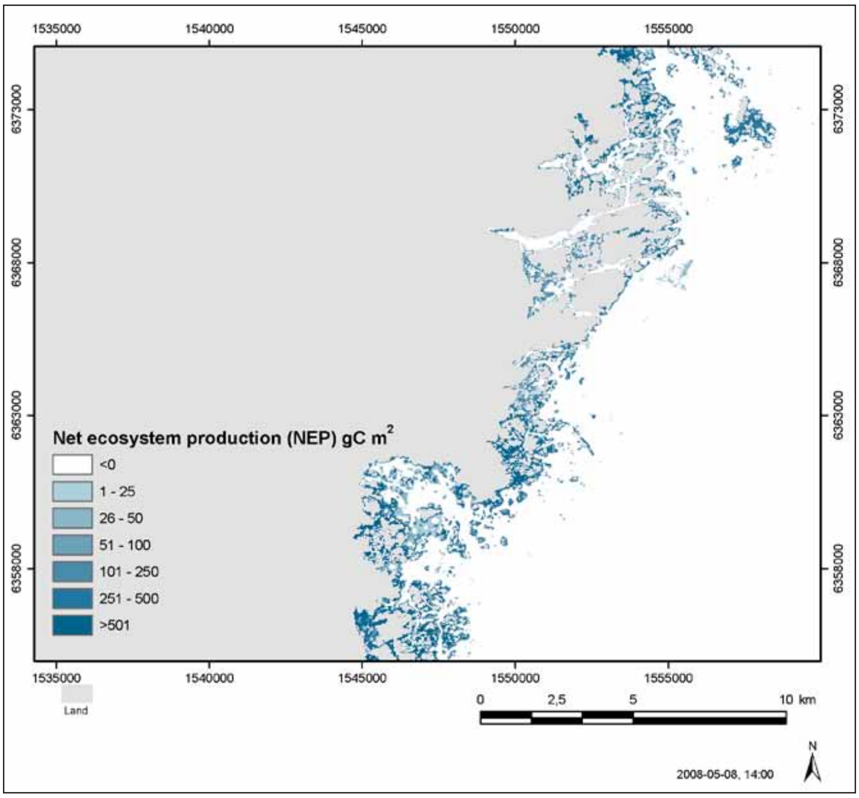


Figure 4-44. *The net ecosystem production (NEP) (gC m^{-2} y^{-1}) in the marine basins in the Laxemar-Simpevarp area. Higher NEP is indicated by darker blue colour.*

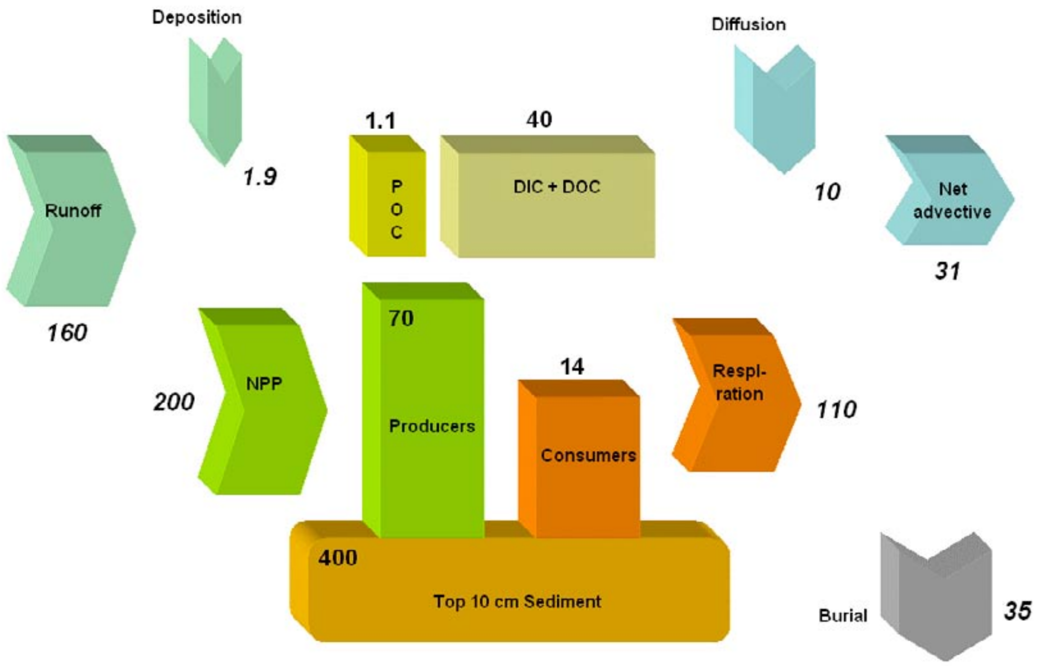


Figure 4-45. *Major pools (gC m^{-2}) and fluxes (gC m^{-2} y^{-1}) of carbon in to and out from Basin 508 in the Laxemar-Simpevarp area. Boxes and arrows denote the relative (square root transformed) sizes of pools and fluxes, respectively. NPP and respiration should be regarded as internal processes in the ecosystem, but are included in the figure for comparison with the major fluxes in to and out from the basin.*

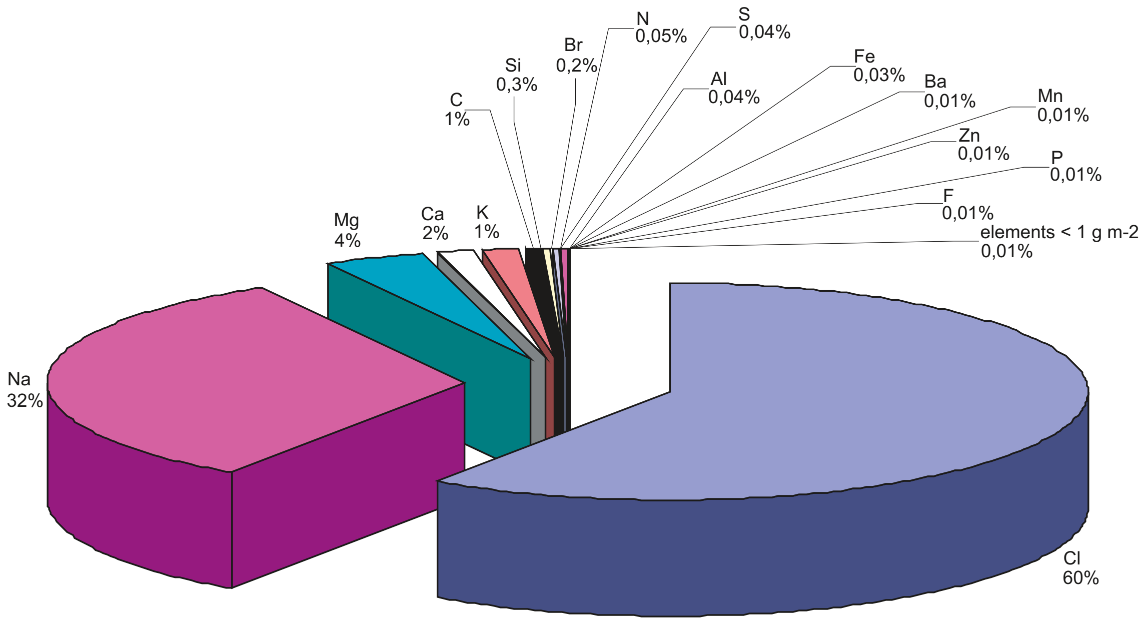


Figure 4-46. *Relative abundance of different elements (based on masses and excluding O and H) in all ecosystem components in the marine model area of Laxemar-Simpevarp, cf. Table 4-22.*

Table 4-22. Abundance of different elements, in total and per m², in the marine model area of Laxemar-Simpevarp. The macronutrients C, N, P are presented first, followed by the other elements in decreasing order of abundance.

Element	Total amount (tonnes)	(g m^{-2})	Element	Total amount (tonnes)	(g m^{-2})
C	**43,256**	**32**	Nd	6	0.05
N	**3,172**	**27**	Cu	5	0.05
P	**428**	**4**	Zr	5	0.04
Cl	3,782,910	31,845	Cr	4	0.03
Na	2,050,584	17,262	Ni	4	0.03
Mg	246,345	2,074	Yb	4	0.03
Ca	104,939	883	Pb	3	0.03
K	79,666	671	V	3	0.02
Si	17,361	146	Mo	2	0.02
Br	14,374	121	As	2	0.01
S	2,595	22	Pr	1	0.01
Al	2,382	20	Co	1	0.008
Fe	1,974	17	Sm	1	0.006
Ba	792	7	U	1	0.006
Zn	595	5	Gd	1	0.005
F	518	4	Th	1	0.005
Mn	517	4	Cd	0	0.004
Er	71	0.6	Cs	0.3	0.002
Ti	66	0.6	Se	0.2	0.002
Ho	66	0.6	Tb	0.2	0.001
Dy	65	0.5	Eu	0.2	0.001
Li	36	0.3	Lu	0.1	0.0005
Rb	29	0.2	Tm	0.1	0.0005
I	20	0.2	Hg	0.01	0.00009
Ce	9	0.08			

The distribution of elements among the abiotic (sediment, particulate matter and dissolved phase) and biotic ecosystem components is presented in Figure 4-47. The largest amounts of most elements are found in the abiotic components. However, for some of the non-metals and metalloids, a significant part of the total amount occur in biota.

Iodine, uranium and thorium are three elements that are of special interest for the safety analysis. Due to their different biogeochemical characteristics, the distributions of these elements among the abiotic and biotic ecosystem components were studied in more detail. The largest pool for all these three elements is contained in the sediment, which is exemplified by the results from Basin 508 in Figure 4-48. The distribution of iodine differs from that of the other two elements in that considerably more of this element is found dissolved in the water and in the biotic components.

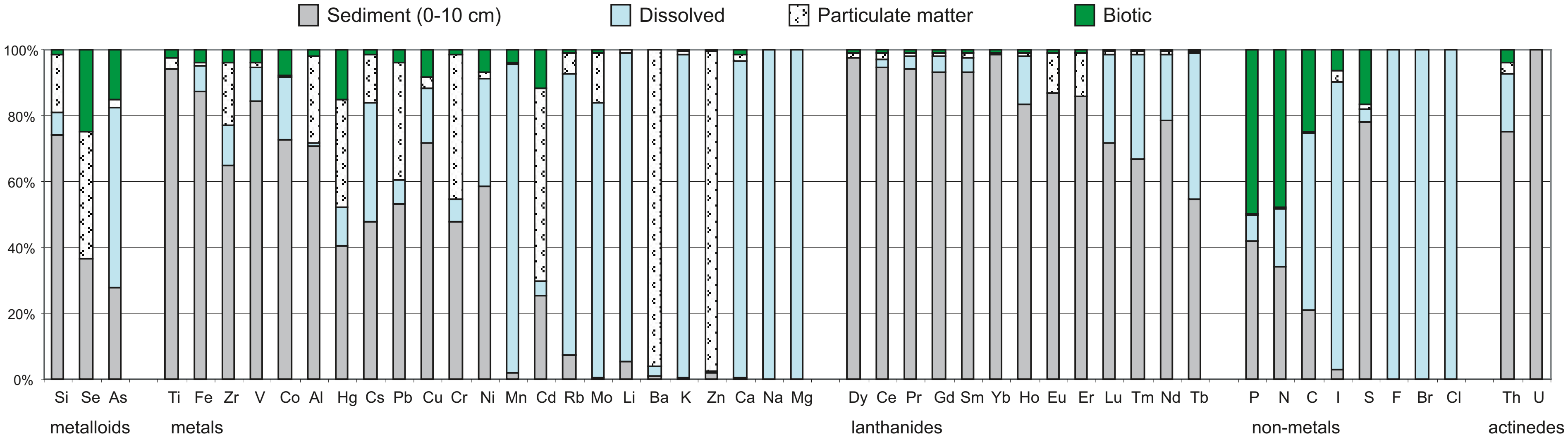


Figure 4-47. *Distribution of different elements among the different ecosystem components in the marine model area of Laxemar-Simpevarp.*

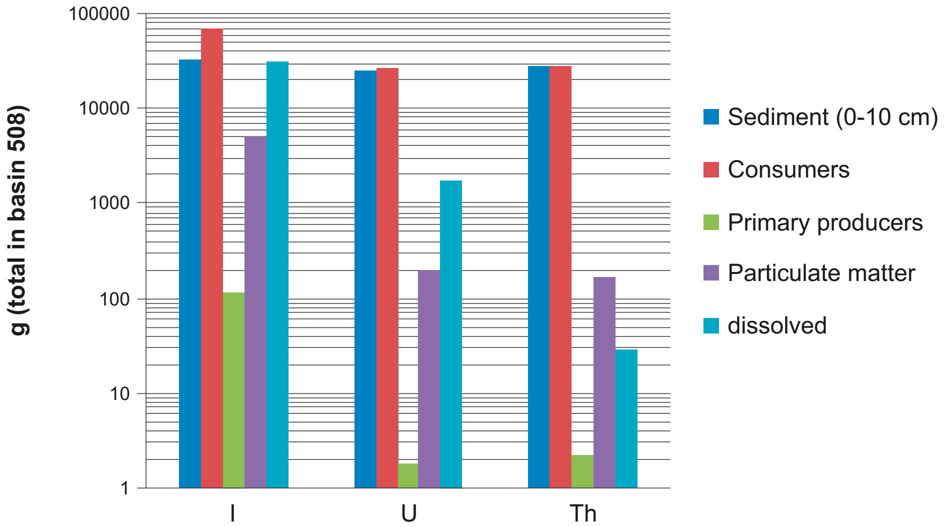


Figure 4-48. *Distribution of iodine, thorium and uranium in biotic and abiotic ecosystem pools in Basin 508 represented as total amount in g. Note the logarithmic scale.*

4.8.4 Conclusions

Below follows the main conclusions from the marine ecosystem models and the mass balance calculations concerning the marine ecosystem at Laxemar-Simpevarp.

- Filter feeders, mainly blue mussels *(Mytilus edulis)*, show the highest biomass of all organism groups in the marine system. However, in some basins, especially in secluded shallow bays, macrophytes dominate the biomass.
- Net Primary Production (NPP) is highest along the shoreline, but is also relatively high in deeper areas with high water transparency.
- The area as a whole is heterotrophic, i.e. more carbon is released than is fixed in biomass. However, some shallow bays in the area with high macrophyte biomass tend to be autotrophic.
- Overall, for the whole area, dissolved carbon in the water phase (DIC and DOC) constitutes the major carbon pool. This is true also for most of the individual basins, but in some of the inner, secluded bays, the sediment constitutes the largest carbon pool.
- The advective flux of carbon between basins, driven by the water fluxes, is the major carbon flux. The second largest flux is contained in the terrestrial runoff, followed by burial of carbon in the sediment.
- The most abundant elements in the marine ecosystem are the major constituents of sea water (Cl, Na, Mg and Ca). The largest amounts of most elements are found in the abiotic components of the ecosystem. However, for some of the non-metals and metalloids, a significant part of the total amount occurs in biota.

4.9 Human population and land use

The following description of the human population and the human land use in Laxemar-Simpevarp is based on the picture given in /Miliander et al. 2004/. The resulting carbon flows to humans from several drainage areas in Laxemar-Simpevarp presented in Section 4.9.3, comprise input data to the terrestrial ecosystem carbon budget in /Löfgren (ed.), 2008/.

4.9.1 Description of the human population in Laxemar-Simpevarp

The Laxemar-Simpevarp regional model area has a low population density (7.4 ind km^{-2} in 2002) and the number of inhabitants has diminished slowly during the 1990s. In total 940 people lived in the regional model area in 2002. The population density is one third of the average density in Kalmar County. 56% of the inhabitants were over 45 years of age compared with 47% in Kalmar County.

The inhabitants live in one- or two- family houses (49.6% of the properties) or in farmhouses (20.5%). There are few multi-dwelling houses (2.2%). In 2002 there were 131 holiday houses in the area and they represent one fifth of the properties, which corresponds to the situation in Kalmar County as a whole. The property density in the Laxemar-Simpevarp area is approximately half the density in Kalmar County. As to new building per unit area, development in the area was almost at the same rate as in the county during the period 1993–2002. On average 1.9 multi-dwellings (no one- or two-family dwellings) were constructed and 2.6 building permits were granted per year between 1993 and 2002.

The ill-health (number of days with sickness benefit or early retirement pension per year and person between 16 and 64 years of age) increased between 1998 and 2002 in Laxemar-Simpevarp as well as in Kalmar County, from 40 in 1998 to 52 in 2002. The increase was of the same magnitude in both Laxemar-Simpevarp and Kalmar County.

The main employment sector is within electricity production and it covers 84% 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 14% is working in that sector. There is, accordingly, a clear net ingoing commuting to the Laxemar-Simpevarp area during day-time due the dominant employer, the OKG Power Company that operates Oskarshamn nuclear power plant. There were, in total, 87 work places within the Laxemar-Simpevarp area in 2002. The majority, 36 sites, are within the business group Agriculture, forestry, hunting and fishing.

Manufacturing industry is the main employment sector among the inhabitants of the Laxemar-Simpevarp area (night-time population). 25% of the inhabitants work within that type of business, whereas 17% work within the second largest type of business, Health and social work.

In the Laxemar-Simpevarp area, 12.3% of the total population was in average non-employed (1997–2001), which was the same magnitude as in Oskarshamn municipality (12.7%) and somewhat lower than in Kalmar county (13.9%). The early retired are proportionately more numerous in Laxemar-Simpevarp than in Kalmar County. Students, the other hand, are proportionately less numerous.

4.9.2 Description of human land use in Laxemar-Simpevarp

The land use in the Laxemar-Simpevarp area differs from the average land use in Kalmar County (Table 4-23). The forest area is far more dominant in the Laxemar-Simpevarp area than in Kalmar County. The proportions of arable land and "other" land types are considerably lower in the Laxemar-Simpevarp area.

Forestry

The forests are influenced by forestry; approximately one third of the forest within the regional model area is younger than 30 years. The average age of the productive forest in the area is approximately 60 years (cf. Table 4-14 in /Löfgren (ed.) 2008/). About one quarter of the logging products are used for pulp production and the rest are used as timber /Miliander et al. 2004/.

Table 4-23. Land use in Kalmar County and the Laxemar-Simpevarp area /Miliander et al. 2004/.

Type of land use	Kalmar county		Laxemar-Simpevarp area	
	Area (hectares)	Percentage distribution (%)	Area (hectares)	Percentage distribution (%)
Arable land	134,878	12	556	4.4
Grazing land	53,007	4.5	465	3.7
Forest	728,605	62	11,251	89
Developed	18,551	1.6	125	1.0
Water	49,470	4.2	268	2.1
Other (wetlands bare rocks, pits etc)	182,049	16	41	0.3
Total	**1,166,560**	**100**	**12,706**	**100**

Source: Areas for Kalmar län from the report Markanvändningen i Sverige, /Table B24 in SCB 1998/:
Areas for Laxemar-Simpevarp calculated from the vegetation classification /Boresjö Bronge and Wester, 2003/

Agriculture

The agriculture in the area is of limited extent. The agricultural area (arable land and grazing land) comprises only 8.1% of the total land area, compared with 16.1% in Kalmar County. Agricultural statistics obtained from Statistics Sweden for the area (area definition in /Miliander et al. 2004/), show that 21% of the arable area (138 ha) is used for seed production and the rest is used for fodder and silage production (see Table 4-24) /Löfgren (ed.), 2008/. The total agricultural area is 1,021 ha, of which 556 ha is arable area and 465 ha is grazing area according to the vegetation map. Hence, seeds are only produced on 13.5% of the total agricultural (field) area. The rest of the agricultural area is assumed to be used for fodder production and grazing (883 ha). The spectrum of cultivated crops in the Laxemar-Simpevarp area is wide; all the crops grown in the county can also be found in the Laxemar-Simpevarp area except for potatoes, sugar beet and oil seed crops. However, barley is the totally dominant crop in the area, covering 66% of the cultivated area (pasture and fodder area excluded).

Table 4-24. Arable land use in the Laxemar-Simpevarp area /Löfgren (ed.), 2008/.

Cultivated crops in the Laxemar-Simpervarp area	Average percentage of the arable area (1995+1999)
Grain, vegetables:	
Winter wheat	0.8
Rye	1.0
Barley	13.8
Oats	3.5
Triticale wheat, mixed grain	0.6
Leguminous plants	1.8
Total:	**21.4**
Fodder, grass:	
Green fodder, plants for silage	2.2
Grass on arable land for hay or silage	51.8
Pasture, seed lay	12.0
Other plants	0.3
Bare fallow, untilled arable land	10.2
Pasture/arable land not utilized	2.1
Total:	**78.6**

The farm density in Laxemar-Simpevarp is on average only 0.2 farms km^{-2} which is somewhat lower than in the county (0.35 farms km^{-2}). There were in total 27 farms (>2 ha) in Laxemar-Simpevarp in 1999.

The total amount of arable land has decreased slightly in Kalmar County between 1990 and 1999, but not in Laxemar-Simpevarp. The amount of land classified as grazing has increased in general in the county, and more significantly in the county as a whole than in Laxemar-Simpevarp. Furthermore, the total number of farms has decreased in general in the county. Larger farms have increased in number though, which means that farms have become fewer but larger.

Crop production

The productivity of the land in the Laxemar-Simpevarp area is below (approximately 84%) the average productivity in the county, when comparing the standard yields for barley. The productivity of barley in Kalmar County is also lower than the average yield in Sweden.

The far most dominating crop is barley (see Table 4-24). Its significance has grown during the 1990s. The average production of barley, including treshing loss and straw yield, calculated from standard yield in the survey district SKO-area 0814 in which Laxemar-Simpevarp is situated, is listed in Table 4-25. The standard yield is the yield of seeds that are gathered during the harvest (straw yield and threshing loss excluded).

Animal product production

The livestock of the domestic animals in the area (area definition in /Miliander et al. 2004/) has been obtained from Statistics Sweden and is compiled in /Miliander et al. 2004/ together with calculated values of the meat and milk production. The production values have been divided by the total area for grazing and fodder production in Laxemar-Simpevarp (see Table 4-26). There are 62 cows, 36 pigs and 7 sheep per km^2 in Laxemar-Simpevarp.

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 cow density in Laxemar-Simpevarp is higher, which can be explained by the fact that only 63% of the cow fodder is self-produced by the farms and the rest is purchased /Swedish Dairy Association 2007/.

Horticulture, aquaculture, mineral extraction

There is no horticulture within Misterhult parish. There is one aquaculture for recreational crayfishing approximately 12 km north of Oskarshamn, near Virkvarns airport in Misterhult parish. There are three active leases for mineral extraction in the parish, all for extraction of decorative stone, none within Laxemar-Simpevarp (Å. Axheden, Länsstyrelsen i Kalmar län, pers. comm.).

Table 4-25. Seed production, including threshing loss and straw yield, in the yield survey district (SKO-0814), county and country /Löfgren (ed.) 2008/.

Standard yield		kg fw/ha		gC $m^{-2}y^{-1}$	
		Mean	SD	Mean	SD
Grain (barley)	Laxemar-Simpevarp (SKO-0814)[1]	4,800	235	190	9
	Kalmar County[2]	5,710	278	226	11
	Sweden[2]	6,184	65	245	3

[1] (SCB 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007)
[2] Mean value for 2003–2006 from www.scb.se, accessed 4 Dec. 2007

Table 4-26. Production of animal products (live biomass and utilized meat), milk and eggs in Laxemar-Simpevarp (average figures for the years 1995 and 1999) presented as carbon per area and year /Löfgren (ed.), 2008/.

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	1,084	342	6,027	
Sheep	17	4		
Pigs	827	353		
Chicken		25		43
Total		**723**	**6,027**	**43**

Water supply

The water use within Laxemar-Simpevarp in the year 2000 has been roughly calculated based on the water use within Oskarshamn municipality the same year as well as the number of inhabitants, work places, farms and holiday houses in Laxemar-Simpevarp. Some assumptions had to be made in order to calculate the water use and the water withdrawal. These assumptions are described in /Miliander et al. 2004/.

The freshwater use at Oskarshamn nuclear power plant (OKG) represents approximately 50% of the total water use within Laxemar-Simpevarp. As the power plant uses water from the lake Götemar, the main part of the withdrawal in the parish is surface water.

The number of work places in the parish is low, only 4% of the work places in Oskarshamn municipality. The water use within the industry sector, excluding the nuclear industry, is therefore estimated to be low, only 7%. In Sweden as a whole industry comprises approximately 65% of the water use. The total withdrawal (surface water and groundwater) of water in Laxemar-Simpevarp is calculated to be 338,400 m^3 per year.

Coastal fishing

Kalmar County is the fifth largest fishing county in Sweden and it contributes more commercial fishing than the rest of the east coast altogether. Fishery is not a very common employment in Oskarshamn municipality though. Fishermen in Borgholm and Västervik municipality catch the main part of the fish. The number of commercial fishermen living in the parish is not known. The statistics indicate that there might be one logbook- or journal-keeping fisherman in the parish.

In the off-shore grid (EU-grid) outside the coast of Kalmar, the catch is predominantly from square 44G7, which begins approximately 10 km northeast of Laxemar-Simpevarp. The average catch has been 4,479 kg km^{-2}, between 1995 and 2002. Among the EU-squares along the coastline, the catch per unit area is largest in square 43G6, in which Laxemar-Simpevarp is located (1,728 kg km^{-2}).

There are eight commercial receivers within Kalmar County that buy fish from small as well as large vessels fishing off the coast of Kalmar County. Fishermen living in Kalmar County caught 4,560 tonnes of fish in 2002, according to the National Board of Fisheries. The same year the commercial receivers in Kalmar County received 18,645 tonnes of fish. This indicates that the receivers obtain fish from vessels coming from other counties. The National Board of Fisheries considers the commercial fishing outside Kalmar County as relatively intense (R. Lundgren, Fiskeriverket, pers. comm.). Even vessels from the west coast operate in this region. 4% of the received catch is used for animal fodder (fish-meal) and the rest for human consumption.

Outdoor life

Wildlife hunting

The species that are mainly hunted for human consumption are moose, roe deer and hare. The average harvest of moose in the parish and the average harvest of roe deer and hare in the local hunting zone (Oskarshamns Norra jaktvårdskrets) that are given in /Miliander et al. 2004/ are applied to the area of Laxemar-Simpevarp.

According to the figures from the County administrative board in Kalmar, moose hunting is more extensive in Misterhult parish (and presumably also in Laxemar-Simpevarp) than in the municipality and county as a whole (0.35 individuals km^{-2} compared to 0.30 respectively 0.19, in 2003). The harvest has been larger than in Oskarshamn municipality and Kalmar County during the entire dataset (1997–2003). The number of harvested moose·per km^2 reached a peak in 2000.

According to the estimated figures concerning the harvest of roe deer and hares in Laxemar-Simpevarp, the harvest of roe deer has on average been 2.15 individuals km^{-2} in the parish during the period 1997–2001. The harvest of European hare (*Sw: fälthare*) has on average been 0.29 individuals km^{-2}, whereas the harvest of Mountain hare (*Sw: skogshare*) has been 0.10 individuals km^{-2} (see Table 4-27).

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 yield have been estimated by direct field surveys in Laxemar-Simpevarp. 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 five years of data by /Kardell and Eriksson 1987/. The results are presented in /Löfgren (ed.) 2008/.

Fishing

Recreational fishing is a common activity in Misterhult parish, both in lakes and coastal areas. Fishing tourism is well developed and still growing. Marströmmen is a well-known, attractive fishing-water, situated close by the Laxemar-Simpevarp area. There is one fishery administration area in Marströmmen that sells fishing licenses. There are no sport fishing clubs registered in Misterhult parish.

Table 4-27. The harvest of free-living mammals in the Laxemar-Simpevarp area, Oskarshamn municipality and Kalmar County /Miliander et al. 2004/.

Game-hunting	Laxemar-Simpevarp mean ind·km^{-2}	SD	Oskarshamn municipality mean ind·km^{-2}	SD	Kalmar County mean ind·km^{-2}	SD
Moose[1]	0.49	0.10	0.43	0.10	0.29	0.05
Roe deer[2]	2.15	0.99				
European hare[2]	0.29	0.11				
Mountain hare[2]	0.10	0.07				

[1] Statistics from The Administrative Board of Kalmar county for 1997-2003
[2] Statistics from The National Association of Huntsmen (1997-2001), reported for the local hunting zone (Oskarshamns Norra jaktvårdskrets)

Other

There are primarily three areas that are used for recreation in and nearby the Laxemar-Simpevarp area /Ottosson 2006/. These are Ostkustleden, Kråkelund and Hamnefjärden, areas that are frequently used by both tourists and local inhabitants. A hike along Ostkustleden goes through forests and pastures and it is possible to sunbathe, fish and pick wild-berries along the trail. Kråkelund, approximately 5 km northeast of Oskarshamn nuclear power plant, attracts many bird-watchers, but it is also a popular place for scuba divers. Hamnefjärden is a unique water area since the water temperature can be up to ten degrees over the normal temperature due to the outlet of cooling water. The water temperature attracts paddlers all year around and sunbathers until late autumn.

4.9.3 Consumption by humans

The human consumption of animal products and vegetables that originates from different drainage areas in Laxemar-Simpevarp 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 4-28.

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 0814), see Table 4-25. The production in each drainage area has been estimated by multiplying the standard yield by the estimated area for grain production. According to Table 4-24, only 21% of the arable area in Laxemar-Simpevarp is used for production of grain and vegetables for human consumption. This figure has been applied to the drainage areas.

Human consumption of domestic-meat

Domestic animals – a regional generic case

The consumption of beef, pork and mutton has been estimated for each drainage area based on the meat production in Laxemar-Simpevarp (see Table 4-28) and the area for fodder production and grazing in each drainage area. The area for fodder production and grazing is assumed to be equal to the total field area, apart from the 21% of arable cultivation.

Human consumption of game-meat

The estimated harvests of moose, roe deer and hare in Laxemar-Simpevarp are given in Table 4-27. The harvest figures in Table 4-28 correspond to the live biomass of the harvested animals, whereas the consumption figures correspond to the part of the live biomass that is utilized. The human consumption figures are calculated according to /Miliander et al. 2004/.

Table 4-28. Human harvest and consumption (g Cy^{-1}) of game meat, domestic animals, milk and crops in some of the drainage areas of the Laxemar-Simpevarp regional model area (according to the "regional generic case", cf. /Löfgren (ed.) 2008/).

Drainage area		Hunting of moose		Hunting of roe deer		Hunting of European hare		Hunting of Mountain hare		Domestic animals		Milk	Crops
		Harvest[1]	Consumption[2]	Harvest[1]	Consumption[2]	Harvest[1]	Consumption[2]	Harvest[1]	Consumption[2]	Harvest[1]	Consumption[2]	Production and consumption	Production and consumption
Area 6:1	mean	23,117	10,171	12,582	5,536	43	19	59	26	556,486	201,716	1.7E+06	6.5E+06
	± SD	*4,975*	*2,189*	*5,828*	*2,564*	*17*	*7.4*	*43*	*19*				*3.2E+05*
Area 7:1	mean	2,461	1,083	1,339	589	1.5	0.7	7.2	3.2	0	0	0	0
	± SD	*530*	*233*	*620*	*273*	*0.6*	*0.3*	*5.2*	*2.3*				*0*
Area 7:2	mean	20,091	8,840	10,935	4,811	21	9	56	25	228,916	82,978	7.2E+05	2.9E+06
	± SD	*4,324*	*1,903*	*5,065*	*2,228*	*8*	*3.6*	*40*	*18*				*1.4E+05*
Area 8:1	mean	5,712	2,513	3,109	1,440	3.0	1.3	17	7.4	13,737	4,979	4.3E+04	0
	± SD	*1,229*	*541*	*1,44*	*634*	*1.2*	*0.5*	*12*	*5.3*				*0*
Area 9:1	mean	21,292	9,369	11,589	5,099	40	17	55	24	516,494	187,22	1.6E+06	5.4E+06
	± SD	*4,583*	*2,016*	*5,368*	*2,362*	*16*	*6.9*	*39*	*17*				*2.6E+05*
Area 9:2	mean	8,854	3,896	4,819	2,120	14.5	6.4	23	10	174,074	63,099	5.4E+05	3.0E+06
	± SD	*1,906*	*838*	*2,232*	*982*	*5.7*	*2.5*	*17*	*7.4*				*1.5E+05*
Area 9:3	mean	2,561	1,127	1,394	613	5.8	2.5	6.3	2.8	71,848	26,044	2.2E+05	1.0E+06
	± SD	*551*	*243*	*646*	*284*	*2.3*	*1.0*	*4.5*	*2.0*				*5.1E+04*
Area 10:1	mean	39,700	17,468	21,608	9,507	59	26	106	47	776,643	281,519	2.4E+06	6.1E+06
	± SD	*8,544*	*3,760*	*10,008*	*4,404*	*23*	*10*	*76*	*34*				*3.0E+05*
Area 10:2	mean	5,309	2,336	2,890	1,271	9.3	4.1	14	6.1	108,610	39,369	3.4E+05	1.4E+06
	± SD	*1,143*	*503*	*1,338*	*589*	*3.7*	*1.6*	*9.9*	*4.4*				*6.8E+04*
Area 10:3	mean	3,685	1,622	2,006	883	4.0	1.8	10	4.5	51,696	18,739	1.6E+05	6.4E+05
	± SD	*793*	*349*	*929*	*409*	*1.6*	*0.7*	*7.4*	*3.2*				*3.1E+04*
Area 10:4	mean	11,552	5,083	6,288	2,767	24	10	29	13	297,902	107,984	9.3E+05	4.0E+06
	± SD	*2,486*	*1,094*	*2,912*	*1,281*	*9.2*	*4.1*	*21*	*9.2*				*1.9E+05*
Area 10:5	mean	3,348	1,473	1,822	802	2.4	1.1	10	4.3	31,456	11,402	9.8E+04	3.5E+05
	± SD	*721*	*317*	*844*	*371*	*0.9*	*0.4*	*6.9*	*3.1*				*1.7E+04*
Area 10:6	mean	10,265	4,516	5,587	2,458	7.6	3.4	30	13	102,688	37,222	3.2E+05	8.6E+05
	± SD	*2,209*	*972*	*2,588*	*1,139*	*3.0*	*1.3*	*21*	*9.4*				*4.2E+04*
Area 10:7	mean	7,027	3,092	3,825	1,683	4.2	1.8	21	9.0	55,806	20,229	1.7E+05	4.8E+05
	± SD	*1,512*	*665*	*1,771*	*779*	*1.6*	*0.7*	*15*	*6.5*				*2.4E+04*

[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 directly and indirectly associated with water flow and transport of dissolved species. The aim of the integrated system description is to describe the conceptual understanding and properties of the deep rock volumes and the upper parts of the bedrock, the transition between the bedrock 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 bedrock and regolith. Solute-transport scenarios of interest include descriptions of transport from the deep bedrock to the surface system, primarily of radionuclide transport associated with hypothetical releases from the planned repository, but also transport from the surface system to the bedrock. The analyses of transport from surface to bedrock 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 bedrock-regolith model domain. 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 bedrock hydrogeology and hydrogeochemistry 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 from the surface system providing information on discharge of deep groundwater could be important for supporting the bedrock modelling.

The Digital Elevation Model (DEM) describing the topography and bathymetry in the Laxemar-Simpevarp 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 2005/. This DEM is classified due to national security reasons, which implies restrictions on its use. Therefore, a non-classified DEM with a resolution of 20 m was developed; it is presented in /Strömgren and Brydsten 2008/. This non-classified DEM is used as a basis for all hydrological and hydrogeological modelling in SDM-Site Laxemar.

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 rock. These descriptions have been produced for the present report, but are also summarised in Chapter 4 of the SDM-Site Laxemar report /SKB 2009/. Some material is also taken from the discipline-specific SDM-Site background reports (specified below).

- 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.

The surface system description that is presented in this report, and summarised in Chapter 4 of the SDM-Site main report /SKB 2009/, represents the final site description delivered to the SR-Site safety assessment and other users. However, some data evaluation and modelling activities are still ongoing, and are therefore not fully reported here. Specifically, evaluations of site data on transport parameters, i.e. sorption parameters obtained from laboratory experiments and concentration measurements in the field, remain to be completed. Final reporting of these activities will be made directly to the SR-Site biosphere modelling project.

5.1.2 Conceptual models for solute transport

The conceptual model of solute transport from a repository in the deep bedrock 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 different 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 ecosystem modelling.

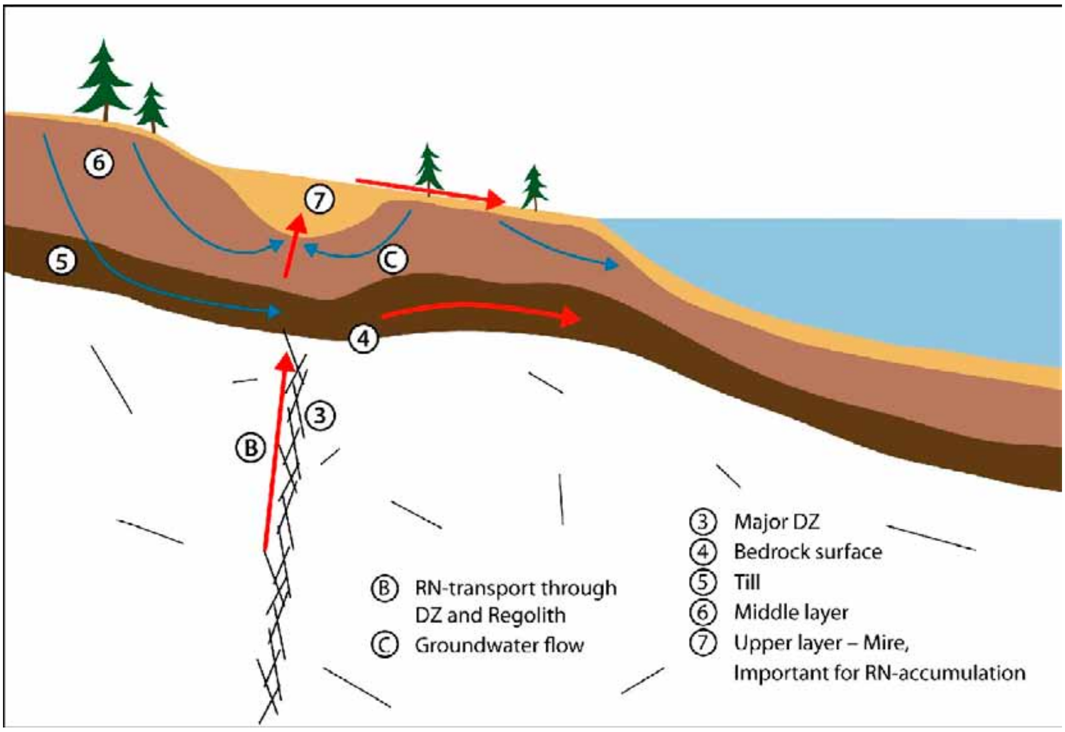


Figure 5-1. *Example illustration of possible solute transport paths to a recipient from a source in the bedrock; RN means radionuclide and DZ deformation zone. Note that the description of the Quaternary deposits in terms of till, middle and upper layers is schematic and does not fully reflect the site-specific geological model.*

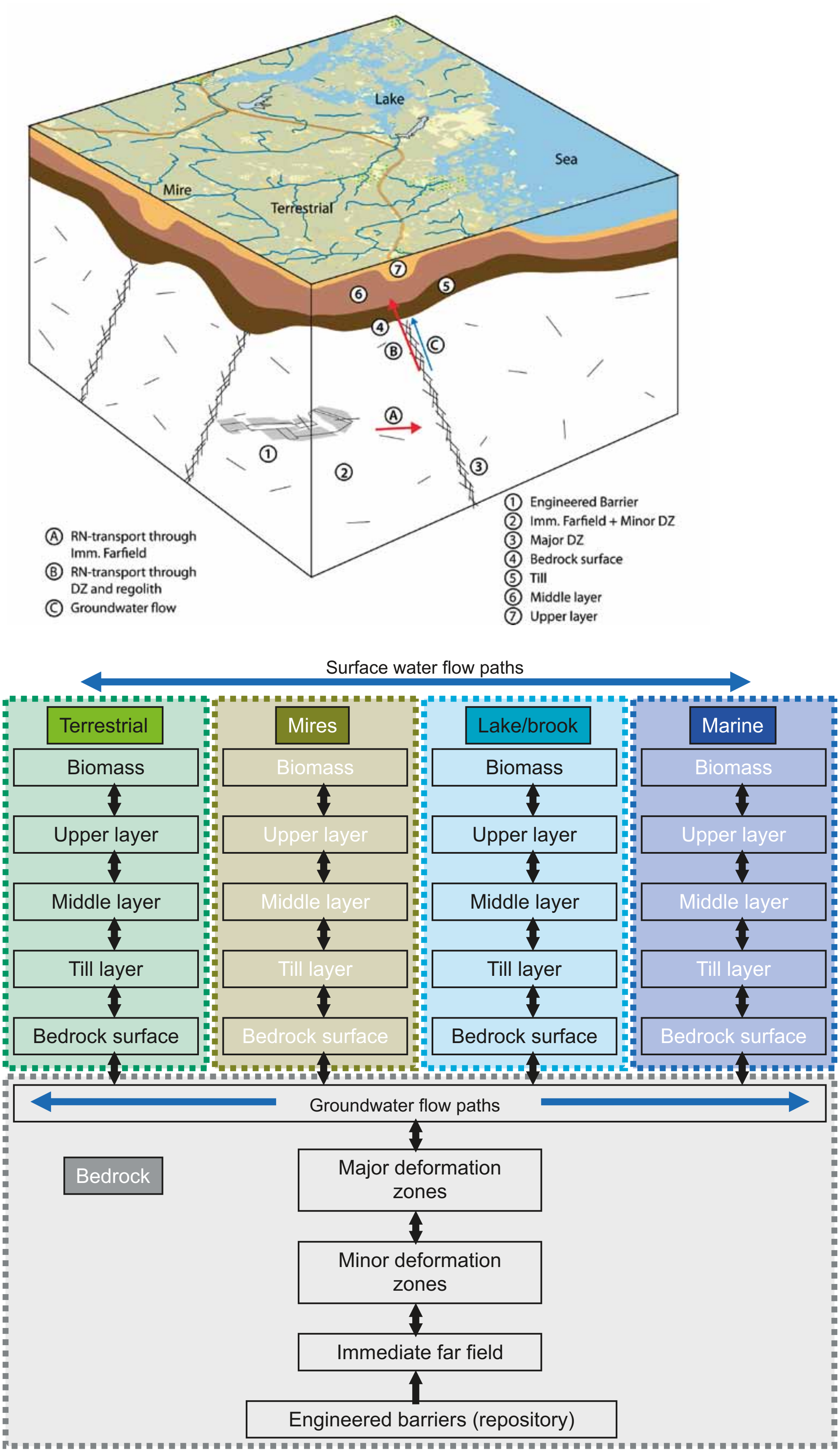


Figure 5-2. *Conceptual illustration of transport domains at the Laxemar-Simpevarp site. The upper figure indicates a hypothetical radionuclide transport path from the repository, through the bedrock, and up to the surface system. The lower figure shows the various compartments that could be involved in a model of this transport, i.e. the sub-systems that need to be parameterised and linked in such a model.*

Figure 5-1 illustrates alternative flow and transport paths in the uppermost part of the system, i.e. that solutes coming from the bedrock could be transported vertically in the regolith up to the ground surface (in this case 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 repository in the deep bedrock to the surface are represented by a set of compartments. Specifically, the lower graph illustrates that different transport paths through the surface system are associated with different sub-systems, and hence different compartments need to be parameterised and linked depending on where transport takes place. For example, deep groundwater and dissolved radionuclides could go to discharge areas in mires or lakes, thereby being transported through different types of "middle" and "upper" layers.

This type of conceptualization 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 characterisation is usually organised in the same way, i.e. based on different types of Quaternary deposits, rock types and structures in the bedrock (different types/sizes of fractures and deformation zones).

All the conceptual models discussed above consider the upward transport of solutes from a hypothetical repository in the deep bedrock, whereas transport scenarios associated with, for example, the composition of the groundwater flowing downwards through the bedrock are not described. Similar flowpath-based or compartment models for downward transport through the regolith and further into the bedrock would 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 in the recharge case, where transport in the rock to a larger extent would take place in smaller structures than those often associated with discharge areas.

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.

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 and bedrock hydrogeological modelling 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 5-3).

The handling of the interfaces in the hydrogeological models is described in the bedrock hydrogeology modelling reports /Rhén et al. 2008, 2009/ and in the reports describing the modelling of the near-surface hydrogeology /Werner et al. 2008, Bosson et al. 2008/. As indicated in Figure 5-3, 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 regional ConnectFlow groundwater flow model had its bottom boundary at a depth of 2,100 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 (including previous modelling stages). The MIKE SHE model used in the SDM-Site Laxemar modelling 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.

5.1.4 Main references

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 of the bedrock geological model as a basis, descriptive models for other geoscientific disciplines (e.g. hydrogeology, hydrogeochemistry and bedrock transport properties) have been developed.

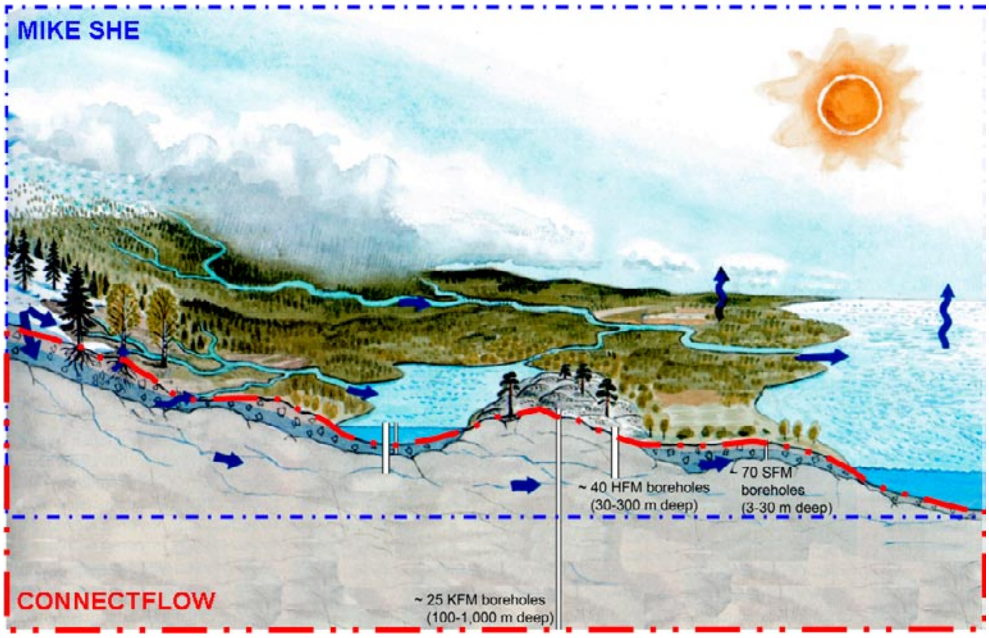


Figure 5-3. *Illustration showing how the modelling of the hydrologic cycle is divided into a surface-based system and a bedrock-based system. The former is modelled with the MIKE SHE numerical modelling tool and the latter with the ConnectFlow modelling tool. Reproduced from /Follin et al. 2007/.*

In the following sections, 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 in this context are listed in Table 5-1. As described above, the present surface system description is summarised in Chapter 4 of the SDM report /SKB 2009/. The SDM report chapters summarising the modelling within each bedrock discipline are indicated in the table below, together with the relevant discipline-specific sections of the present report.

5.2 Geology and hydrogeology

5.2.1 Model areas and bedrock boreholes

The different areas considered in the site investigations and the site descriptive modelling are shown in Figure 1-1. Of particular interest for the SDM-Site Laxemar bedrock modelling are the Laxemar subarea and, in particular, its south-western part. This part of the Laxemar subarea is referred to as the "focused area"; if Laxemar is selected as the repository site, the plan is to place the repository within this area.

In the following summary of the bedrock modelling, there are some references to specific bedrock boreholes. For convenience, and also to show which areas are actually covered in the bedrock investigations, a map showing the locations of cored boreholes (ID beginning with KLX) and percussion boreholes (HLX) in Laxemar is shown in Figure 5-4. As shown on the map, a site where one of the deep cored boreholes is located often also contains several percussion boreholes (i.e. shallower boreholes). However, at some locations several cored boreholes are drilled close to each other. At drill sites with more than one cored borehole, the boreholes are distinguished by different letters (e.g. KLX09A to KLX09G in the northern part of Laxemar).

The rectangle indicated in Figure 5-4 is the "SDM-Site local model area", within which all Laxemar boreholes except HLX08 are found. This area is essentially equivalent to the Laxemar subarea, but is somewhat extended to the south. It should be noted that there are boreholes also within the Simpevarp subarea (Figure 1-1), although not shown or discussed here.

Table 5-1. Main references describing the geological, hydrogeological and hydrogeochemical modelling in SDM-Site Laxemar.

	SDM-Site/Surface system report ref.	Background reports
Geology		
Bedrock	Chapter 5 *	R-08-54 /Wahlgren et al. 2008/
Surface	Sections 3.5, 4.4 **	R-08-05 /Sohlenius and Hedenström 2008/
Hydrogeology		
Bedrock	Chapter 8 *	R-08-78 /Rhén et al. 2008/ R-08-91 /Rhén et al. 2009/
Surface	Sections 3.4, 4.3 **	R-08-71 /Werner 2008/ R-08-72 /Bosson et al. 2008/
Hydrogeochemistry		
Bedrock	Chapter 9 *	R-08-93 /Laaksoharju et al. 2009/
Surface	Sections 3.6, 4.5 **	R-08-46 /Tröjbom et al. 2008/

* SDM-Site report /SKB 2009/
** Sections of this report

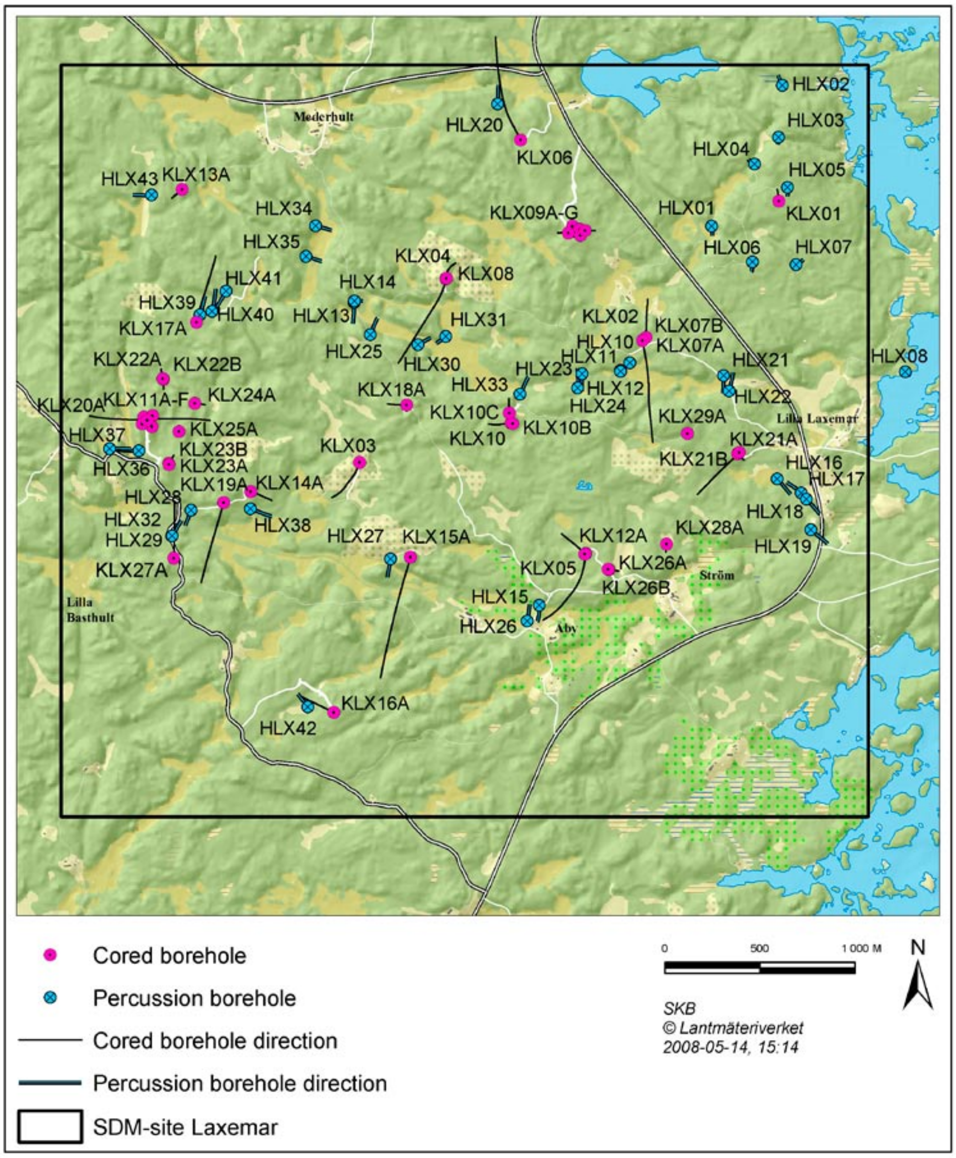


***Figure 5-4.** Locations of drill sites and the boreholes at Laxemar from which data were available for model version SDM-Site Laxemar /Wahlgren et al. 2008/.*

5.2.2 Geological description

Overview of bedrock geology

The SDM-Site Laxemar modelling of bedrock geology is described in /Wahlgren et al. 2008/, from which report the contents of this section have been taken. Only a brief summary is given here; for details, the reader is referred to /Wahlgren et al. 2008/ and/or Chapter 5 of the main SDM report /SKB 2009/.

Laxemar is dominated by a geological unit referred to as the Transscandinavian Igneous Belt (TIB). The bedrock is dominated by well preserved c. 1.8 Ga intrusive rocks varying in composition between granite-syenitoid-dioritoid-gabbroid. The most prominent ductile structures at Laxemar are discrete, low-temperature, brittle-ductile to ductile shear zones of mesoscopic to regional character, which are related to the waning stages of the Svecokarelian orogeny. Subsequently the rock mass has been subjected to repeated phases of brittle deformation, under varying regional stress regimes, involving reactivation along earlier formed structures.

There are indications that the ductile anisotropy, including both larger ductile shear zones as well as the weak to faint foliation, minor shear zones and mylonites, has had an influence on the later brittle deformation. With few exceptions, the deterministically modelled deformation zones at Laxemar are characterised by brittle deformation although virtually all the zones have their origin in an earlier ductile regime. The brittle history of the Laxemar-Simpevarp area is complex and involves a series of reactivation events that have prevented the construction of a consistent simplistic model covering their development.

Analysis and modelling of geological data

The geological work during the SDM Site Laxemar modelling stage has involved the continued development of deterministic models for rock domains (RSM) and deformation zones (ZSM), the identification and deterministic modelling of fracture domains (FSM), and the development of statistical models for fractures and minor deformation zones (geological discrete fracture network (DFN) modelling). The geological DFN model addresses fractures/structures with a size of less than 1 km, which is the lower cut-off of structures included in the deterministic modelling of deformation zones. In order to take account of variability in data resolution, deterministic models for rock domains and deformation zones are presented in both regional and local scale model volumes, while the geological DFN model is valid only within specific fracture domains inside the Laxemar local model volume.

The outputs of the deterministic modelling work are geometric models in RVS format for rock domains, deformation zones and fracture domains, including detailed property tables for rock domains and deformation zones and a description of fracture domains. The outputs of the geological DFN modelling process are recommended parameters or statistical distributions that describe fracture set orientations, sizes, volumetric intensities, spatial correlations and models, and other parameters (lithology and scaling corrections, termination matrices) that are necessary for building stochastic models.

Rock domains and deformation zones

Figure 5-5 shows the rock domains within the local model area (cf. Figure 5-4), and Figure 5-6 rock domains and deterministically modelled deformation zones in the same area. Note that the different colours indicating the deformation zones in Figure 5-6 correspond to different confidence levels (i.e. different degrees of uncertainty regarding their existence). Since the boundaries between the rock domains generally are not vertical, the horizontal distribution of the domains varies with depth. This is illustrated in Figure 5-7, which shows a three-dimensional model of the regional model volume (see Figure 1-1 for a definition of the corresponding model area).

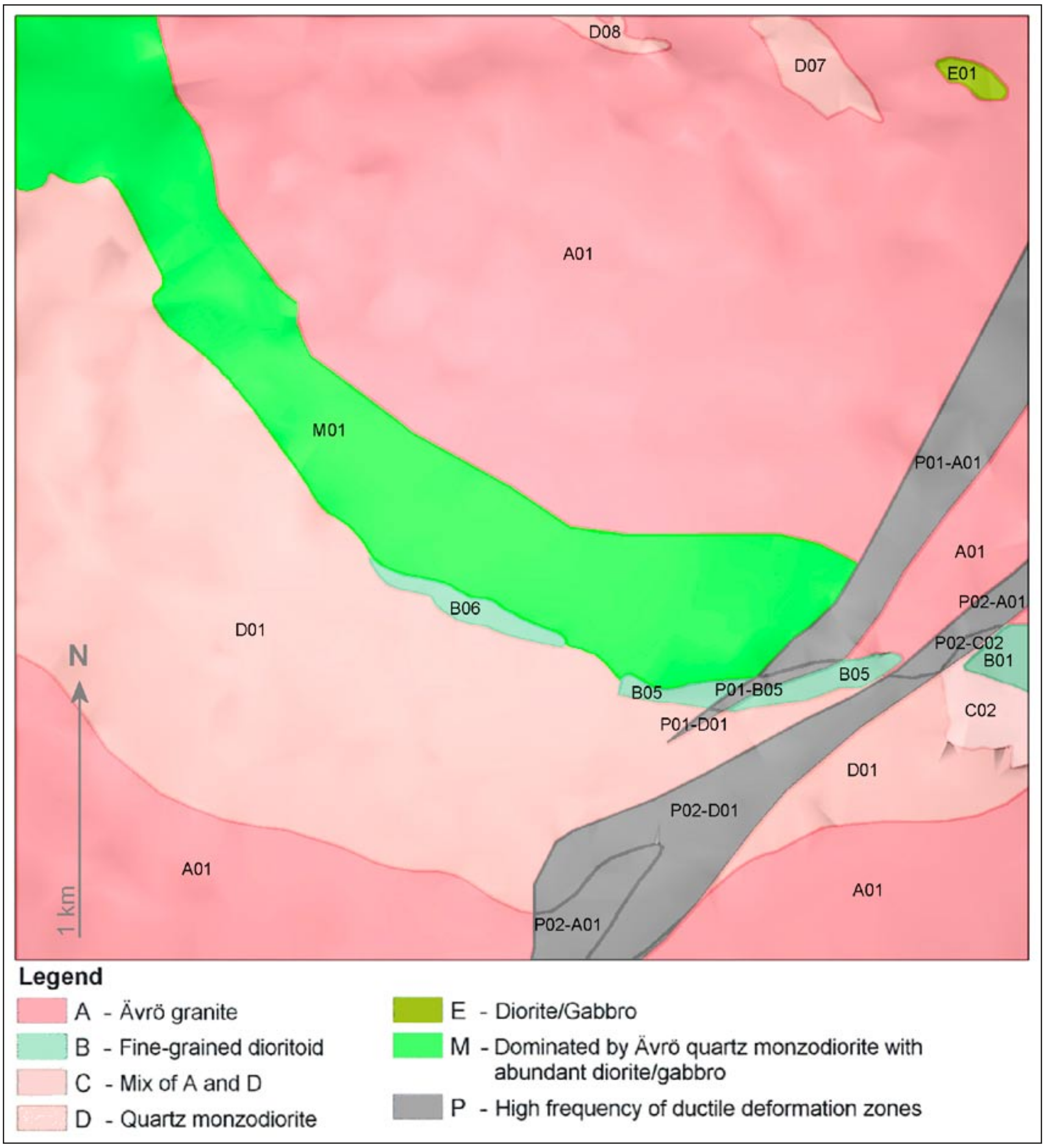


Figure 5-5. *Two-dimensional model at the surface for rock domains in the Laxemar local model area /Wahlgren et al. 2008/. For simplicity, the prefix RSM has been excluded in the denomination of the rock domains.*

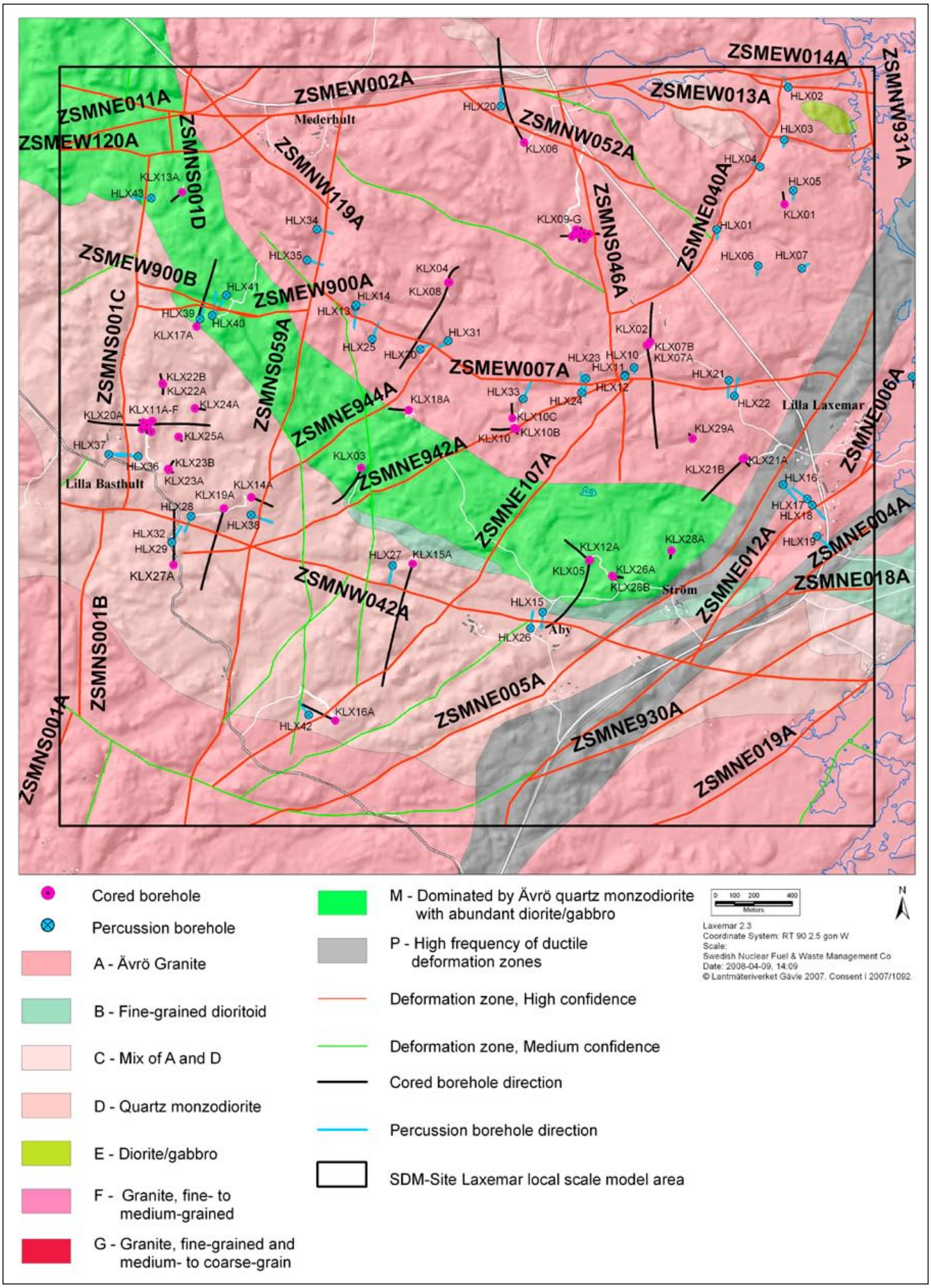


Figure 5-6. *Overview of the deformation zones and rock domains modelled deterministically in the Laxemar local model area /Wahlgren et al. 2008/.*

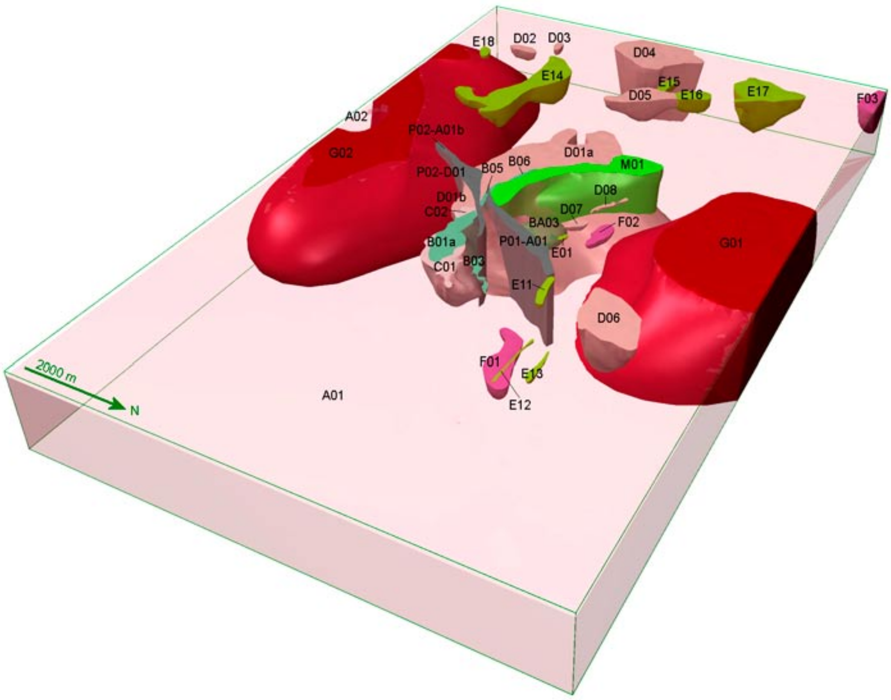


Figure 5-7. *Three-dimensional model of rock domains in the regional model volume /Wahlgren et al. 2008/. For simplicity, the prefix RSM has been excluded in the denomination of the rock domains. View to the south-west.*

Rock domain RSMD01 (i.e. the area marked "D01" in Figure 5-5), which is strongly dominated by equigranular quartz monzodiorite (c. 89%), and RSMM01 ("M01" in Figure 5-5), which is dominated by finely porphyritic Ävrö quartz monzodiorite (c. 75%) and a relatively large amount of diorite/gabbro (c. 16%), occupy the focused volume at Laxemar (cf. Figure 1-1). Characteristic subordinate rock types are fine-grained granite (c. 5% in both domains), fine-grained diorite-gabbro (c. 2% in both domains) and pegmatite (1.5 and 0.5%, respectively). Furthermore, the occurrence of dolerite is estimated to comprise 2% of the RSMD01 domain. Alteration in RSMD01 outside DZs as seen in the extended single-hole interpretation (ESHI) comprises equal amounts of oxidation (red staining) and saussuritisation (c. 10% of each), while oxidation dominates in RSMM01 (c. 14%).

The regional scale ductile deformation zones (Figure 5-6) strike NNE-SSW and NE-SW, are subvertical, and are characterised by sinistral strike-slip displacements, while E-W oriented zones, though more strongly overprinted by brittle deformation, display moderate to steep dips to the south or north. It should be noted that the regional and local major deformation zones, although the majority have a ductile precursor, are mainly brittle in character.

By comparing Figure 1-1 and Figure 5-6, it is seen that the focused volume is bounded in the west by the N-S oriented, steeply dipping deformation zone ZSMNS001C, in the south by the WNW-ESE oriented, moderately south-dipping ZSMNW042A, in the north by the E-W oriented, moderately north-dipping ZSMEW007A (cf. fracture domain FSM_EW007 below) and in the east by the the NE-SW oriented, steeply to subvertically dipping ZSMNE005A, the latter of which corresponds to the rock domain RSMP01. All these zones, with the exception of ZSMNE005A, are mainly brittle in character and ZSMNS001C in the west is occupied by a dolerite dyke.

The focused volume is transected by a series of smaller deformation zones with a variety of orientations and with dips varying from sub-vertical to sub-horizontal. Apart from a characteristic increase in fracture frequency, most of the deformation zones at Laxemar commonly contain associated fault rocks, such as different types of cataclasites, breccias and fault gouge. All available evidence indicates that multiple episodes of deformation took place within a broadly-defined brittle regime under different physical conditions.

The thickness of the deformation zones, including the transition zone and core, inside the focused volume is up to a few tens of metres. It is judged that the presence of undetected deformation zones inside the focused volume, which are significantly longer than 3 km, is highly unlikely.

Fracture domains and geological DFN modelling

Fracture domains provide a large-scale conceptual framework for describing spatial heterogeneity in rock fracturing. Figure 5-8 shows the SDM-Site Laxemar fracture domain model in a section at ground level. Similar to the rock domains, the horizontal distribution of fracture domains varies with depth; this depth dependence is illustrated in a set of sections in /Wahlgren et al. 2008/.

The six identified fracture domains at Laxemar (FSM_C, FSM_EW007, FSM_N, FSM_NE005, FSM_S, and FSM_W) are for the most part bounded by deformation zones, and were identified using contrasts in relative fracture frequencies between orientation sets and between open and sealed fractures. The fracture domains exist inside a volume (bounded by the "fracture domain envelope") smaller than the local model volume. Patterns of relative fracture intensity inside each domain appear to correspond well to the tectonic history interpreted as part of the deformation zone modelling.

Bedrock fracturing outside of deformation zones at Laxemar can be described in terms of four distinct orientation sets: A subvertically-dipping, N-S striking set that appears to be the oldest; an ENE-WSW striking subvertically-dipping set; a WNW-ESE striking subvertically dipping set; and a sub-horizontally to moderately dipping set of fractures that generally strike N-S to NNW (SH set). Fracture sizes are described according to a power-law (Pareto) distribution of equivalent radii, with parameters dependent on which set of model assumptions were used. The majority of the fractures encountered during drilling at Laxemar are sealed. Open and partly open fractures make up from 15–45% of the fracture population in most cored boreholes.

The intensity of fracturing within a given fracture domain is described in terms of the average volumetric intensity of a given orientation set. Fracture set intensity was not found to be a function of depth or rock domain at a given statistical significance level, although weak to moderate correlations between specific lithologies and fracture intensity were noted.

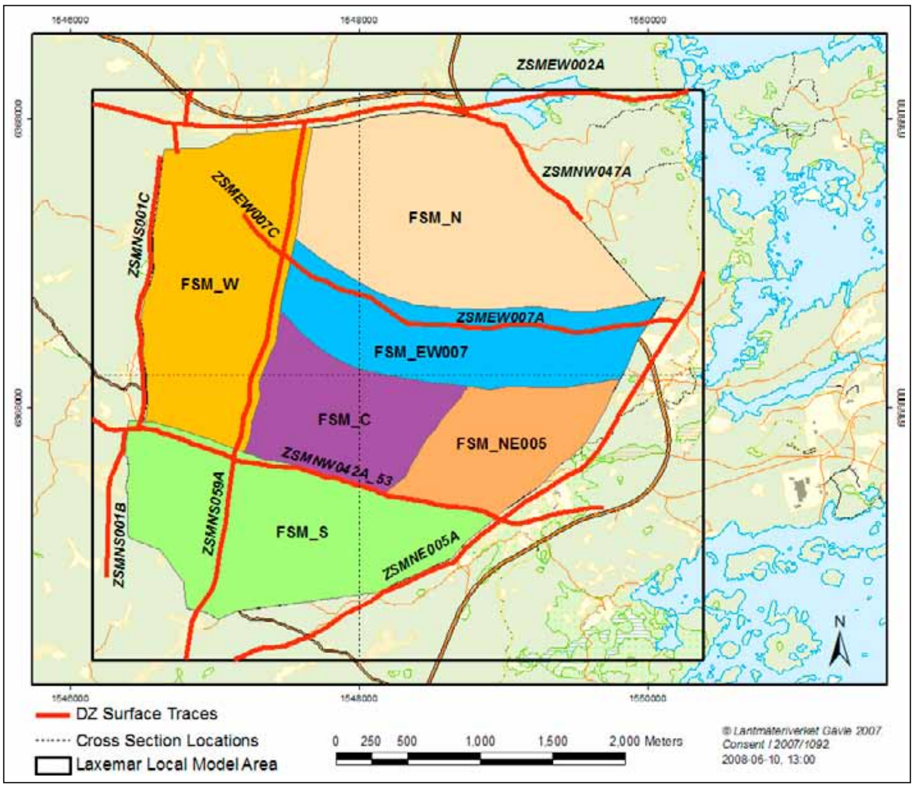


Figure 5-8. Illustration of the SDM-Site Laxemar fracture domain model in a section at ground level /Wahlgren et al. 2008/.

Description of near-surface rock

The general lithological variation in the near-surface part of the rock domains in Laxemar-Simpevarp does not differ from that observed at repository depth. The weathering of the bedrock surface is commonly insignificant, i.e. existing rock types are fresh, except in places where the bedrock surface has been intersected by deformation zones, in particular those of brittle character, and water-bearing fractures.

A schematic cross-section of the uppermost part of the bedrock and the typical stratigraphical distribution of Quaternary deposits in a valley is shown in Figure 5-9. The distribution and properties of Quaternary deposits in the Laxemar-Simpevarp area is described in Section 4.4. The photographs in Figure 5-9 show three varieties of the uppermost bedrock. In the core of the deformation zone, the bedrock is so strongly deformed and altered that the contact with the glacial overburden is difficult to define. The most important differences between the uppermost part of the bedrock and the bedrock at deeper levels are further described below.

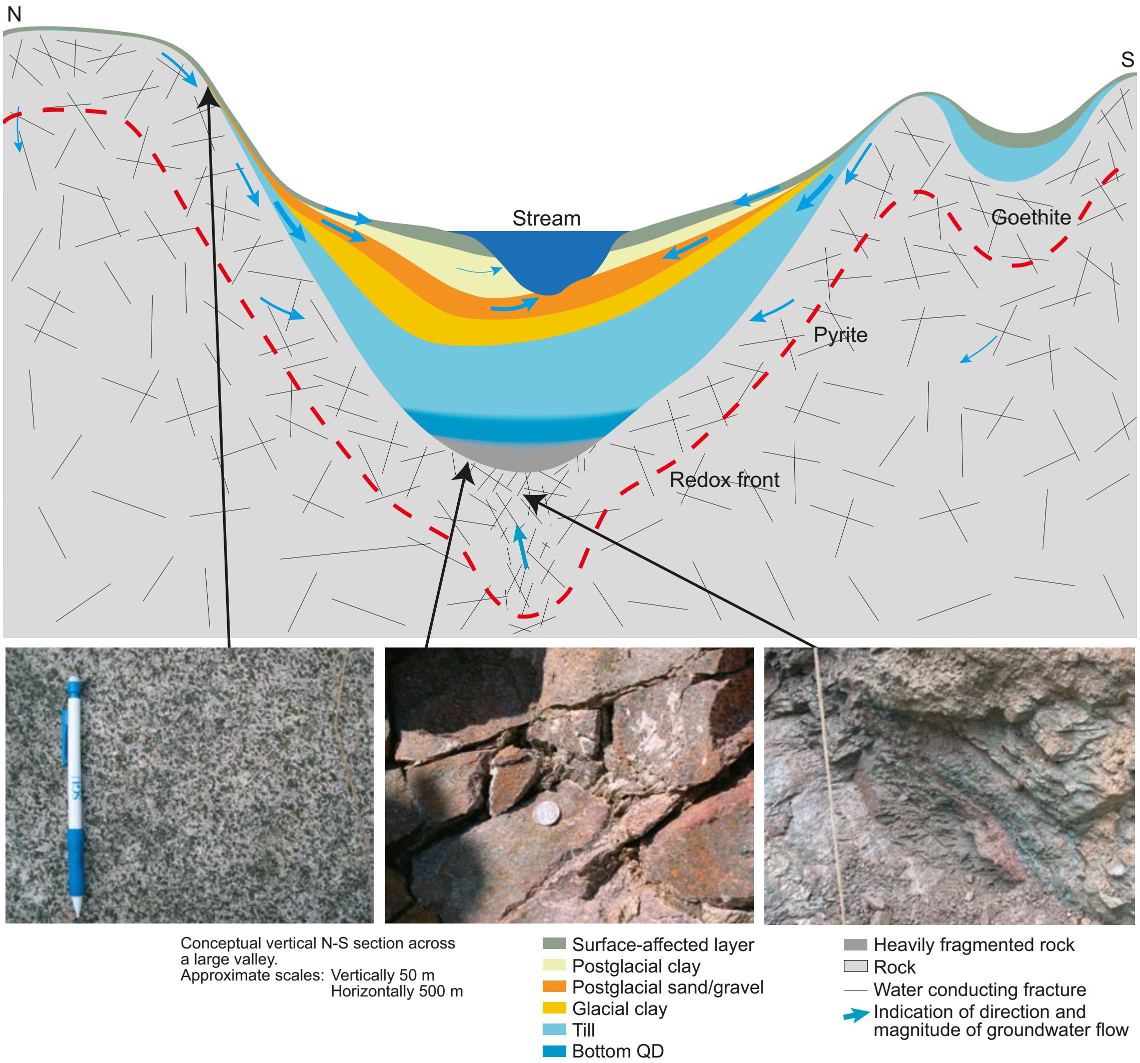


Figure 5-9. *Schematic cross-section of the uppermost part of the bedrock. The photographs show (left) fresh bedrock surface in areas outside deformation zones, exemplified by quartz monzodiorite in southern Laxemar, (middle) strongly fractured bedrock in a trench across deformation zone ZSMNS059A where several of the fractures are filled with glacial sediments /Sohlenius et al. 2006/, (right) the contact between glacial overburden and the strongly deformed core of a brittle deformation zone associated with ZSMEW007A in central Laxemar /Sohlenius et al. 2006/.*

Location of the redox front

An important issue in the description of the uppermost part of the bedrock is the location of the redox front, see /Drake and Tullborg 2008, 2009/. The location of the redox front has been evaluated by analyses of fracture minerals, chemistry and U-series isotopes. The distribution of the redox sensitive minerals pyrite and goethite in open fractures shows that the redox front, i.e. the transition from mainly goethite in the fractures above the front to mainly pyrite below it, generally occurs at a depth of approximately 15–20 m (Figure 5-10). Furthermore, the calcite distribution shows leaching of calcite in fractures in the upper 20–30 m of the bedrock and positive Ce-anomalies suggesting oxidation of Ce down to 20 m depth.

The U-series isotopes show disequilibrium in near-surface fracture fillings indicating mobility of U during the last 1 Ma. In the upper 20 m, U is mainly removed due to oxidation. There are indications of both deposition and removal of U in the depth interval 35–55 m, which indicates a transition to reducing conditions. Below 55 m depth, signs of recent U deposition as well as the occurrence of secular equilibrium indicate reducing conditions. Scattered goethite occurrences below the redox front (down to 90 m) and signs of U removal at 35–55 m depth generally correlate with sections of high transmissivity (and/or high fracture frequency). For a more comprehensive evaluation and description of the location of the redox front in the bedrock at Laxemar, see /Drake and Tullborg 2008, 2009/.

Variation in fracture frequency

An analysis of the variation in fracture frequency in the upper 100 m of the bedrock, outside deformation zones as defined in the extended single-hole interpretation, indicates a slight gradual increase in the frequency of open fractures from an elevation of –100 m and upwards towards the ground surface (Figure 5-11). In this context, it should be noted that the amount of data is limited in the uppermost part of existing drill cores, since mapping is generally only carried out in sections with corresponding BIPS images. However, fractures have also been mapped in some sections of which no BIPS images are available.

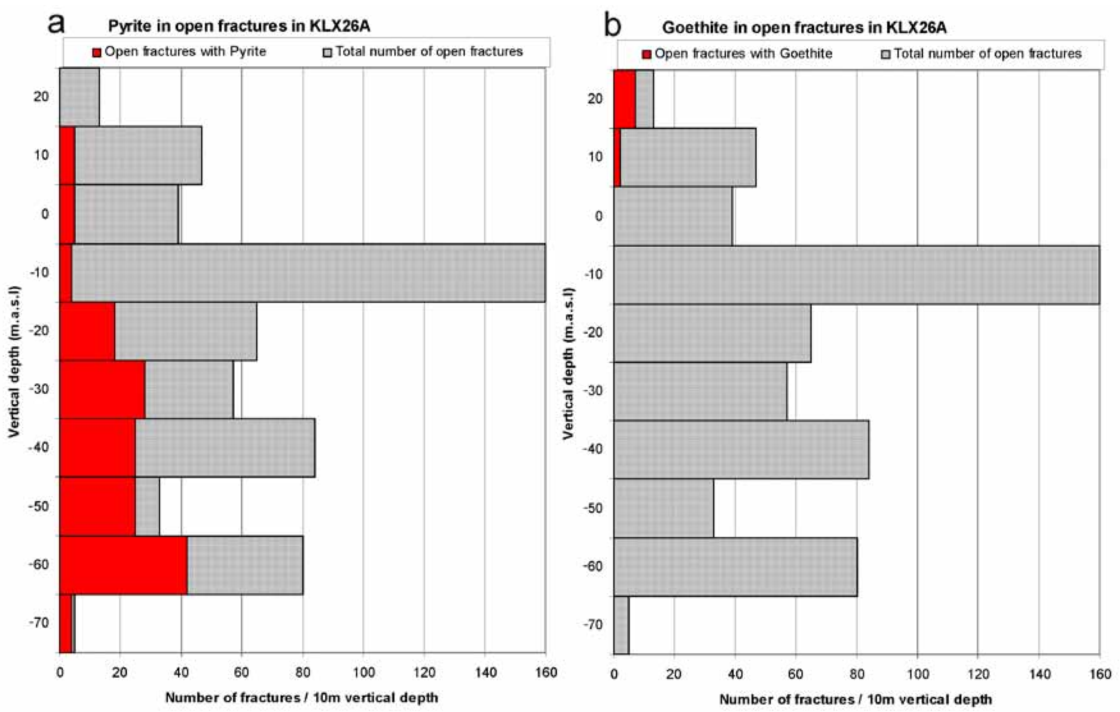


Figure 5-10. *Variation with depth of pyrite (a) and goethite (b) along open fractures in KLX26A. The total number of open fractures per 10-metre borehole interval is also shown (figure from /Drake and Tullborg 2009/).*

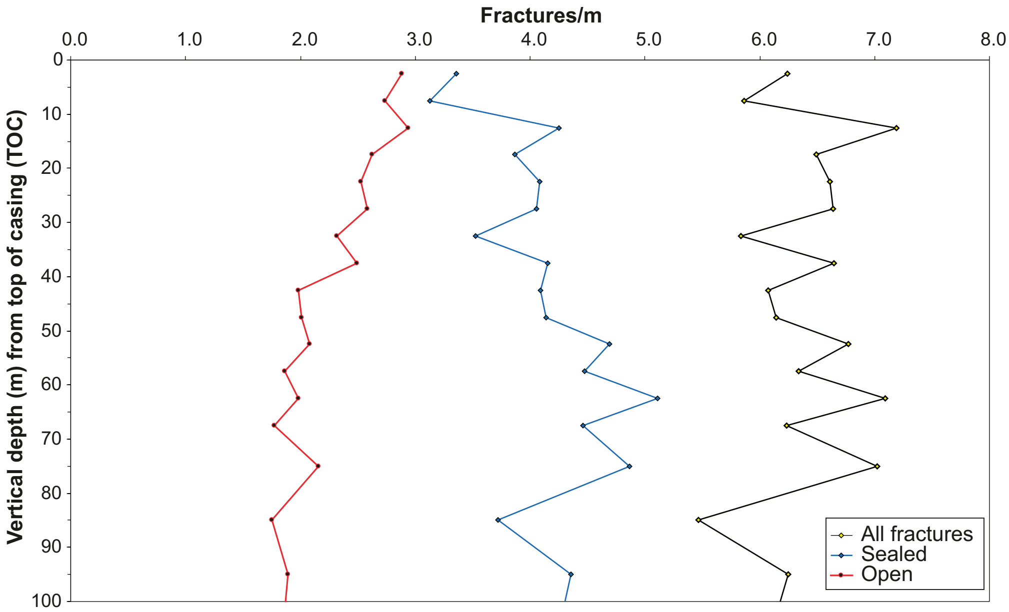


Figure 5-11. *Open fractures (red line and symbols), sealed fractures (blue) and total number of fractures (black) per metre for 5-metre intervals in the uppermost 100 m of the bedrock.*

The increase in open fracture frequency appears to be coupled to a decrease in frequency of sealed fractures (Figure 5-11). This might indicate that at least some of the open fractures constitute reactivated sealed fractures. Furthermore, there is a tendency of an increase of sub-horizontal to gently dipping open fractures towards the ground surface (Figure 5-12). This may indicate that their origin, at least partly, is related to stress release, and that they represent sheet joints (Figure 5-13).

The calculated fracture frequency is mainly based on borehole data from fracture domain FSM_W (KLX11B-F, KLX14A, KLX22A-B, KLX23A-B, KLX24A, KLX25A) and fracture domain FSM_N (KLX07B, KLX09B-G), since available data are concentrated in these domains. For a definition and detailed description of fracture domains, see /Wahlgren et al. 2008/; a brief description is provided above.

As is evident from Figure 5-14 and Figure 5-15, the frequencies of open and sealed fractures differ between FSM_N and FSM_W in the upper 100 m of the bedrock. FSM_W displays a higher frequency of open fractures and a lower frequency of sealed fractures compared with FSM_N. In addition, there is a tendency of decreasing frequency of open fractures and increasing frequency of sealed fractures towards the ground surface in FSM_W, whereas FSM_N shows the opposite relation, although only for the upper 60 m for sealed fractures (cf. Figure 5-14 and Figure 5-15).

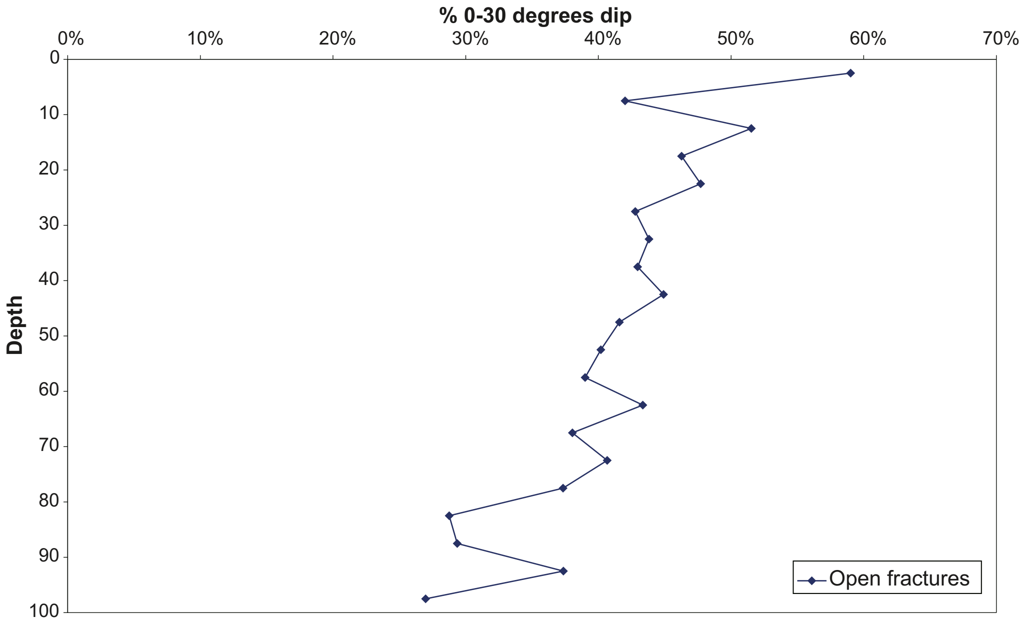


Figure 5-12. *Depth variation in percentage of sub-horizontal to gently dipping fractures per metre for 5-metre intervals in the uppermost 100 m of the bedrock.*

Figure 5-13. *Example of sub-horizontal structure (presumed sheet joint) in Ävrö granite.*

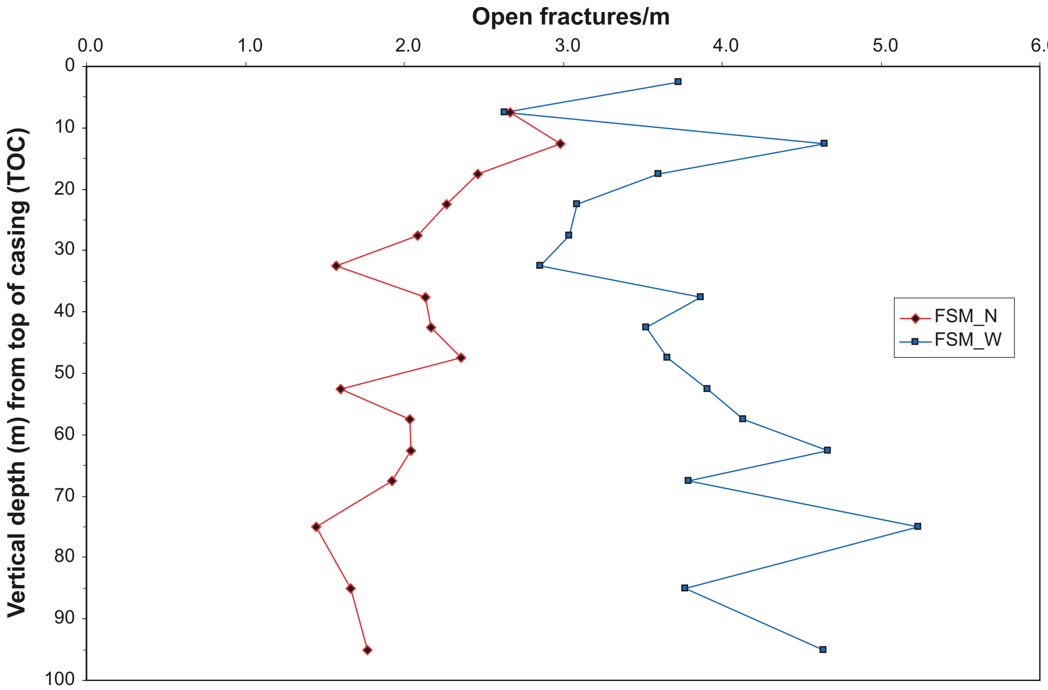


Figure 5-14. Open fractures per metre for 5-metre intervals in the uppermost 100 m in fracture domains FSM_N (red line and symbols) and FSM_W (blue).

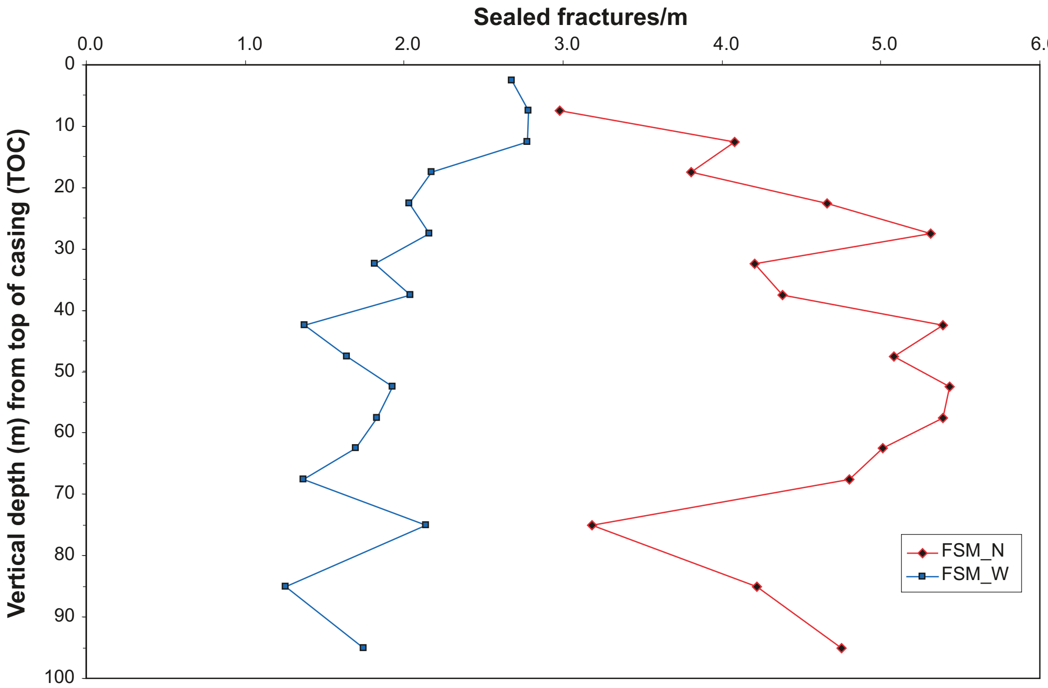


Figure 5-15. Sealed fractures per meter for 5-metre intervals in the uppermost 100 m in fracture domains FSM_N (red line and symbols) and FSM_W (blue).

5.2.3 Hydrogeological description

Overview of bedrock hydrogeology

The SDM-Site hydrogeological modelling of the bedrock, including data evaluations, conceptual modelling and numerical modelling of groundwater flow, is presented in /Rhén et al. 2008, 2009/ and associated background reports. The modelling and the resulting model(s) are summarised in Chapter 8 in the main SDM report /SKB 2009/. Figure 5-16 shows a generalised section illustrating the overall conceptual model of hydrology and hydrogeology in the Laxemar-Simpevarp area. Table 4-3 (Section 4.3) gives an overview of the hydrogeological properties of the QD and the bedrock, using rough estimates of the hydraulic conductivity (K) as the indicator parameter.

As indicated in Figure 5-16, the bedrock hydrogeology in the Laxemar-Simpevarp area can from a conceptual point of view be divided and described in terms of the following depth intervals, here denoted dZ1–dZ4 to distinguish them from the notation used in the QD depth and stratigraphy model:

- dZ1 (0–150 m depth): Near-surface rock characterised by a high frequency of conductive fractures.
- dZ2 (150–400 m depth): Intermediate-depth rock characterised by an intermediate frequency of conductive fractures.
- dZ3 (400–650 m depth): Rock at repository level characterised by a low frequency of conductive fractures.
- dZ4 (650 m and deeper): Deep rock characterised by a sparse network of conductive fractures.

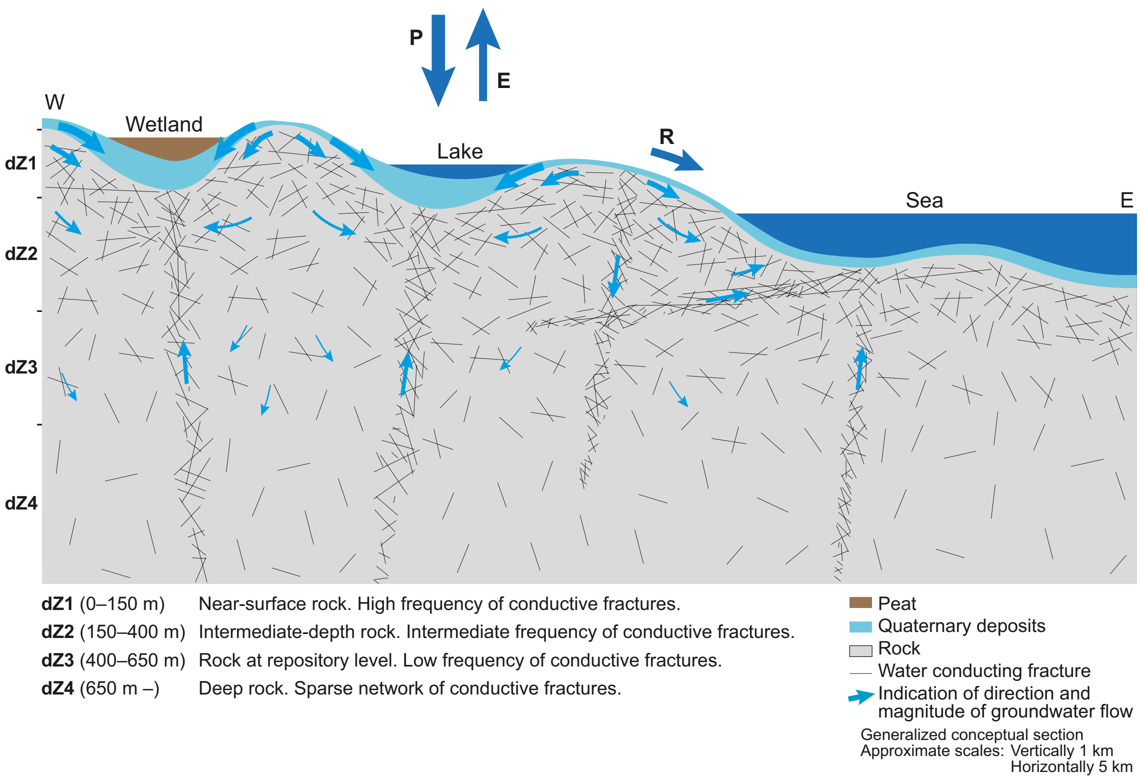


Figure 5-16. *Generalised section illustrating the conceptual model of hydrology and hydrogeology at Laxemar-Simpevarp /Werner 2008/. Note the different horizontal (5 km) and vertical (1 km) scales, and that the thickness of the QD is exaggerated in the figure.*

The geological description of the bedrock (summarised Section 5.2.2) shows that the rock within the Laxemar-Simpevarp regional model area (or rather, volume) is dominated by a rock type denoted Ävrö granite, whereas large parts of the SDM-Site Laxemar local model area (volume) also contain the rock types Quartz monzodiorite and Ävrö quartz monzodiorite, with abundant diorite/gabbro. The deformation zone (DZ) model /Wahlgren et al. 2008/ contains 209 DZ within the regional model area, whereas 70 DZ have been identified within the local model area. The hydrogeological properties of the identified rock types and DZ, organised within a framework of hydraulic domains as outlined below, is the basis for the quantitative hydrogeological modelling.

As described in detail in /Rhén et al. 2008, 2009/, the hydrogeological modelling of the bedrock includes the identification and hydrogeological parameterisation of hydraulic domains representing the deterministically modelled deformation zones (Hydraulic Conductor Domain, HCD) and the less fractured rock between these zones (Hydraulic Rock mass Domain, HRD). In this context, the regolith is described in terms of a separate hydraulic domain (Hydraulic Soil Domain, HSD).

The division into hydraulic domains constitutes the basis for the conceptual modelling, the planning of the site investigations and the numerical simulations carried out in support of the SDM. The flow models used in the SDM take into account the shoreline displacement in the Fennoscandian Shield during Holocene time, i.e. between 8,000 BC and 2,000 AD. The basis for the identification of the HCD and HRD is the geological deformation zones (DZ) and a so-called Geo-DFN model (DFN is short for discrete fracture network). The Geo-DFN is a stochastic representation of the fractured rock outside the DZ, which is hydrogeologically parameterised in terms of a so-called Hydro-DFN /Rhén et al. 2008/.

The parameterisation of the HCD and the HRD (i.e. the Hydro-DFN) constitutes a platform for constructing regional-scale ECPM (equivalent continuum porous medium) numerical groundwater flow models. Within the SDM-Site Laxemar modelling, ConnectFlow has been the main tool for modelling of groundwater flow in the rock /Rhén et al. 2008, 2009/. Detailed analyses of the spatial distribution of fractures and their hydrogeological properties motivated so-called fracture domains to be defined (Section 5.2.2). In a subsequent step, these fracture domains were slightly modified geometrically to define HRD (Figure 5-17) that were used within the hydrogeological modelling of the rock.

Concerning modelling results, some key findings of the modelling of the HCD (the deterministically modelled DZ) were summarised as follows /Rhén et al. 2009/:

- Data evaluations and modelling show that the HCD are characterised by a clear trend of decreasing transmissivity with depth and significant lateral heterogeneity.
- The confirmatory testing with the regional groundwater flow model has shown that in general the primary assessed transmissivity models for the HCD (based on the hydraulic test results) comply with the confirmatory model testing performed, however with a general slight reduction in transmissivity (1/3) below –150 m elevation. In a few HCD larger corrections of the transmissivities were applied.
- The role of N-S dolerite dykes associated with ZSMNS001A-C and ZSMNS059A as flow barriers appears confirmed by discontinuities in natural head measurement in cored boreholes. A similar effect arising from clayey fracture fill or fault gouge in ZSMEW002A and ZSMNW042A-west also seems to be confirmed when evaluating the natural heads.

According to /Rhén et al. 2009/, the main findings of the data interpretation and confirmatory testing of the HRD model (the fractured rock between the HCD) are:

- Regional scale groundwater flow and solute transport simulation tests of palaeohydrogeology, natural head measurements and hydraulic interference test data have confirmed that hydrogeological properties implied by the Hydro-DFN model base case provide an appropriate description of the hydrogeological situation in the bedrock. Only relatively minor modifications were considered necessary to obtain acceptable comparisons between the flow model results and field data.
- A slight reduction (1/3) in hydraulic conductivity below –150 m elevation improved the palaeohydrogeological calibration.
- Sensitivity studies suggest a slight increase (a factor 3) in hydraulic conductivity above –150 m elevation was benefical to both the natural head and palaeohydrogeology calibration to measured hydrogeochemistry (although such change was not included in the base case model).

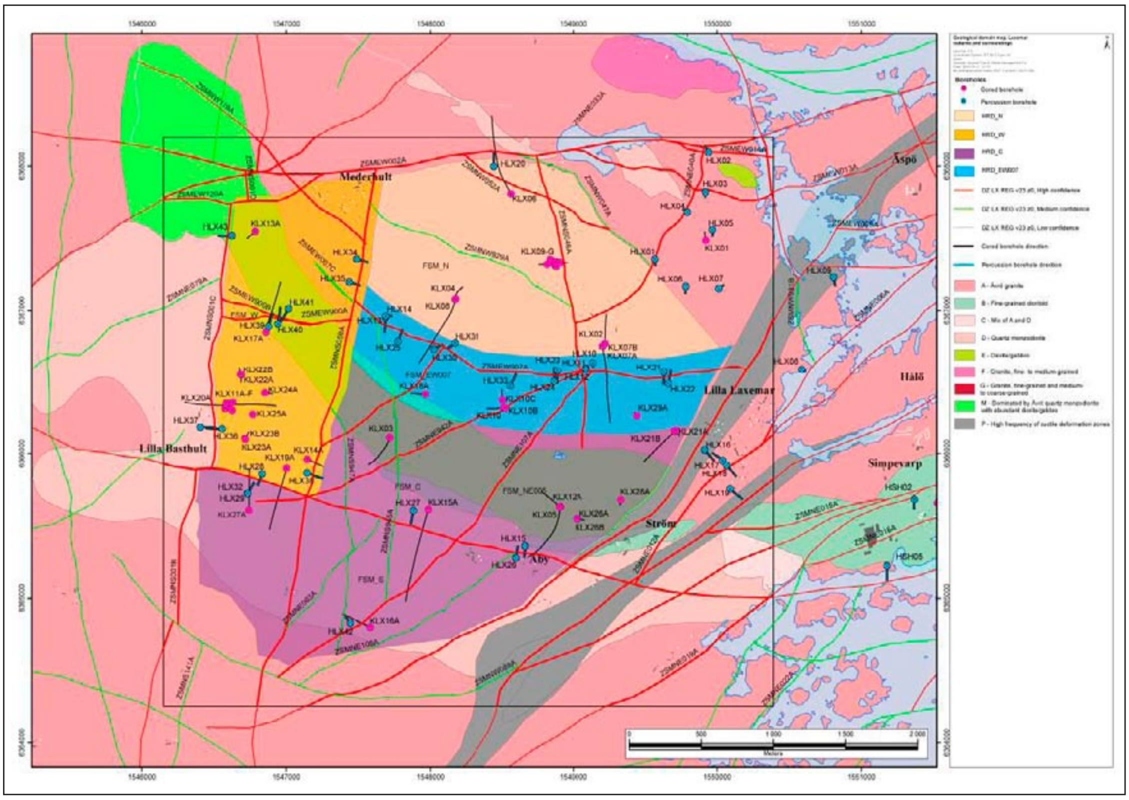


Figure 5-17. *Hydraulic rock domains (HRD, coloured areas) and deterministic deformation zones (lines) within the SDM-Site Laxemar local model area /Rhén et al. 2008/.*

Regarding the HSD model, which constitutes a simplified representation of the QD compared to that used in the surface system modelling (e.g. the MIKE SHE flow modelling), the ConnectFlow numerical modelling indicated that it was appropriate to introduce anisotropy by generally decreasing the vertical hydraulic conductivities to 1/10 of the originally suggested (isotropic) values. It was also found that in order to reproduce the drawdowns on mainland Laxemar-Simpevarp resulting from pumping in the Äspö Hard Rock Laboratory, it was necessary to use low-permeable QD (with properties corresponding to gyttja) in the bays around Äspö.

Description of near-surface rock

Hydrogeological properties

Single-hole test methods that have been used to obtain hydrogeological data from core boreholes in Laxemar include PSS (Pipe String System) and PFL (Posiva Flow Log; PFL is used to measure 5-m sections, PFL-s, and fracture/feature specific transmissivities, PFL-f), whereas the HTHB (Swedish abbreviation for *Hydraulic Test System for Percussion Boreholes*) method has been used for tests in percussion boreholes /Rhén et al. 2008/. In most cases, measurements started below elevations of c. –100 m, and no tests have been performed in the upper c. 5–10 m of the rock. One reason for this is that the borehole casing generally makes it impossible to test the upper part of the borehole. Further, water injection was not used in most boreholes, which would be needed to test the uppermost rock as one generally applies a 10-m drawdown during PFL logging.

PSS tests were performed in 5, 20 or 100 m long core borehole sections. However, in most cases PSS measurements started below elevations of c. –100 m, and 5-m tests were only made in borehole sections below elevations of –300 m. This implies that most PSS-test data for the near-surface rock comprise the test scales 20 and 100 m, and do not include the upper c. 100 m of the rock. PFL tests (test scale 5 m) have been performed in some short core boreholes. In the upper c. 100 m of the rock, tests in percussion boreholes were conducted on the 100-m scale by means of transient HTHB or airlift methods during drilling.

At two locations, around core boreholes KLX09 and KLX11A, several short core boreholes were drilled and dense information on geological features as well as hydrogeological characteristics are available /Rhén et al. 2008/. Injections of water in the uppermost sections were also made in core boreholes KLX11B-F. A number of short core boreholes were also drilled, with the objective of investigating possible minor deformation zones and also providing geological and hydrogeological data for the near-surface rock.

Hydrogeological test data for the rock indicate that the hydraulic conductivity of the rock decreases with depth, both within deformation zones and within the rock mass between the deformation zones. This depth trend is most pronounced in the upper c. 100–200 m of the rock. The deformation zones are mostly subvertical and typically one order of magnitude more conductive than the surrounding rock. Many deformation zones coincide with and outcrop in valleys, which at many locations also are associated with more conductive QD above the rock compared with other parts of the area.

In the rock mass between the deformation zones and above –150 m there is a slightly higher intensity of sets of horizontal flowing fractures compared to vertical sets. This circumstance, in combination with relatively low stress levels close to the surface (smaller rock load), probably results in that the anisotropy changes with depth: The horizontal conductive fractures are significant or dominant in the near-surface rock, but at deeper levels the sets of horizontal fractures generally become less significant compared with the vertical fracture sets. The tests on the 100-m scale indicate that the rock above –150 m has a geometric average hydraulic conductivity of c. $1 \cdot 10^{-7}$ m/s when considering the entire data set (HCD and HRD), also in the rock mass between deformation zones. For the elevation interval from –150 m to –400 m the geometric average hydraulic conductivity is c. $3.5 \cdot 10^{-8}$ m/s for the entire data set (HCD and HRD). The rock mass between the deformation zones in this depth interval has a geometrical average hydraulic conductivity of c. $1.7 \cdot 10^{-8}$ m/s.

PFL-s tests (test scale: 5 m) indicate that the rock mass between the deformation zones and above –150 m has a geometric average hydraulic conductivity of c. $4.9 \cdot 10^{-9}$ m/s. In the elevation interval –150 m to –400 m, the geometric average hydraulic conductivity is approximately $9.3 \cdot 10^{-11}$ m/s for the rock mass between deformation zones. Similar depth trends can also be observed from the PFL-f data set. The frequency of open fractures decreases slightly with depth, whereas the frequency of flowing fractures (transmissivity values > $1 \cdot 10^{-9}$ m^2/s) decreases significantly below elevations of –50 to –150 m (the variation is rather large between the different HRD).

The horizontal set of flowing fractures has a slightly higher fracture intensity above –150 m compared with deeper levels. Combining this with the relatively low stress levels near the rock surface probably results in a horizontal hydraulic conductivity of the near-surface rock significantly higher than that of to deeper levels. The hydrogeological properties are probably anisotropic; subhorizontal fractures possibly have a higher horizontal hydraulic conductivity than vertical fractures in the upper 50–150 m of the rock. It is likely that the horizontal fracture set is less dominant at depths below –50 m to –150 m below the ground surface, such that the four sets defined in the Hydro-DFN model becomes rather equally important, or that the E-W set slight dominates in some areas, as suggested by the Hydro-DFN model.

Due to the lack of near-surface borehole data (see above), the hydrogeological properties of the uppermost part of the rock need to be assessed qualitatively, e.g. based on the current understanding of the influence from geological (glacial) processes. Generally, one can assume a glacial influence in the upper c. 100–150 m of rock. It can be speculated that the uppermost part of the rock (say, the uppermost 5–10 m) is more fractured and more conductive than the deeper parts of the rock. This can be explained by the influence from the latest glaciation. In particular, the glacial influence may be pronounced on south-eastern slopes of the rock surface, due to the ice movement from NW towards SE, i.e. plucking on the lee side of the ice advance.

According to /Rhén et al. 2008/, hydrogeological properties data that can confirm such a hypothesis are difficult to collect and presently not available. However, trenches have been excavated in the QD across some of the deformation zones in the valleys /Sohlenius et al. 2006/. It was found that part of the near-surface rock is heavily weathered and fractured, and thereby possibly more conductive than the more intact rock further below. It can therefore be assumed that a large fraction of the groundwater flow towards the discharge areas in the valleys takes place in the QD and in the upper c. 10 m of the rock. Evidence of fractured near-surface rock and occurrence of a somewhat diffuse QD-bedrock contact zone has also been obtained from QD drillings in the valleys /Sohlenius et al. 2006, Morosini et al. 2007/. Furthermore, interference tests have, at least in a qualitative sense, demonstrated the existence of hydraulic connections between outcropping deformation zones and QD /Werner et al. 2008/.

Point-water heads in the rock

In this section, the point-water head data available in the Laxemar 2.3 dataset are briefly described; /Werner et al. 2008/ provide more detailed presentations and analyses of the head data. For an overview of the locations of the boreholes, see Figure 5-4. The data show that the overall average point-water heads are highest in Laxemar, and only slightly above the sea-water level closer to the coast. The lowest and highest average point-water heads (i.e. time-averaged heads per borehole section) are –0.6 and 20.1 m in percussion boreholes and –2.1 and 15.5 m in cored boreholes in Laxemar. Note that all borehole sections are included in this analysis, also those with short time series of head data.

There are relatively small temporal fluctuations of point-water heads in rock. Only taking into account borehole sections with 150 data days or more, the average point-water head variation (i.e. maximum minus minimum) is 1.9 m in the percussion boreholes and 1.5 m in the cored boreholes.

Figure 5-18 investigates possible correlations between point-water heads in percussion boreholes and the topography of the ground surface, plotting average groundwater levels versus ground-surface elevations. Note that this scattergram only includes borehole sections with more than 150 data days. For boreholes with packers, data for the uppermost borehole section are shown. Two artesian percussion boreholes can be observed, namely HLX15 and HLX28, with average point-water heads in the upper borehole sections approximately 0.9 m above the ground surface. Overall, there seems to be less correlation between point-water heads in the upper parts of the rock and ground-surface elevations, compared with that between groundwater levels in QD and the corresponding ground elevations (Figure 4-13). However, Figure 5-18 still indicates that some correlation exists.

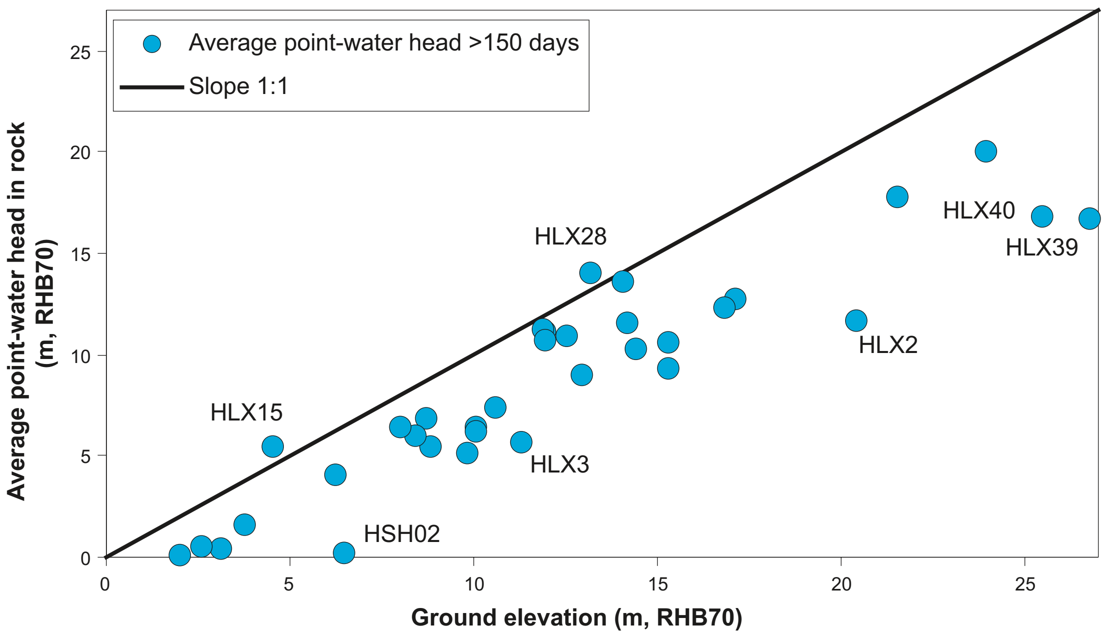


Figure 5-18. *Plot of ground elevation versus average point-water heads in percussion boreholes /Werner et al. 2008/. Note that for boreholes with packers, data for the uppermost borehole sections are used. Also note that data only for borehole sections with more than 150 data days are shown.*

Interactions between surface and bedrock

Figure 5-19 shows a conceptual vertical W-E section along a large valley in Laxemar. As visualized in this figure, groundwater discharge from the upper rock/QD part of the system to the surface (surface waters) is strongly influenced by the geometry and the hydrogeological properties of the QD overlying the till. Moreover, there is also an influence on this process by the horizontal extent and the hydrogeological properties of the upper rock (including the deformation zones) and the high-conductive QD overlying the rock in the valleys.

The large valleys in Laxemar-Simpevarp are hence characterised by groundwater discharge to the surface, as well as by more horizontal groundwater flow along the valley in the upper rock/QD system; groundwater discharge to the surface is facilitated in areas where there are no layers of glacial clay and postglacial sediments above the till. This is further illustrated in Figure 5-20, which shows the influence of the geometry and the hydrogeological properties of the QD on the conditions for groundwater discharge to the surface system, including the interaction between near-surface groundwater and surface water.

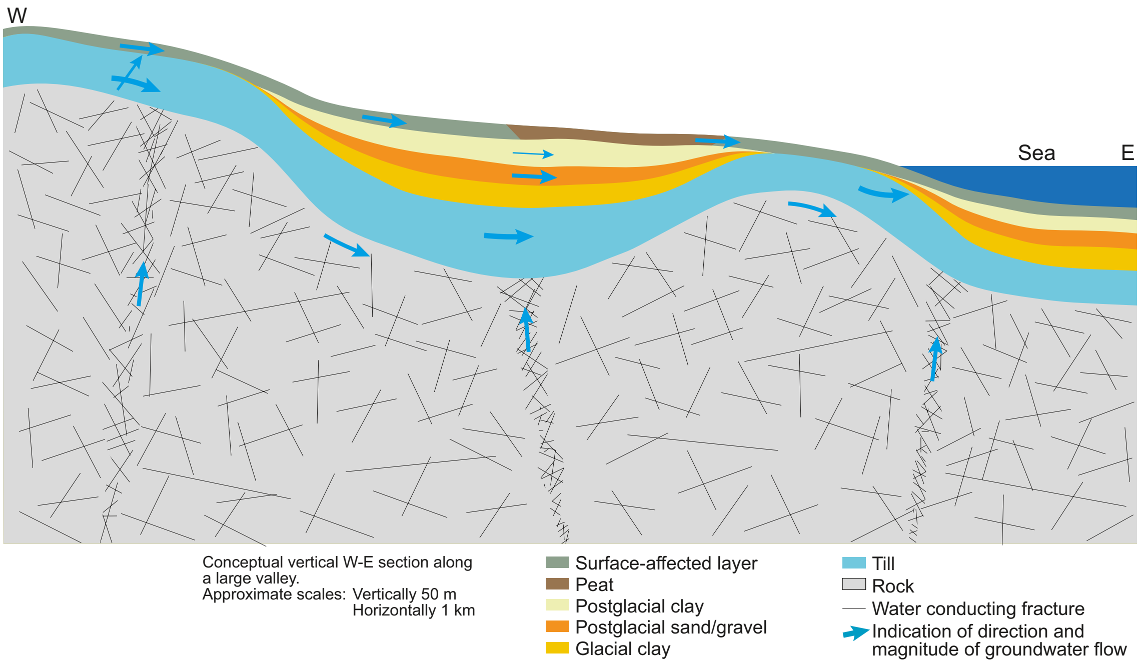


Figure 5-19. *Conceptual vertical W-E section along a large valley in Laxemar /Werner 2008/. Note the different horizontal (1 km) and vertical (50 m) scales in the figure.*

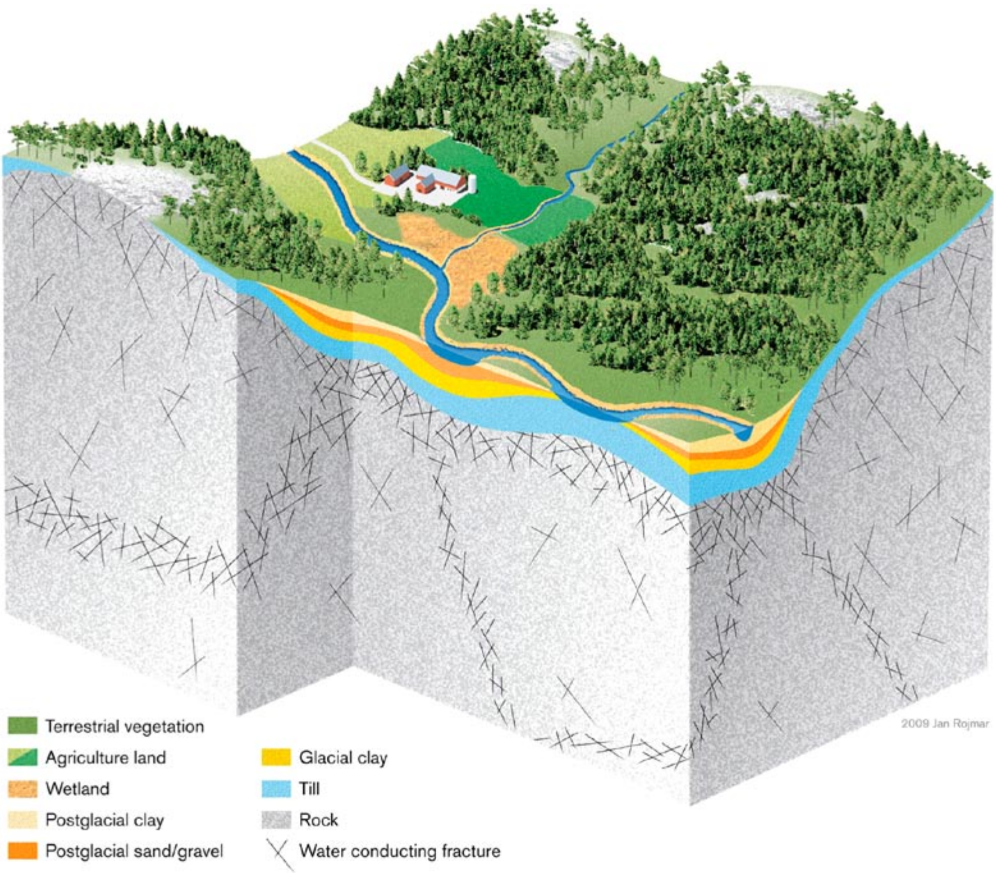


Figure 5-20. *Conceptual "semi-3D" sketch of a large valley in Laxemar illustrating realistic variations in geology and their potential implications for the contact between near-surface groundwater and surface water /Werner 2008/.*

The above concepts of sub-flow systems and discharge are further illustrated using MIKE SHE-calculated hydraulic heads and groundwater flow directions in vertical cross sections at different locations in Laxemar. Specifically, Figure 5-21 shows model-calculated heads and flow directions in a c. 400 m long N-S section across the Laxemarån stream valley, in the vicinity of percussion borehole HLX15 (cf. Figure 5-4). Figure 5-22 shows corresponding modelling results in a c. 6.5 km long W-E section along the same stream valley. The upper plots in these two figures show results for a point in time (April 8, 2006) representing wet conditions, whereas the lower plots represent dry conditions (July 13, 2006).

In the cross-valley section (Figure 5-21), groundwater flow is mainly directed from the higher-altitude areas towards the valley bottom, acting as a ”drain” for groundwater flow in the rock. The local topography has a larger influence on groundwater-flow patterns closer to the ground surface. This can be seen in Figure 5-21 in the form of near-surface groundwater flow systems with more local-scale recharge/discharge patterns.

According to the along-valley modelling results (Figure 5-22), there is a regional W-E head gradient (i.e. from inland areas towards the sea), and generally also head gradients directed from the rock to the QD. It can be noted that the influence of the sea boundary is less farther from the coast, which implies that there is more pronounced groundwater discharge from the rock towards the ground surface in the inland part of the section. As also noted in the across-valley section (Figure 5-21), the local topography has a larger influence on groundwater-flow patterns closer to the ground surface. Hence, the MIKE SHE modelling results indicate that there may be near-surface groundwater flow systems with more local-scale recharge/discharge patterns along the large valleys of Laxemar.

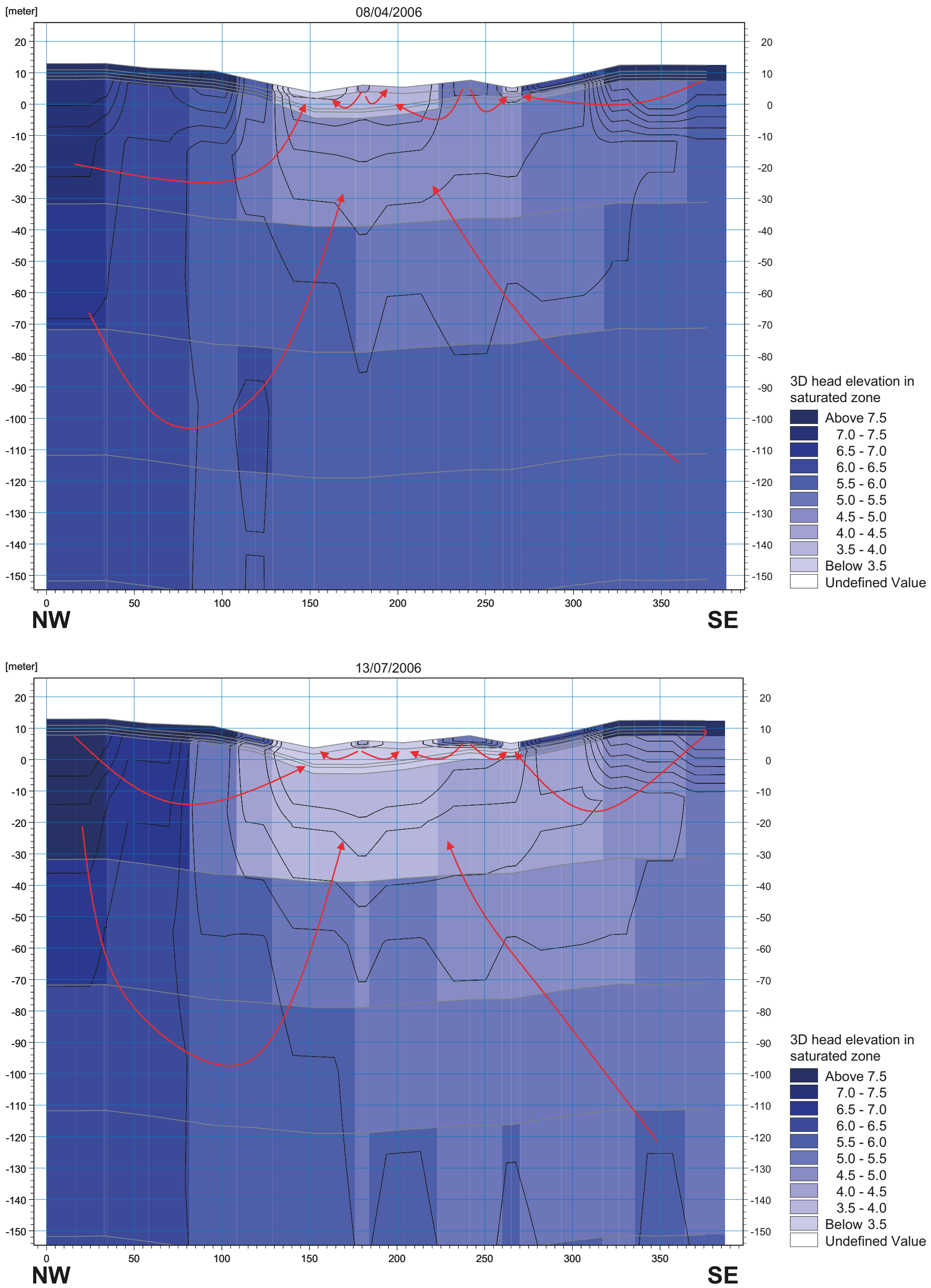
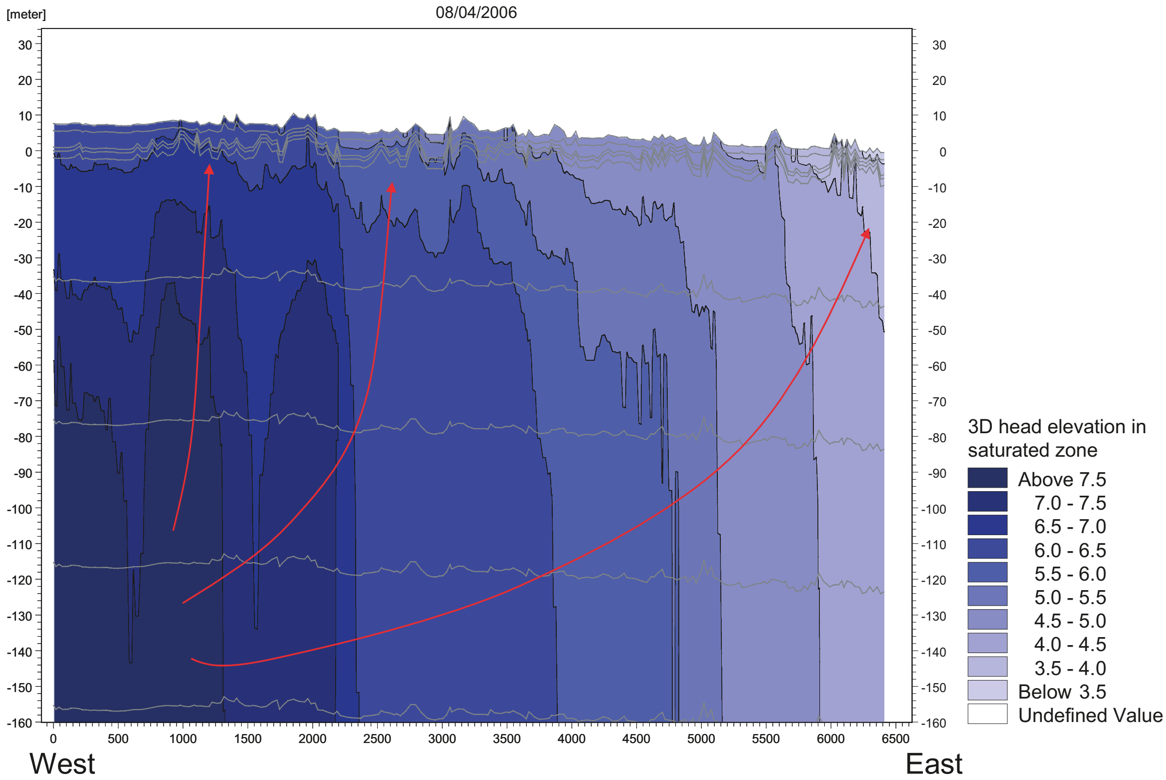


Figure 5-21. *MIKE SHE-calculated hydraulic heads (metres) and groundwater flow directions (red arrows) in a c. 400 m long N-S section across the Laxemarån stream valley, in the vicinity of percussion borehole HLX15 /Werner 2008/. The plots show hydraulic heads down to –150 m representing wet conditions (upper plot; April 8, 2006) and dry conditions (lower plot; July 13, 2006).*



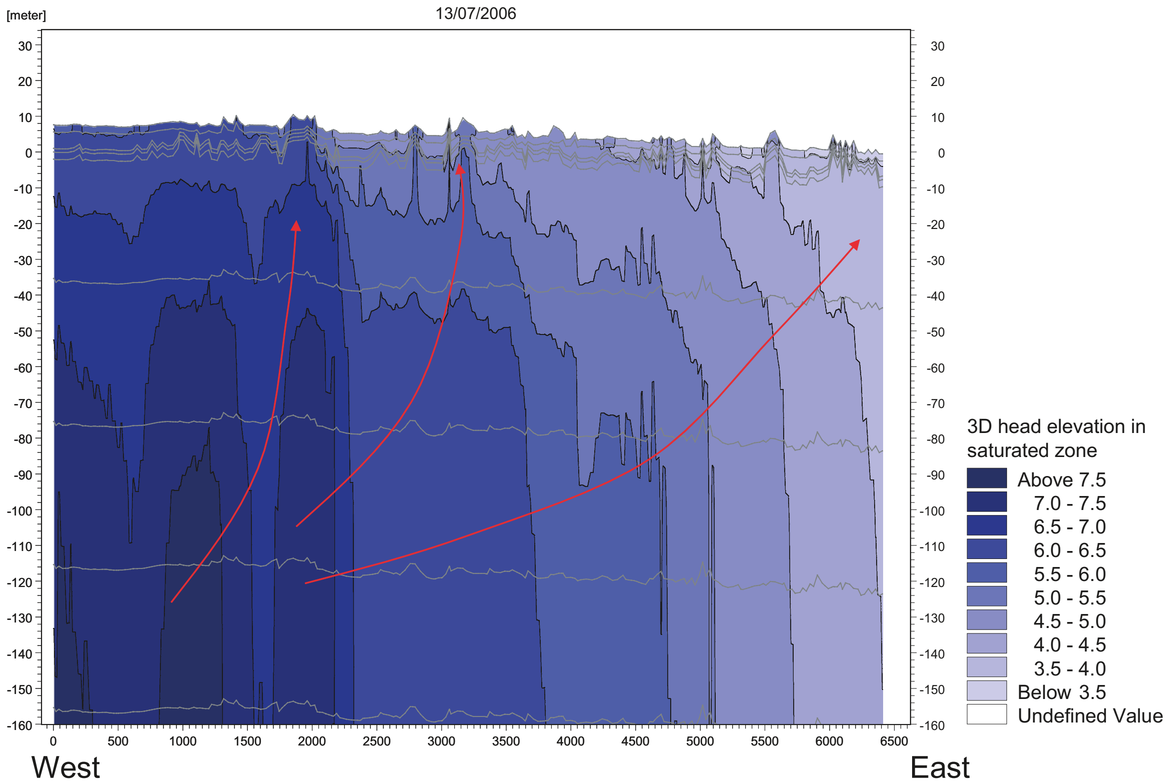


Figure 5-22. *MIKE SHE-calculated hydraulic heads (metres) and groundwater flow directions (red arrows) in a c. 6.5 km long W-E section along the Laxemarån stream valley /Werner 2008/. The plots show hydraulic heads down to –150 m representing wet conditions (upper plot; April 8, 2006) and dry conditions (lower plot; July 13, 2006).*

When evaluating the MIKE SHE modelling results, especially what they say about flow systems involving the rock, it should be noted that the parameterisation of the bedrock part of the model is based on an early delivery from the bedrock modelling, which is not identical to the final SDM-Site hydrogeology model (see /Bosson et al. 2008/ for details). However, the differences between the final model and that providing the input to the MIKE SHE model are judged to be sufficiently small for the flow modelling results presented here, and in /Bosson et al. 2008/, to be relevant. Conversely, it was decided not to present solute transport modelling results obtained using this flow model, primarily because the details of flow paths, discharge points and related parameters (e.g. travel times) are highly sensitive to the hydrogeological parameter values.

Interactions between lake water and groundwater in the underlying QD and rock are illustrated in Figure 5-23, showing MIKE SHE-calculated hydraulic heads and groundwater flow directions in a c. 1.4 km long W-E section across Lake Frisksjön. The upper plot shows results for a point in time (April 8, 2006) representing wet conditions, whereas the lower plot represents dry conditions (July 13, 2006).

The across-lake hydraulic heads and groundwater flow directions resemble the across-valley case (Figure 5-21); groundwater flow is mainly directed from the higher-altitude areas towards the lake, which acts as a ”drain” for groundwater flow in the rock. Compared with the Laxemarån stream valley bottom, the lake represents a relatively large drain, influencing groundwater flow both in the rock and the QD. It can also be noted that there are small hydraulic-head gradients in the QD below the central parts of lake, which supports the conclusion drawn from monitoring data, i.e. that the interactions between lake water and groundwater in the underlying QD are limited to near-shore areas. In the lower plot, it is also seen that the hydraulic heads in the QD below the lake decrease during dry periods.

5.3 Hydrogeochemistry

5.3.1 Hydrogeochemical overview

The Laxemar subarea is an area of groundwater recharge and shows classical systematic changes in groundwater chemistry with depth, which accompany decreasing hydraulic conductivity values and lower groundwater flow rates in the bedrock with increasing depth (cf. Table 4-3). The major groundwater feature is that the groundwater composition is mainly a result of transport (mixing) of groundwaters of different origins (deep groundwater, glacial water, Littorina Sea water and meteoric water).

The groundwater compositions are, or have been, modified by reactions ranging from fast (e.g. redox reactions catalysed by microorganisms, ion exchange, and calcite equilibrium) to long-term water-rock reactions such as aluminosilicate equilibrium at depth. Despite these changes, the alkalinity and redox buffer capacity provided by the bedrock and the microbial metabolisms is driven by comparatively fast reactions (hundreds of years). Hence, the pH and Eh variability of the contacting groundwaters is restricted to a narrow and stable range.

Postglacial meteoric water dominates in the depth interval between 100 to 150 metres of the bedrock and may be present in decreasing amounts also at intermediate depth. Only parts of the Laxemar subarea were covered by the Littorina Sea water and even this has had limited impact, resulting in relatively minor influence, especially in the central part and towards the west and north-west. Weak Littorina signatures are found in groundwaters to the south-east close to the Simpevarp subarea at various depths between 200 and 680 m in boreholes KLX10A, KLX15A and KLX01.

Clear evidence of glacial water components is commonly present in the approximately 300 to 600 m depth interval, especially in the west and central parts of the area. These waters are usually low in chloride (1,000–2,500 mg/L Cl). Decreasing hydraulic conductivity of the bedrock with depth is reflected in different mixing/reaction environments, and increasing residence times of the groundwater. At depths greater than 1,200 m, low-flow to stagnant conditions prevail.

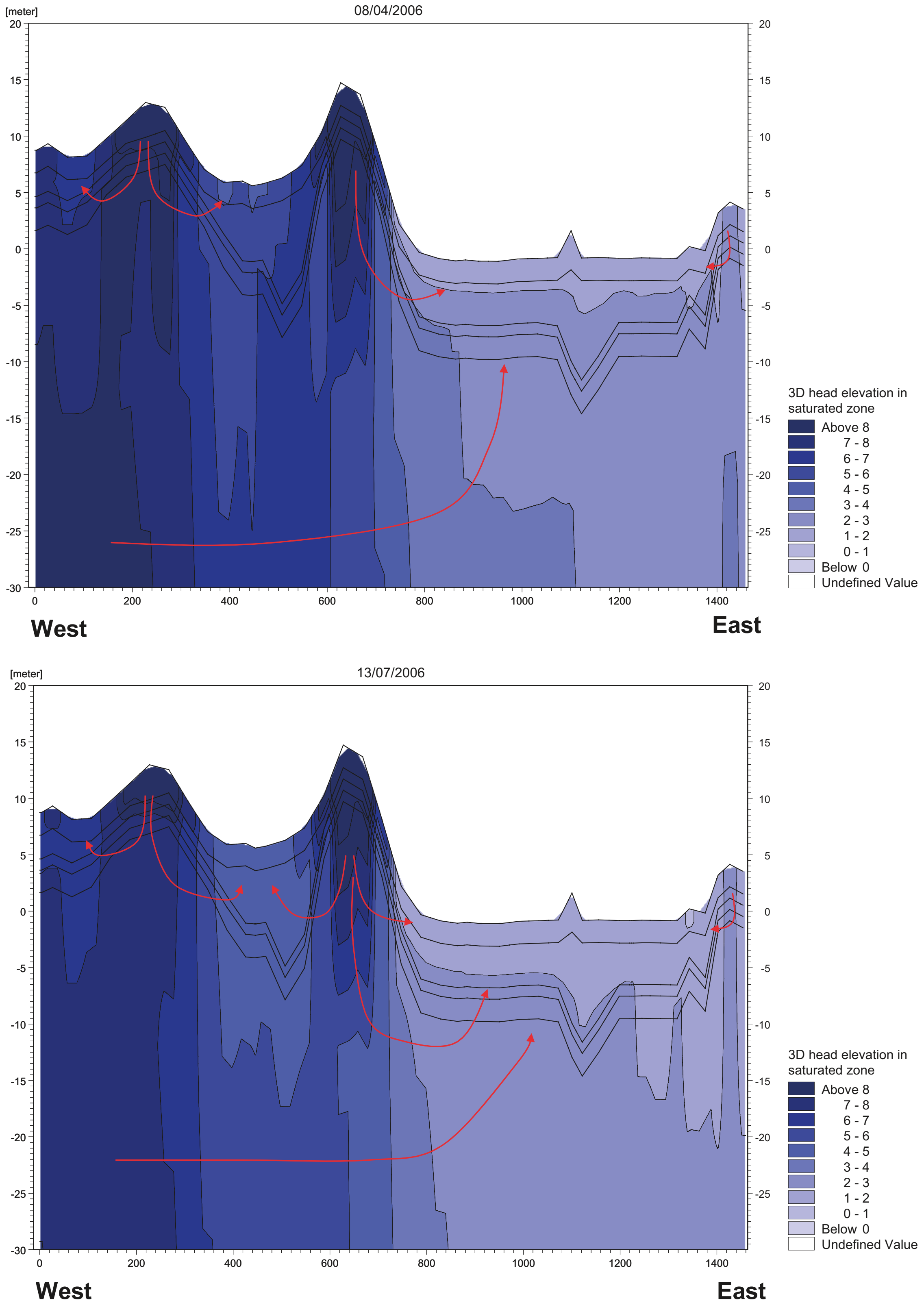


Figure 5-23. *MIKE SHE-calculated hydraulic heads (metres) and groundwater flow directions (red arrows) in a c. 1.4 km long W-E section across Lake Frisksjön /Werner 2008/. The plots show hydraulic heads down to c. –30 m representing wet conditions (upper plot; April 8, 2006) and dry conditions (lower plot; July 13, 2006).*

Dissolved oxygen is consumed in the shallow, upper part (50 m) of the bedrock, generally resulting in reducing groundwater conditions already at these depths. Redox-sensitive species such as iron and manganese are generally present in low concentrations in the deeper groundwaters in Laxemar (less than 1 mg/L Fe^{2+} and 0.5 mg/L Mn^{2+}) compared with the near surface waters (up to 10 mg/L Fe^{2+} and below 2.0 mg/L Mn^{2+}). However, Fe and Mn-reducing bacteria are identified at all depths analysed for microbes.

Easily accessible Fe-oxyhydroxides and Mn-oxides on the fracture walls decrease with depth, and the relatively low Eh (–275 mV) measured at shallow depths (c. 170 m) indicate that Fe- and Mn-reducers participate in the control of the redox system only in the very upper part of the bedrock (potentially down to around 100 m). At greater depths, between 170 to 500 m, measured Eh values are well below 200 mV and seem to correlate with the number of sulphate-reducing bacteria. Furthermore, high $\delta^{34}S_{(SO4)}$ values and correspondingly low sulphate contents occur together, which describes the importance of sulphate reduction at depths between 100 m and at least 500 m.

Less information is available on the redox system at greater depths, with only one measured Eh-value (KLX01: –680 m) and only one section (KLX03: –922 m) analysed for microbe identification (indicating no cultivable sulphate reducers). Taking into consideration that the system below 600 m is much less dynamic, which implies limitations on the amounts of nutrients available for microbial activity, lower sulphide production is assumed at these depths. Nevertheless, dissolved sulphide has been measured in several borehole sections sampled below 550 m. This general lack of data implies that the redox system is less well characterised at these depths.

The measured colloid content decreases with depth. This is to be expected due to the increasing ionic strength that destabilises the colloids; for example, the colloid content is less than 20 µg/L at depths greater than 350 m. The measured gas content in the groundwater is in the range 50–110 mL/L, and is dominated by N_2. The helium and argon contents increase with depth indicating a possible input from deep gas sources.

The major groundwater features can be summarised as follows (see /Laaksoharju et al. 2009/ for detailed descriptions of the various water types).

- *The 0–20 m depth interval* is hydrogeologically active and dominated by recharging meteoric water or Fresh groundwater (< 200 mg/L Cl) of Na-Ca-HCO_3 (SO_4) type showing large variations in pH and redox conditions.
- *The 20–250 m depth interval* is dominated by Fresh, Mixed Brackish and Brackish Glacial groundwaters of Na-Ca-HCO_3 (SO_4) to Na-Ca-Cl-HCO_3 types, showing increasingly stable reducing conditions with increasing depth. The residence times of the groundwaters are in the order of decades to several thousands of years.
- *The 250–600 m depth interval* is dominated by Brackish Glacial, Brackish Non-marine and Transition groundwaters of Na-Ca-Cl-(HCO_3) type. Redox conditions are reducing and low Eh values (–245 to –303 mV) are typically controlled by the interplay between the iron and especially the sulphur systems. The significant portions of glacial waters in this depth interval and the significant increase of non-marine groundwaters with depth indicate that groundwaters older than 14,000 years are becoming increasingly important.
- *The 600–1,200 m depth interval* is dominated by Brackish Non-marine to Saline (±Brackish Glacial and Transition) groundwaters of Na-Ca-Cl-(SO_4) to Ca-Na-Cl-(SO_4) types. These groundwaters show very low magnesium values and they are clearly reducing (–220 to –265 mV). Interpretation of chlorine-36 measurements on the saline groundwaters suggest long residence times of hundreds of thousands of years. This interpretation is supported by the low-flow to stagnant hydraulic conditions.
- pH-values are between 7.2 and 8.6 in the groundwaters and do not show any clear variation trend with depth. pH is mainly controlled by calcite dissolution-precipitation reactions and, probably, microbial activity. Influence of other common chemical processes, such as aluminosilicate dissolution-precipitation or cation exchange, are probably of secondary importance.

5.3.2 Interactions between surface and bedrock

The freshwater systems in the Laxemar-Simpevarp area are generally classified as mesotrophic brown-water types. Most waters are markedly coloured due to the high content of humic substances, which implies high levels of dissolved organic carbon. Streams and lakes are also relatively rich in nitrogen and phosphorus. Fresh surface water and shallow groundwater in the area are neutral to slightly acid, and concentrations of most major ions are normal in a Swedish perspective /Tröjbom and Söderbäck 2006/.

The topography of the Laxemar-Simpevarp area is characterised by elevated areas covered by thin or no Quaternary deposits, intersected by deep fissure valleys filled with thick sediments. These topographical characteristics, in combination with the post-glacial shoreline displacement, are two important factors determining the hydrochemistry of the surface system in the area. A detailed evaluation of the hydrochemistry of surface waters and shallow groundwaters in the Laxemar-Simpevarp area can be found in /Tröjbom et al. 2008/. Below follows a summary of the most important findings from that study.

In areas of low elevation close to the coast, marine remnants in the Quaternary deposits (manifested e.g. as elevated chloride concentrations) have a significant influence on the hydrochemistry, whereas areas situated at higher elevation are mostly influenced by atmospheric deposition and weathering processes. The vegetation cover has also great impact on the hydrochemistry of the surface system.

Degradation of biogenic carbon generates large amounts of H^+ ions, which drive weathering processes and ion-exchange processes in the Quaternary deposits, as well as in the upper parts of the bedrock. Most of the degradation occurs in aerobic environments on or near the ground surface, but also microbial sulphate reduction in anaerobic, organic sediments is important. This process also takes place in deeper parts of the groundwater system. This situation, together with inorganic processes and the groundwater flow in the upper part of the bedrock, govern the development of the redox front as illustrated in Figure 5-24.

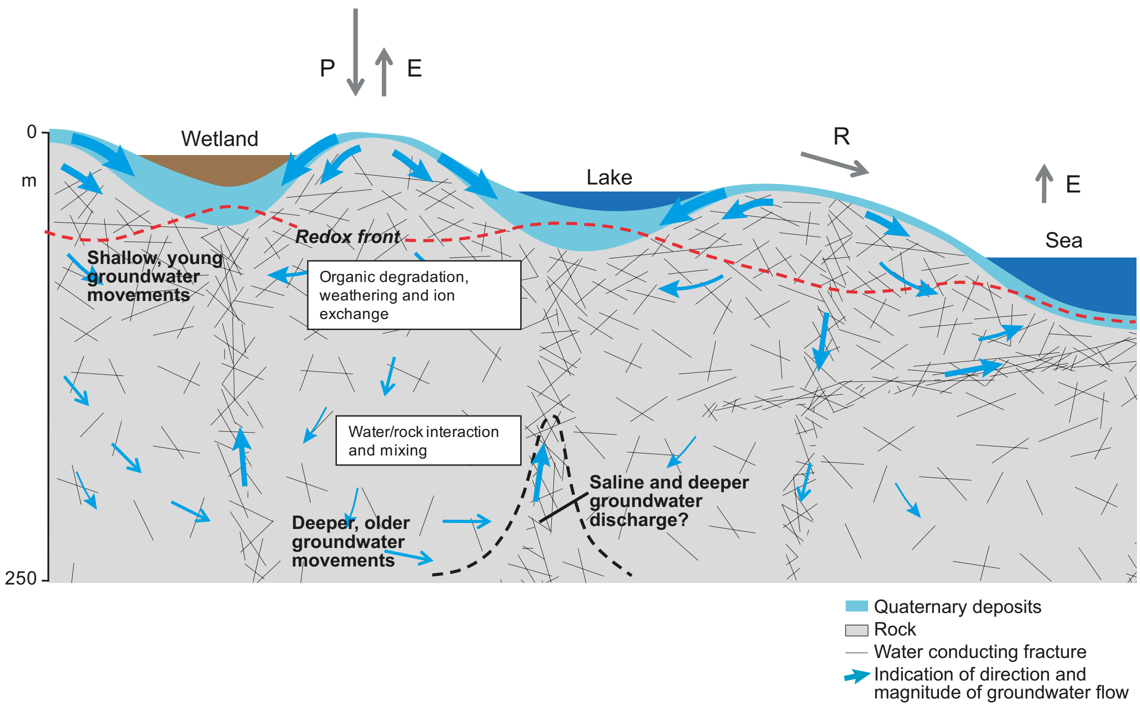


Figure 5-24. Simplified W-E cross-section of the Laxemar-Simpevarp area illustrating the major groundwater flow patterns and some important hydrochemical processes and properties in the Quaternary deposits and in the upper 250 m of the bedrock. P=precipitation, E=evapotranspiration, R=runoff. (N.B. The vertical and horizontal scales in the figure are distorted, mainly by exaggerating the more surficial parts).

The hydrochemistry observed today in the surficial parts of the groundwater system (i.e. extending down to c. –250 m) is partly a consequence of the palaeo-hydrological past. In higher elevated areas, meteoric recharge has had a great influence on the observed hydrochemistry, which is usually characterised by dilute fresh water of low ionic strength. The meteoric recharge in the western parts of the area gives rise to two different groundwater flow movements or (sub-)systems; a) a shallow young groundwater system which partly discharges towards the east, and b) a deeper/older groundwater pathway which merges with an overall regional flow at greater depth (below –250 m) discharging further east /Rhén et al. 2009, Laaksoharju et al. 2009/.

Recharge to the deeper parts of the bedrock is probably augmented in the close vicinity of deformation zones in the more inland parts of the Laxemar-Simpevarp area. The low-elevation eastern part constitutes discharge areas for the regional flow, and groundwater discharge from deeper levels is associated with deformation zones located below lakes and brackish coastal basins and bays.

The depth variation of the current redox front is caused by the varying recharge/discharge conditions, as well as by the varying redox capacity of the Quaternary deposits, the bedrock and its fracture minerals. Typically, the depth is about 20 m below ground surface. As indicated in Figure 5-24, oxygenated water tends to invade deeper in deformation zones characterised by downward flow, resulting in a lowering of the redox front locally to about 60 m below ground surface. This condition is reversed at deformation zones subjected to regional discharge.

In areas at low elevation close to the coast, elevated levels of ions of marine origin (i.e. Cl, Mg, Na, K) in shallow groundwater indicates ongoing out-flushing of marine relicts that have remained in the groundwater since the area was covered by saline sea water during the Littorina stage or later. However, at most locations in the Laxemar-Simpevarp area, this flushing is more or less complete and observed concentrations of ions of marine origin can be explained mainly by deposition and anthropogenic sources.

As much as two thirds of the chloride transported by the freshwater surface system in the area is estimated to originate from an anthropogenic source, namely road salt. Marine relicts, in combination with regional groundwater flow patterns, may explain the observed anomalous composition of water at shallow groundwater sampling points in till beneath lake and sea sediments. These sites are predominantly located close to major deformation zones, and may potentially indicate discharge points for deep groundwater.

On a regional scale, meteoric recharge and the subsequent flushing of ions results in the conceptual model described in /Tröjbom et al. 2008/ and illustrated in Figure 5-24. The interaction between the shallow and deeper groundwater results in complex mixtures of different water types. At lower depths, recharging meteoric water is mixed with portions of old glacial/old meteoric water. In the subsequent movement of these waters, processes associated with water/rock interactions take place, which can be seen in the chemistry of these waters.

A groundwater chemical transition zone between –200 m and –500 m is developed over large parts of the Laxemar-Simpevarp area, indicated by the occurrence of brackish glacial water types. These waters are mixed with more saline, relict marine waters in the discharge areas in the east. Local recharge/discharge and development of smaller circulation cells in the eastern area are indicated by the occurrence of tritium-free shallow groundwater.

The following conceptual model may explain the hydrochemistry on a regional scale, applicable to a depth of –250 m, cf. Figure 5-24:

- In low-altitude areas close to the coast, relict marine water prevails in the deeper parts of the deposits and in the upper parts of the bedrock. The high salinity compared with present Baltic Sea water, in combination with negative values of deuterium excess, indicates that this relict sea water is probably a remnant of the Littorina Sea stage when sea water with a Cl concentration of approximately 6,500 mgL^{-1} infiltrated the Quaternary deposits and the bedrock.
- In the Quaternary deposits of low-altitude areas, intermediate Cl concentrations, in combination with meteoric $\delta^{18}O$ isotope signatures, indicate ongoing flushing of relict marine remnants (e.g. Littorina).

- In areas at slightly higher altitudes, which have been covered by sea water after the latest glaciation, meteoric isotope signatures and low Cl concentrations indicate that marine influences have been washed out due to the meteoric recharge.
- In areas located above the highest coastline of the Littorina Sea, there are no indications of relict marine remnants, which is as expected. Cl concentrations in surface water and shallow groundwater in these areas can be fully explained by deposition and anthropogenic point sources such as road salt.
- The deep saline signatures observed at two locations may possibly be explained by the influence of deep groundwater discharge. Both these sites are located in the vicinity of major deformation zones, which have been proposed as potential locations for deep groundwater discharge. The differing water isotope signatures seen at these two sites indicate, however, that the soil tube located below the coastal bay Borholmsfjärden is affected by regional or local meteoric discharge originating from the higher elevated areas in the north, whereas the soil tube located below Lake Frisksjön probably reflects a more stagnant relict marine groundwater less influenced by ongoing meteoric recharge.

An important question in the hydrochemical evaluation is whether there are any indications of deep groundwater discharge into the surface system. It can be concluded from observations of major elements and environmental isotopes in shallow groundwater that deep groundwater signatures are present in the Quaternary deposits in some areas with potential deep discharge near the coast. In more inland areas, no deep signatures have been detected, either in surface water or in groundwater. This indicates that shallow meteoric recharge/discharge patterns dominate, and it is highly unlikely that any regional deep discharge occurs in these areas.

5.3.3 Hydrochemical indications of microbiological processes in the surface system

Microbiological investigations and modelling of the bedrock have been performed as a part of the bedrock hydrogeochemistry program. The results are summarised in /Laaksoharju et al. 2009/ and 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 2009/, hydrochemical data from groundwater monitoring wells in the regolith and percussion-drilled boreholes in the upper rock were evaluated from a microbiological perspective.

For the surface system microbiology evaluation, hydrogeochemical data were gathered from soil pipes at depths from 1.6 to 16.5 m and from percussion-drilled boreholes having mid-point depths of between 28.5 and 131 m. Only a few of the percussion-drilled boreholes had packers installed; therefore, the sampled sections were in many cases very long, allowing groundwaters from many different depths to mix. Oxygen and oxidation-reduction potential (ORP) had not been measured in groundwater from soil pipes or percussion-drilled boreholes. The evaluation in /Hallbeck 2009/ therefore focused on species that could indicate ongoing anaerobic microbial processes, such as nitrite, ferrous iron, dissolved manganese, and sulphide.

Even though many of the soil pipes were located in similar environments and at relatively similar depths, ranging from 3.5 to 6 m, they displayed individual chemical profiles in terms of chemical species related to microbial activity. The evaluation also showed that the microbial activity could not be linked to recharge-discharge classes of soil pipes, i.e. recharge, discharge, or intermittent. Because no oxygen analyses or ORP measurements were available, it was difficult to draw any conclusions as to the presence of oxygen. Based on the presence of the reduced species ferrous iron and sulphide, however, it was concluded that reduced conditions prevailed at most sampled depths. No obvious seasonal variation controlled by the DOC amounts was found. Soil pipes located in similar biotopes displayed similar chemical signatures regarding DOC, while soil pipes in forested areas generally displayed evidence of high DOC levels.

Thus, it was found that active microbial processes could not be conclusively identified, but the chemistry gave an 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. A depth limit for oxygen penetration could not be established from this dataset. The samples from the percussion-drilled boreholes started at a depth of 28.5 m; notably, they were missing for the 7–28.5 m depth interval, the interval where the depth limit for oxygen intrusion was established at the Olkiluoto site in Finland /Hallbeck 2009/.

5.4 Transport conditions and retention parameters

5.4.1 Flow paths and discharge points

As briefly explained above, no transport modellering was performed with the MIKE SHE model in the SDM-Site stage. In SDM-Site Forsmark, and also in earlier stages of the Laxemar site descriptive modelling, transport modelling in the form of particle tracking and advection-dispersion simulations was carried out to support the site description. The reason for not presenting this type of modelling results here was that the bedrock part of the MIKE SHE model was not fully equivalent to the final bedrock hydrogeology model reported in /Rhén et al. 2009/, which implied uncertainties as to transport quantifications obtained using this MIKE SHE model.

However, modelling results in preceding modelling stages have clearly shown that the large-scale recharge-discharge pattern, including that associated with the bedrock is topographically controlled, with discharge areas in the valleys on land and in their extensions in the sea bays, see e.g. /Werner et al. 2006, 2007/. Although the hydrogeological models have been further developed in the present site description, there is no reason to believe that this general recharge-discharge pattern has changed.

Earlier modelling studies have also shown that the differences between the discharge points obtained with different models (i.e. "surface" and "bedrock" models) are small. The models provided consistent results indicating relatively small uncertainties in discharge points, and hence in "biosphere objects" identified in the safety assessment dose modelling. Specifically, particles released at a certain depth (c. 150 m) in the MIKE SHE model at locations given by flow paths calculated using ConnectFlow showed small deviations in discharge locations on the ground surface compared with those given by the continued transport in the ConnectFlow model /Werner et al. 2007/.

Although the details concerning the specific layout of the repository and hypothetical radionuclide releases from it are not considered within the site descriptive modelling, it is of some interest to get a rough picture of potential discharge areas for groundwater passing through the repository volume. Furthermore, earlier results from such studies are of limited use because the repository location has changed slightly since the Laxemar 1.2 modelling. Figure 5-25 shows discharge points calculated with the SDM-Site base case ConnectFlow model for a particle release within the planned repository area only /Rhén et al. 2009/. Different colours of the discharge points indicate different release areas (corresponding to different HRD) within the repository area.

The results in Figure 5-25 show that exit points are located along the deformation zones, which, in turn, coincide with the valleys. In particular, many discharge points are found along the deformation zone in the Laxemarån valley (i.e. the band of yellow points in the figure).

Whereas the overall picture of groundwater recharge and discharge, as well as the main areas where discharge of deep groundwater takes place, can be regarded as relatively well established, also the field observations and modelling results providing information on the details of, in particular, groundwater discharge need to be compiled and presented. This means that it is also of interest to know more precisely where in a valley the groundwater discharges, and hence through which parts of the surface system a flow path of discharging deep groundwater and dissolved substances from a hypothetical repository release would go.

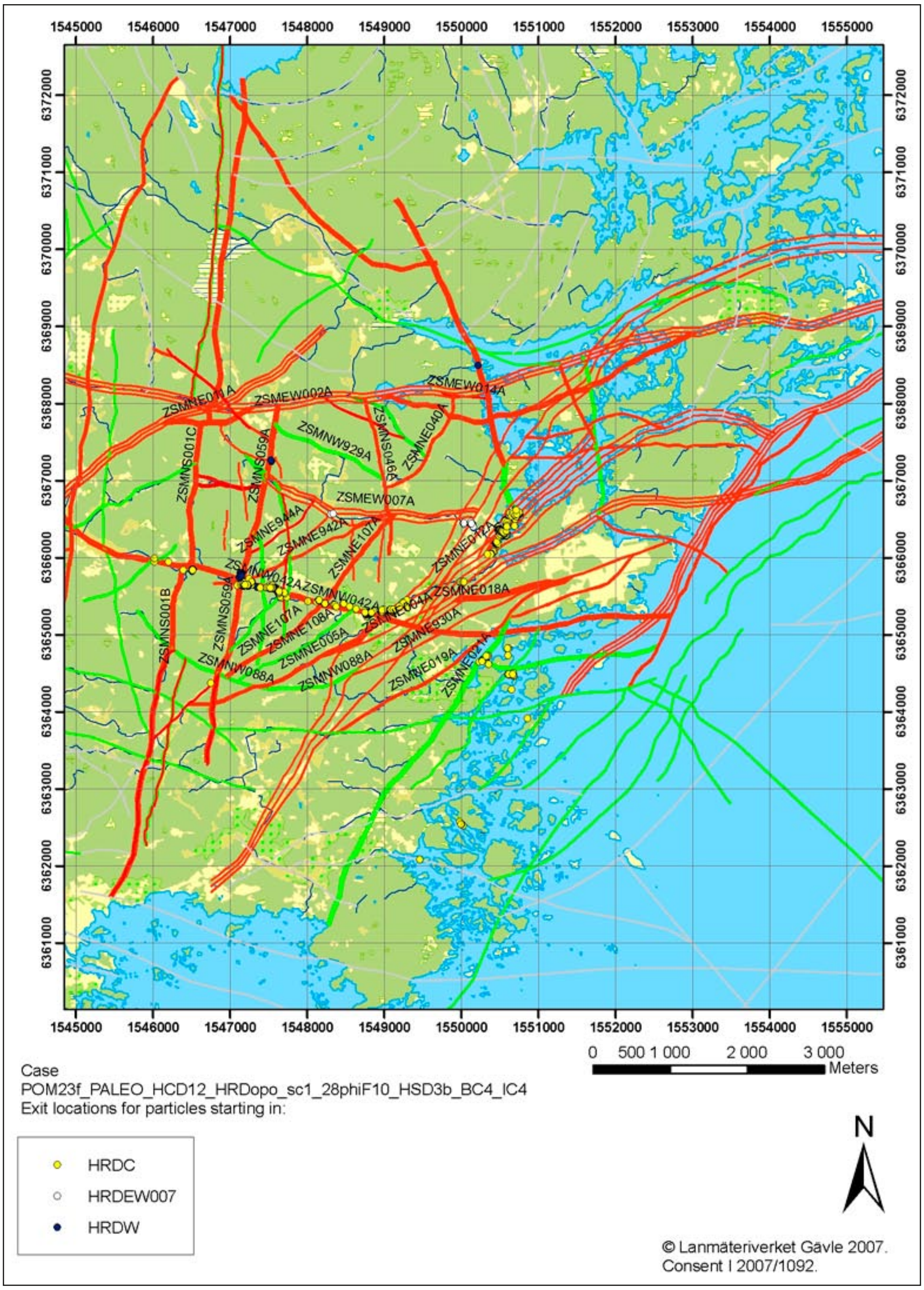


Figure 5-25. *Discharge (exit) points on the ground surface of particles released within the foot-print of the planned repository /Rhén et al. 2009/. Flow paths are calculated using the base case ConnectFlow model and the discharge points are coloured according to which HRD they were released in. Deformation zones (HCD) are shown as red or green lines (representing different confidence levels).*

Some observations and results that are relevant in this context can be summarised as follows:

- Generally, the QD directly overlying the bedrock are characterised by high hydraulic conductivity (K) values. The K-values appear to be even higher in the deeper parts of the larger valleys. There is also evidendence of highly fractured upper bedrock and a somewhat diffuse contact between bedrock and QD in places /Werner 2008, Werner et al. 2008/
- Groundwater level measurements show that the hydraulic gradients in the valleys are directed upwards (from the till to the ground surface) and along the valleys (towards the sea). At the locations where comparisons can be made, vertical (upward) gradients are larger than those driving horizontal transport in the till along the valleys.
- When taking both the differences in gradients (larger in the vertical direction) and in K-values (larger for horizontal flow along the valleys) into account, both flow directions are considered possible. This means that the local conditions determine the details of groundwater discharge; the groundwater coming from the rock likely flows along the valley until it reaches an area where the low-K QD are thinner or missing, see Figure 5-19 and Figure 5-20.
- Highly concentrated groundwater discharge from the bedrock was observed in excavated trenches /Sohlenius et al. 2006/.
- Hydraulic contact between deformation zones in rock and overlying QD was confirmed by interference and tracer tests in valleys /Werner 2008, Morosini and Wass 2006/. However, these investigations also showed large differences between different observation points, which indicate spatial variability and localised contacts.
- Drillings in QD in potential groundwater discharge areas, i.e. wetlands, sea bays and Lake Frisksjön, showed that the sediments in the lake and in the deeper parts of the bays are thick /Johansson et al. 2006/. This indicates that the groundwater is more or less immobile in some places below the lake and the bays and that the main hydraulic contact between groundwater and surface water is in near-shore areas /Werner 2008/.

Chemical indications of groundwater discharge are discussed in Section 5.3 above.

5.4.2 Properties affecting radionuclide retention

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 Laxemar modelling are presented in in /Crawford and Sidborn 2009/ and underlying reports; the modelling and the results are summarised in Chapter 10 of the SDM-Site main report /SKB 2009/. The field and laboratory investigations within the bedrock transport programme are focused on determining a set of parameters to be 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 K_d-values are also radionuclide- and water-specific and are therefore presented for selected combinations 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", in which site-specific sets of rock types, fracture types and deformation zone materials are identified and parameterised /Selnert et al. 2009/.

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 the most detailed description of the conditions at repository depth and that the level of detail decreases with increasing transport distance along hypothetical flow and transport paths from the repository to the surface system. This is mainly because transport following a hypothetical release from the repository 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 /Crawford and Sidborn 2009/.

This means that no description specifically dealing with the properties of the upper rock can be obtained from the bedrock transport modelling. However, it should be noted retention parameters for the rock and fracture types in the retardation model can be used as long as the geological and hydrochemical conditions are the same as those for which the parameter values were determined. Among the water types used in the sorption measurements is a fresh diluted $Ca\text{-}HCO_3$ water corresponding to the groundwater now present in the upper 100 m of the bedrock /Selnert et al. 2009/.

Transport conditions in the regolith

In the transport scenario outlined above, retention processes in the regolith could also contribute to the overall retention effect on radionuclides released in the deep rock. Similar to the 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 Section 3.5), and the hydrochemical monitoring (Table 3-7). The physical and chemical properties of Quaternary deposits and the groundwater there are described in /Sohlenius and Hedenström 2008/, see also Table 4-11 and Table 4-12 in the present report, and /Tröjbom et al. 2008/.

Among the site investigations in the Laxemar-Simpevarp area there are in particular two multidisciplinary investigations that have provided data on properties relevant for the assessment of solute transport conditions in the Quaternary deposits:

- The excavations and drillings performed in a set of cross-sections across valleys in the Laxemar area. Specifically, excavations down to the bedrock surface were carried out in three valley cross-sections and drillings to the bedrock in another section. One more excavation was done, but the bedrock surface was not reached at that location. The investigations and the results of the associated field and laboratory studies were reported in /Sohlenius et al. 2006/.
- The investigations in the three main valleys in Laxemar, i.e. the Mederhult, Ekerumsån and Laxemarån valleys, which were carried out primarily to obtain data from locations with deep QD. These investigations included groundwater and QD sampling and characterisation of QD and water samples to be used in batch sorption experiments (cf. below). The results are reported in /Morosini et al. 2007/, which mainly covers the field investigations and the characterisation of physical properties, and in /Lundin et al. 2007/, which primarily presents the mineralogical and chemical investigations.

These investigations included a multitude of different activities, including geological and hydrogeological characterisation, installations of groundwater monitoring wells, groundwater and QD sampling, and measurements of of a variety of mineralogical, chemical and physical parameters. In this section, we focus on the parameters that are relevant for radionuclide retention; for information on the other investigations and parameters, the reader is referred to /Sohlenius et al. 2006, Morosini et al. 2007, Lundin et al. 2007/.

The studies outlined above provide data on the following properties and parameters of importance for the assessment of solute retention in the Laxemar-Simpevarp area:

- Chemical compositions, i.e. elemental compositions (major and minor constituents and trace elements), of QD.
- Organic content, pH values and redox conditions in the groundwater.
- Contents of clay, organic material, and calcium carbonate in the QD.
- Mineralogical compositions: primary minerals and clay mineralogy.
- Chemical properties of solid surfaces: individual exchangeable cations and total cation exchange capacity (CEC) and BET surface areas.
- Physical properties of QD: grain-size distribution, porosity, density and water content.

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 perhaps less accessible) parameters are summarised in the following. Table 5-2 shows selected results from the characterisation of QD samples used in batch sorption experiments (laboratory measurements of K_d-values). Eight different samples representing QD materials ranging from peat to till were included in the sorption study, and hence also in the sample characterisation. Since some of the original samples available did not contain enough material for all analyses in the extensive characterisation programme, pooled samples consisting of mixed and homogenised sub-samples of the same QD types had to be used in some cases. Pooled samples have sample ID beginning with ASM and single samples (original samples that were large enough) ID beginning with PSM.

In Table 5-2, the samples are sorted from top to bottom in accordance with the general QD stratigraphy in the area (Section 4.4); note, however, that the samples come from different drilling locations (in different valleys) and hence do not represent a single vertical profile. The results presented here include carbon contents, TOC (total organic carbon), pH-values, CEC (cation exchange capacity) and BET surface areas of the QD samples. They are just examples of the data provided in /Lundin et al. 2007/, where all mineralogical, geochemical and hydrochemical data (including groundwater sampling) are reported and the analytical methods are described.

It is seen in Table 5-2 that the largest cation exchange capacities and BET surface areas, both of which can be assumed to be correlated to the sorption capacity, are low for the sand and till samples and considerably higher for the others. The highest CEC value was obtained for the gyttja sample, with peat/gyttja and clay gyttja also showing relatively high values. Concerning BET, the highest value was obtained for the clay sample followed by the clay gyttja and then the gyttja and peat/gyttja samples. This indicates that the organic material contributes more to the CEC than to the BET, which is dominated by the surfaces of the mineral parts of the samples.

For obvious reasons, the total carbon contents and the TOC values are highest for the peat/gyttja and gyttja followed by the clay gyttja samples, whereas sand and till show very low values of these parameters. Note that the organic contents of the samples here are described by two parameters measuring different quantities (total and organic carbon), which (consequently) were obtained using different methods, and at different laboratories, see /Lundin et al. 2007/ for details. Also other parameters describing the organic content are available in the dataset, e.g. LOI (loss on ignition).

The pH in H_2O, giving actual field values (also other pH values have been measured), showed fairly low values in the sand (3.89) and also in the gyttja and one clay gyttja sample (4.26), whereas the peat/gyttja pH was slightly higher(4.81). Considerably higher pH-values, from 6.3 to 7.2, were found in the sand and till samples.

Table 5-2. Selected results from the characterisation of samples used in batch sorption experiments; the data are taken from /Lundin et al. 2007/.

Sample ID[1]	QD type	Carbon (w %)	TOC (g/kg dw)	pH_{H2O}	CEC ($mmol_c$/100 g dw)	BET (m^2/g)
ASM000124	Peat/gyttja[2]	15.0	170	4.81	42.5	12.4
PSM001477:2	Gyttja	19.9	160	4.26	85.2	10.2
ASM000125	Clay gyttja[3]	5.38	51	4.26	32.1	19.6
PSM001472:3	Clay gyttja[3]	6.20	55	5.75	25.7	19.2
PSM001477:4	Sand	0.05	0.8	3.89	2.01	0.2
PSM001477:5	Clay	0.43	3.8	6.33	13.3	27.1
ASM000126	Till	0.09	< 0.5	6.94	4.51	1.2
PSM001472:7	Till	0.06	< 0.5	7.25	4.69	1.0

[1] ASM samples are pooled samples (consisting of 2-3 sub-samples), PSM samples are single samples.
[2] One sub-sample in this pooled sample originally classified as peat was later re-classified as gyttja.
[3] The full classification of these samples is clay gyttja/gyttja clay.

As part of the characterisation of the QD samples, different forms of extractions of various elements (e.g. Fe, Al, K, P, Mg and Ca) were performed. The aim of these extractions and subsequent chemical analyses was to study the different forms in which the elements existed in the QD, especially the amounts available for surface processes that could affect solute retention. Table 5-3 shows Fe and Al concentrations measured following *Aqua Regia* and dithionite citrate extractions of the QD samples.

The *Aqua Regia* extraction is intended to give the total potentially available contents of the elements, whereas the dithionite citrate extraction is used to quantify the amounts of complex bound elements, as in oxides and amorphous compounds, which are considered important for the adsorption in the QD. As shown in Table 5-3, the *Aqua Regia* results showed relatively small variations between the QD materials; for Fe the highest value, which was obtained for clay, was about five times larger than the lowest (sand). The variations are only slightly larger for Al, with the same samples giving the highest and lowest values.

The dithionite citrate extraction showed somewhat different results; as expected, concentrations were lower for all samples, but the relations between them had also changed (Table 5-3). The Fe contents were relatively high and more or less the same for the peat/gyttja, gyttja and clay samples, and low for the till and the sand. Comparing the two extractions, it was found that the dithionite citrate Fe content (i.e. the complex bound Fe) was 35–40% of that in the *Aqua Regia* extraction for peat/gyttja and gyttja, c. 20% for the clay, and 4–11% for the remaining samples. The dithionite citrate Al contents were very high in the peat/gyttja sample and relatively high in the gyttja and clay, whereas the contents were very low in the till and sand samples.

Mineralogical analyses of both primary minerals and the clay mineralogy were performed. Seven QD samples were analysed by X-ray diffraction (the peat/gyttja sample was excluded), in order to characterise their mineral contents. Minerals in the matrix fractions (grain size fraction < 2 mm) of the till samples and in the bulk sand sample were determined qualitatively and quantitatively. Minerals in the clay fractions of the tills were determined separately but only qualitatively. In the clay sample, in the clay gyttja samples and in the gyttja sample, the bulk samples as well as the clay fractions were analysed qualitatively.

The matrix of the till samples was dominated by quartz, plagioclase and K-feldspar; in addition, peaks from amphibole (hornblende), chlorite, muscovite and calcite were present. The clay fractions of the till samples were dominated by illite and chlorite. The clay sample bulk analysis showed that it was dominated by quartz, plagioclase, K-feldspar, illite and chlorite. Amphibole (hornblende) peaks were also present. The clay fraction of the clay sample was dominated by illite, chlorite and kaolinite.

Table 5-3. Results of *Aqua Regia* and dithionite citrate extractions of samples used in batch sorption experiments; the data are taken from /Lundin et al. 2007/.

Sample ID[1]	QD type[1]	Al, *Aqua Regia* (g/kg dw)	Al, dith. citr. (g/kg dw)	Fe, *Aqua Regia* (g/kg dw)	Fe, dith. citr. (g/kg dw)
ASM000124	Peat/gyttja	24.1	3.66	15.7	6.25
PSM001477:2	Gyttja	11.4	0.76	14.6	5.05
ASM000125	Clay gyttja	19.4	0.37	24.2	2.61
PSM001472:3	Clay gyttja	22.4	0.17	28.5	1.15
PSM001477:4	Sand	3.0	0.06	6.8	0.69
PSM001477:5	Clay	26.1	0.78	32.8	5.75
ASM000126	Till	6.1	0.05	17.4	0.99
PSM001472:7	Till	4.6	0.03	9.8	0.58

[1] See Table 5-2 for explanations of ID and QD classifications.

As mentioned above, also the excavation and drilling activities reported in /Sohlenius et al. 2006/ were accompanied by an extensive sampling and analysis programme. Mineralogical, chemical and physical characterisation including most of the parameters measured in the sorption sample characterisation exemplified above was carried out. Among other things, additional CEC and "surface reactions" data from 33 samples are available. This means that there exists a relatively large database describing the transport conditions in the Laxemar QD, which constitutes a good basis for future safety assessment calculations of radionuclide transport.

Most of the QD samples analysed in the investigation reported in /Sohlenius et al. 2006/ were taken in smaller valleys than those in the investigation discussed above, i.e. in valleys of more shallow QD where the rock surface could be reached by excavation. Therefore, sampling was primarily made in a set of profiles extending from the ground surface and down to depths of c. 3 metres. Nevertheless, the results were largely consistent with those reported in /Lundin et al. 2007/. Some observations and analytical results in /Sohlenius et al. 2006/ that are considered to be of particular interest for solute retention are summarised below.

- The chemical conditions in the QD are to large extent influenced by the high contents of organic material and clay. This furnishes relatively high pH both in the upper and deep QD layers. Carbon and nitrogen show the common stratification with higher contents in the upper layers and decreasing contents with depth.
- The mineral and chemical composition of the till reflects that of the local bedrock, which indicates short distances of transportation. This means that mineralogical data for describing the till could be imported from the bedrock investigations. A more extensive petrographic investigation comparing the rock with boulders and gravel in the Laxemar area was reported in /Bergman and Sohlenius 2007/. It was concluded that most of the boulders and gravel analysed had been transported only short distances.
- Illite is the dominating clay mineral followed by chlorite and kaolinite. This is in accordance with other mineralogical studies of water deposited clays from other parts of Sweden. The results indicate that most of the clays only to a small degree have been affected by chemical weathering.
- A comparison with the SGU national database shows that the chemical composition of the till in the Laxemar-Simpevarp area can be regarded as normal in a Swedish context.
- The overall pattern for pH in the QD profiles of the trenches showed comparably low values between 4.5 and 6 in the upper layers with higher values in deeper layers reaching around 7 or higher at depths below 2 metres.
- Carbon contents in the profiles showed similar patterns for the excavated trenches with relatively high values in the upper soil layers, mainly between 0.7% and 5% in the mineral soil, decreasing with depth to low values (< 0.2%) at depths larger than about one metre.
- Cation exchange capacities (CEC) in profiles of high organic contents showed fairly high values, e.g. 40–60 $mmol_c$/100 g down to depth of 1.5 m in one of these profiles. In this particular profile, CEC was lower below 1.5 m depth, although still relatively high (about 9 $mmol_c$/100 g) due to the clay content. A pattern with relatively high CEC in the top layers, followed by much lower CEC values where the organic contents were lower, and then higher CEC again in more clay-rich layers at depths of 2-3 metres was observed in other profiles. In one of the trenches, a fairly uniform CEC distribution was observed with values around 10 $mmol_c$/100 g from the ground surface down to 3 m depth.
- Iron appears in several different forms being precipitated as hydroxides or complex bound to other elements, especially the organic material. In the investigated trenches in Laxemar, the depth stratification showed similarities to several other elements with some systematic differences among the profiles. A similar set of extractions as described above for the "deep valley" samples was performed; the results are given in /Sohlenius et al. 2006/.

5.4.3 Radionuclide retention parameters

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 sorbed and aqueous concentrations are related by a constant coefficient, the K_d value. This is the modelling approach used in the SKB safety assessment modelling, although solutes also may be subject to other retention processes (primarily diffusion). In the safety assessment modelling, also other distribution coefficients are used for describing, for instance, the solute distribution between water and biota. These parameters 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 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. Reactive transport modelling combining advective transport and mechanistically modelled radionuclide retention was performed in the site descriptive modelling of Forsmark /Grandia et al. 2007, Sena et al. 2008/.

In the SDM-Site Laxemar work, data collection and evaluations intended to provide a basis for both K_d-based and mechanistic retention models have been performed. These activities, some of which are still ongoing, are summarised in the remainder of the present section. Ongoing activities, most notably the evaluation of laboratory sorption experiments, will be delivered directly to the safety assessment modelling (i.e. not as a part of an SDM).

K_d values based on ratios of measured concentrations

In a recently reported investigation /Sheppard et al. 2009/, site-specific data on Kd values were obtained by measuring the aqueous (pore water) and sorbed concentrations of a large number of elements in QD samples. Sampling for these measurements was performed at both Forsmark and Laxemar-Simpevarp; samples were taken at three locations at Forsmark and four locations at Laxemar-Simpevarp. In Laxemar-Simpevarp, the following Quaternary deposits and environments were included in the sampling programme: sandy till from an oak forest, clay gyttja from a fen in an alder forest, clay gyttja from an open fen, and peat from a former fen in a spruce forest.

At each sampling location, ten sub-samples were taken at a depth of c. 0.3 m. The individual sub-samples were "randomly" collected from an area of around 30 m^2. The ten sub-samples from each sampling area were mixed into one general sample, which was used for further analyses. As a supporting characterisation, grain-size analyses and measurements of the calcite and organic material contents were performed on the till samples. The samples and some results from the sample characterisation are presented in Table 5-4.

Table 5-4. Quaternary deposits used in concentration measurements for Kd calculations and results of sample characterisation /Sheppard et al. 2009/.

ID number	Quaternary deposit	Environment	Clay (%)[1]	Organic carbon (%)[2]	pH[3]
ASM001440	peat	former fen, spruce forest	29	28	4.0
ASM001434	clay gyttja	fen, alder forest	27	21	5.0
PSM000277	clay gyttja	open fen	26	20	5.0
ASM001426	sandy till	oak forest	1	1.7	5.0

[1] Determined by hydrometer method on the mineral fraction only.

[2] Determined by wet oxidation for the till and loss on ignition for the other QD.

[3] Determined by litmus paper on soil water paste allowed to stand for >30 minutes.

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 Kd values based on the concentration ratios. Site-specific Kd values of suspended material and sediments in lakes and sea bays are also reported in /Sheppard et al. 2009/. The sampling and chemical analyses performed to obtain these Kd data are described in /Engdahl et al. 2008/.

The sampling and analysis procedures outlined above resulted in site-specific K_d values for 53 elements; see /Sheppard et al. 2009/ for a detailed presentation of the data. In some cases, K_d are not available for all elements and samples due to aquous and/or sorbed concentrations being below detection limits. For some of these element/sample combinations, above-detection limit values were obtained for one phase only, whereby maximum or minimum Kd values could be given.

For two elements, Cl and I, also “spiked” (adsorption) K_d were measured by adding tracer to (sub-) samples, in addition to the “native” (desorption) K_d measured for all elements according to the methods outlined above. The results obtained with the two K_d measurement methods are compared in /Sheppard et al. 2009/, and the relevance of the methods for describing retention in the longterm safety assessment context is discussed.

The site-specific K_d dataset was evaluated using literature data, i.e. existing databases usually consisting of data from many investigations. Specifically, literature data were used to develop regression equations intended to enable prediction of best-estimate K_d values for selected elements and a specific set of soil properties. The regression equations based on literature data were used to produce site-specific “predictions”, which then were compared with the measured K_d values. However, due to the large variations in K_d values in the various databases employed (including the site data), only statistical measures are meaningful when evaluating these comparisons.

The statistical method used to derive the predictive equations reported in /Sheppard et al. 2009/ was forward stepwise multiple regression. In this method, the user defines the dependent variable (here $\log_{10}(K_d)$ for most elements) and a series of potential independent variables. The final regression equation may contain anywhere from none to all the potential independent variables, with only those that are statistically significant remaining. In total, 29 elements were included in the analysis attempting to establish predictive equations. SKB site data were available for 23 of these elements.

A large number of independent variables can be considered; however, to be practical these needed to be limited to parameters commonly measured both in literature studies and in the soils at the SKB sites. The minimum list of independent variables consisted of soil pH, clay content and organic carbon, and the product of pH and clay content; the last parameter was included based on previous experience as a way to consider the interaction between these two variables. The independent variable most often found to significantly affect K_d was soil pH. Not all the literature K_d values had all the independent variables explicitly measured in the manner required. Where possible, generic estimates or other surrogate data were then applied in the regression analysis.

Table 5-5 presents measured Kd values of selected elements in all Laxemar QD samples, and the parameters included in the final regression equations that were derived from the analysis of literature data. Relatively large variations in Kd among the four samples are evident for many elements. As expected, large variations among the different elements can also be observed. It is seen that soil pH is included in most regression equations; Sr is the only element for which neither pH nor the combined pH and clay content parameter is included in the resulting regression equation.

Regarding variability and the associated uncertainty, it is noted in /Sheppard et al. 2009/ that values of K_d have substantial inherent variations with a typical GSD (geometric standard deviation) of about 3 to 5, which implies a 95^{th} percentile confidence range of about 80-fold to 600-fold. These ranges apply to situations where some attributes of the soil are known; variations in generic values are usually larger. This means that many efforts to obtain site-specific values are potentially misleading; differences in K_d of less than 10-fold are seldom meaningful. However, developing statistically valid relationships to predict K_d values for specific soils is still considered important, as long as the overall level of uncertainty is not forgotten.

Table 5-5. Measured Kd values in L/kg of selected elements and parameters in derived regression equations for predicting Kd based on literature data (from /Sheppard et al. 2009/).

Element	Measured K_d values in QD samples (L/kg)				Parameters in resulting regression equation[1]
	Peat ASM001440	Clay gyttja ASM001434	Clay gyttja PSM000277	Sandy till ASM001426	
Caesium	57,000	25,000	31,000	21,000	pH, pH×clay
Molybdenum	6,800	1,200	3,300	410	clay, org-C, pH×clay
Nickel	710	460	450	530	pH, org-C
Selenium	130	56	140	41	pH, pH×clay
Strontium	68	59	30	1,300	clay
Thorium	9,300	14,000	34,000	5,500	pH
Uranium	12,000	5,700	44,000	1,800	pH, pH×clay or pH×clay only[2]

[1] Regression parameters: pH = soil pH, clay = clay content, org-C = organic carbon content, pH×clay = product of pH and clay content.

[2] Different regression equations for pH above (pH and pH×clay) and below (pH×clay only) 5.5.

It is concluded in /Sheppard et al. 2009/ that it is possible to select values of K_d for soils and sediments that are the best estimates from the data available, and to show that these values would differ in a statistically significant manner as site conditions differ. For example, the soil K_d values for U varied notably with pH, and so if soil pH varied from site to site, or with time because of natural processes or human activities, then it is possible to assign revised best estimate K_d values for the changed soil pH. Among the literature-based regression equations to predict soil K_d values, the median residual GSD was 4.3, which implies 95th percentile confidence bounds 18-fold above and below the recommended values.

Concerning the sediment K_d values, which were calculated based on concentrations reported in /Engdahl et al. 2008/ and presented and evaluated in /Sheppard et al. 2009/, the inherent variability in values implies that the differences among the sources of data were not statistically meaningful. Thus, data specific to the SKB sites were not different, overall, from the global literature, and one could therefore justifiably draw K_d values for use in safety assessment from any of these sources, or from them all collectively.

However, key advantages of the SKB data are the consistent measurement methods and the clear differentiation in values between K_d for benthic sediments and suspended particulate matter. It is also important to note that the SKB freshwater K_d values for I and Cl, and perhaps also for Se, Mn and Ni, were in the value range where Kd is important to safety assessment and deviated to some extent from the corresponding global literature. Given these arguments, it may be appropriate to use the SKB data for risk assessment of sites on the east coast of Sweden, when available /Sheppard et al. 2009/.

K_d values from batch sorption experiments

As mentioned above, site-specific K_d values have also been measured in batch sorption experiments on QD samples from Laxemar. The samples included in this programme and some results from the sample characterisation are described above, see Table 5-2 for a listing of the QD types included and some parameter values measured in the sample characterisation /Lundin et al. 2007/. Additional characterisation data are provided in Table 5-3. The current status of this programme (as of June, 2009) is that the sorption experiments have been finalised and the evaluation of the results is on-going. An SKB P-series data report presenting the experimental results has been published /Holgersson 2009/.

In the batch sorption experiments, solid material from the QD samples is mixed with water that contains the radionuclides of which sorption is to be studied. The sorption of the radionuclides on/in the solid material is quantified by measuring the change in aqueous concentrations. The ratio of solid- and aqueous-phase concentrations is expected to stabilise after some time, which gives the K_d value.

Both natural groundwater from Laxemar and synthetic (laboratory produced) water are used in the present programme. In both cases, the waters are “spiked” with radionuclides at concentrations judged to be suitable for the forthcoming analyses and K_d determinations. The concentration levels in this “spiking” and the relatively short contact times between water and solid material are the main differences between the batch sorption experiments and the natural concentration K_d calculations described in the preceding section (see also /Sheppard et al. 2009/ for a discussion on different types of K_d measurements).

An important aspect of the evaluation of the batch sorption experiments is to investigate potential relations between K_d values and the parameters measured in the sample characterisation. Thus, not only the actual K_d are of interest, but also (or even primarily) to develop the understanding of how they depend on the various underlying conditions quantified in the sample characterisation. Another important part of the evaluation is to evaluate the experimental procedure as such; the methodology is not as well established as that used for measuring K_d on rock samples and may need to be modified in future experiments.

Batch experiments investigating sorption of radiotracers of I, Cs, Sr, Ni, Eu, U and Np were performed using eight selected soil samples (Table 5-2) and one natural groundwater. The solid:liquid ratio in the experiments was 1:48, and sampling was made at 3 hours, 1 day, 7 days, 14 days, 40 days and 130 days after the start of the experiments. The same type of batch sorption experiments were also made with a synthetic groundwater. The recipe for the synthetic groundwater was based on the analyses of the natural groundwater, except that the dissolved organic matter was omitted.

A separate series of supporting experiments, without radionuclide tracers, was carried out for measuring the evolution of pH and Eh. Additional supporting measurements were made of a large number of chemical parameters, using samples taken after 14 and 130 days only. These measurements are intended to support the evaluation of the experiments. In particular, the results will help explaining the differences in sorption among the various combinations of radionuclide, Quaternary deposit and water composition investigated.

In the following, some experimental results reported in /Holgersson 2009/ are summarised. However, quantitative information in the form of K_d values is not given here; this type of results will be reported in connection with the evaluation.

- According to /Holgersson 2009/, the general trend of the batch sorption results shows specific surface-corrected distribution coefficients that increase with time. However, the rate of change is decreasing and the distribution coefficients generally approach constant values. The reasons for the increase in sorption with time and other changes in chemistry during the experiments (i.e. in master variables) will be investigated in the evaluation.
- Iodine sorption is generally below the lower detection limit and very few data could be collected for this tracer. Eu generally shows the strongest sorption and some measurements on the later sampling occasions show values above the upper measurement limit.
- Results from the batch experiments with peat and natural groundwater at 130 days show the following order of increasing sorption: Sr, Ni, Np, Eu, U and Cs. For the synthetic groundwater Eu and U sorption is stronger, at least initially, compared with the natural groundwater, but for Cs the sorption is weaker over the whole sampling period.
- The results for sorption on the two clay gyttja samples with natural groundwater show the weakest sorption for Sr and the strongest for Eu, whereas the order of the other radionuclides differs for the two samples.
- The order of increasing sorption on clay with natural groundwater after 130 days is: U, Sr, Np, Ni, Cs and Eu. For synthetic groundwater, U and Ni sorption is stronger, and for Cs it is weaker.
- Sorption on the two till samples in the experiments with natural groundwater is weakest for U and strongest for Eu. For the till samples Cs is the second most strongly sorbing radionuclide, whereas the relative strength among the other radionuclides differs for the two samples.
- The data in /Holgersson 2009/ also show that pH increases during the sampling period by about 0.5 units in all experiments, whereas Eh decreases.
- As intended, the TOC concentration was much higher in the natural groundwater (~1 mM), whereas it was below the detection limit in the synthetic groundwater (< 0.2 mM). However, TOC contributions from the solid phases complicate the pattern.

5.5 Concluding remarks

This chapter summarised 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 properties governing solute transport from bedrock to regolith were described.

The description of the bedrock geology and, in particular, the hydrogeological models derived using this description as a basic input, emphasise topographical control of the groundwater flow pattern with discharge areas located in valleys and other depressions. The general features of this system can be regarded as well established, whereas the details of groundwater discharge, i.e. where in a given valley it takes place, appears to be strongly dependent on the local geological-hydrogeological heterogeneity. However, there exists a relatively large amount of data that can be used as a basis for more detailed identification and description of discharge areas.

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 Laxemar. 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.

Some of the parameters required for assessing the solute retention conditions in the regolith are presented in this site description, whereas the presentation of others, most notably K_d values of the different Quaternary deposits at the site, is incomplete. Calculations of site-specific K_d values based on measured concentrations have been performed and reported /Sheppard et al. 2009/, and also K_d values from batch sorption experiments on samples from the site /Holgersson 2009/ will become available.

Within the SDM-Site Laxemar framework, transport modelling in the form of particle tracking simulations has been performed using ConnectFlow /Rhén et al. 2009/. However, no transport modelling results produced using MIKE SHE, which otherwise is the tool used for surface/near-surface flow and transport modelling, are presented in SDM-Site Laxemar. Some important observations can be made in the transport modelling results produced to date, but additional modelling would be required if a more detailed understanding of the transport in the uppermost part of the system is needed.

6 Concluding synthesis of the surface system at Laxemar

6.1 General description

The Laxemar-Simpevarp area is located along the coastline of the Baltic Sea in south-eastern Sweden. The area, which is typical for this part of eastern Sweden, is characterised by a relatively flat topography in a fissure valley landscape, dominated by coniferous forests. The predominantly thin Quaternary deposits are mainly located in the valleys, whereas the high-altitude areas are dominated by exposed bedrock or thin layers of till and peat. Glacial till is the most common Quaternary deposit and covers half of the terrestrial part of the regional model area.

The latest deglaciation in Laxemar-Simpevarp took place during the Preboreal climatic stage, c. 12,000 years ago. The whole regional model area is situated below the highest shoreline. At the deglaciation, the shoreline was situated c. 20 km west of the regional model area, which, depending on the local topography, was covered by 50–100 m of sea water. The first parts of the regional model area emerged from the sea around 9,400 BC. Accordingly, the shoreline displacement has strongly affected the landscape development, especially during the first millennia after the deglaciation. Shoreline regression has prevailed, although at a lower rate, and the rate of land uplift during the past 100 years has been c. 1 mm per year.

According to the conceptual description of the Quaternary deposits, sandy-gravelly till is overlying the bedrock in the whole area, also in most areas with exposed/shallow rock (which may have an overburden depth of up to c. 0.5 m). The exceptions are some of the exposed/shallow rock areas, in which organic soil and a thin vegetation layer is directly overlying the rock. The sandy till is characterised by a relatively high hydraulic conductivity (c. $4 \cdot 10^{-5}$ $m \cdot s^{-1}$). Furthermore, there are indications that the hydraulic conductivity of the Quaternary deposits overlying the bedrock in the deepest parts of the large valleys is about one order of magnitude higher compared with that in other parts of the area.

The annual average precipitation in the area is c. 600 mm and the annual specific discharge is c. 170 mm. The precipitation demonstrates a near-coastal gradient, with less precipitation at the coast compared with areas further inland. Groundwater levels in the Quaternary deposits are shallow; according to monitoring data, the average depth to the groundwater table is less than 1 m during more than half of the year. Generally, the depth to the groundwater table is larger in high-elevation areas than in low-elevation areas, but this variation is much smaller than the variation in absolute groundwater levels in the area. Accordingly, there is a close correlation between the ground-surface topography and groundwater levels in the Quaternary deposits, which in turn implies that topography has a strong influence on near-surface patterns of groundwater recharge and discharge.

Most of the regional model area (73%) is covered by forests, dominated by Scots pine (Sw: *tall*) and Norway spruce (Sw: *gran*). Deciduous trees are more common near the coast, making the mixed forest the second most common forest type. Wetlands are less frequent and cover only 1% of the area, whereas agricultural land covers c. 8%. The agricultural land consists of arable land and grasslands. Many 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/.

There are five lakes and a number of small streams in the regional model area. Only one of the lakes, Lake Frisksjön, is situated within the Laxemar local model area. Typically, the lakes are small with relatively shallow depths. They are characterised as mesotrophic brown-water lakes, i.e. with moderate nutrient concentrations and with brown water colour. The water colour is caused by high input of organic matter from the surrounding catchments. Because of the brownish water, light penetration is poor and the depth of the photic zone is generally small. In accordance, macrophyte coverage is small in the lakes and the biota is dominated by heterotrophic organisms, particularly bacteria. Perch is the dominant fish species in lakes in the area, in numbers, as well as in weight. Most of the streams in the area are small with mostly calm or slowly flowing water. Many streams are dry in the summer, but a few, such as Laxemarån, have a permanent water flow. Both lakes and streams in the area are to a large extent influenced by human activities, e.g. lowering of the lake water levels and altering the stream channels by various technical encroachments.

The marine area in Laxemar-Simpevarp is separated from the open sea in the east by the island of Öland, forming a funnel-like strait with its wide end to the north and the narrow end southwards. The bottom along the coast slopes gradually in the offshore direction. The maximum depth recorded in the regional model area is c. 45 m. The marine area can be divided into three subareas with more or less distinct characteristics concerning ecosystem structuring factors such as wave exposure, light penetration and substrate type. These subareas are; secluded bays, shallow exposed archipelago, and deep, exposed areas.

The average light penetration depth (Secchi depth) at the marine sampling sites is 5.5 m, which is low compared to the national monitoring station located further out in the Baltic Proper (8.7 m). However, the light penetration varies within the area, and the sheltered inner bays have Secchi depths of only 2–3 m. The salinity in the outer, exposed parts of the regional model area is 6.8 psu (practical salinity units), which is similar to that in the Baltic Proper, whereas the salinity at sampling stations in the inner bays is lower (mean values between 5.5 and 6.3 psu) and varies strongly over time due to the influence of freshwater from land.

In conclusion, the surface system site description has increased the general understanding of how the site functions in terms of properties in different volumes, main functional units, processes and system descriptions of different scientific disciplines. The initial conceptual model, 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 accumulation of matter in and between different parts of the surface system at Laxemar-Simpevarp.

The site description will be used in safety assessments to provide input data on properties, identification of relevant processes, and an overall system conceptualization 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 (SKB R-08-19).
- The terrestrial ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (SKB R-08-01).
- The limnic ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (SKB R-08-02).
- The marine ecosystems at Forsmark and Laxemar. Site descriptive modelling, SDM-Site (SKB R-08-03).
- Hydrochemistry of surface water and shallow groundwater. Site descriptive modelling, SDM-Site Laxemar (SKB R-08-46).
- Description of surface hydrology and near-surface hydrogeology at Laxemar-Simpevarp. Site descriptive modelling, SDM-Site Forsmark (SKB R-08-71).
- Description of regolith at Laxemar-Simpevarp. Site descriptive modelling, SDM-Site Laxemar (SKB R-08-05).

The present site description covers all available information on the natural system at Laxemar-Simpevarp. Nowhere else in Sweden, except for the corresponding description of the Forsmark area, are such comprehensive background data and models available for environmental impact assessments (EIA's). Main SDM references for the EIA are the ecosystem reports covering the biotic and abiotic descriptions of the Laxemar-Simpevarp surface system. Data on the hydrology and the properties of the Quaternary deposits are also available, together with the chemical description of water, soil and biota. No description on nature values, as defined by the general society, 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 conceptualization 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

All QD in the Laxemar area have most probably been deposited during or after the latest deglaciation. The Baltic Sea completely covered the investigated area after the latest deglaciation. The geographical distribution and depth of the QD is largely determined by the topography of the underlying bedrock. Areas with exposed bedrock and a thin till cover dominate the whole regional model area, including the sea floor. These areas are crossed by a number of fissure valleys where the regolith cover is considerably thicker. Glacial clay with a thin cover of sand is the dominating surface deposit in the valleys on the sea floor. In the bays and land areas, the valleys are dominated by clay gyttja, which at many locations in the terrestrial areas is covered by a thin layer of peat. The groundwater table in many of the former wetlands has been artificially lowered to obtain land for forestry and agriculture, which has caused the peat to partly or completely oxidise. There are several glaciofluvial deposits, with a north strike, in the investigated area. As land uplift proceeds, some new areas are being subjected to erosion at the same time as other new areas are becoming lakes and sheltered bays where fine-grained sediments can accumulate. The stratigraphical distribution of QD in the investigated area is rather uniform. Till is the oldest QD in the area, and is consequently resting directly upon the bedrock surface. The till in the valleys is often overlain by glacial clay, which in many valleys is overlain by a thin layer of sand followed by clay gyttja and peat. The till has a low content of fine material and is dominated by sand and gravel. The contents of elements in the regolith from the Laxemar area are close to the Swedish averages.

A comprehensive description of the regolith at Laxemar-Simpevarp 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

The site investigations at Laxemar-Simpevarp included comprehensive investigations of meteorology, hydrology and near-surface hydrogeology: monitoring was undertaken of meteorology (including ”winter parameters” such as snow depth and ice freeze/breakup), surface-water levels in lakes and bays of the Baltic Sea, stream discharges, groundwater levels in the QD and point-water heads in the rock. Moreover, different types of field- and laboratory tests were conducted for hydrogeological characterisation of the QD and the interaction between groundwater in the QD and groundwater in the rock.

Sandy-gravelly till overlies the bedrock in almost the whole area. The high-altitude areas are dominated by shallow deposits / exposed bedrock (QD depth less than c. 0.5 m). The sandy-till has a relatively high hydraulic conductivity, whereas there are indications that the hydraulic conductivity of the QD overlying the bedrock in the deepest parts of the large valleys is about one order of magnitude higher than that of till in other parts of the area. Four main hydrogeological type areas have been defined: High-altitude areas, large and small valleys, glaciofluvial deposits, and hummocky moraine areas. Moreover, the conceptual modelling includes parameterizations of the overall hydrogeological flow domains (QD and rock).

The characteristics of the main hydrogeological flow domains (QD and rock) imply that one can identify two main sub-flow systems for groundwater flow: One system located in the upper part of the bedrock (say 0–10 m) and the QD, which overlies a larger-scale flow system primarily associated with deformation zones in the rock. According to the conceptual hydrogeological model, groundwater recharge primarily takes place in high-altitude areas, dominated by shallow deposits / exposed rock.

Groundwater discharge is conceptually thought to take place in the low-altitude areas, corresponding to the ”valley” type area as defined in the conceptual hydrogeological model. Groundwater discharge from the bedrock to the QD primarily takes place at locations where deformation zones outcrop in the valleys; groundwater discharge from the deep bedrock is less likely in areas where there are no outcropping deformation zones. Groundwater discharge from the upper bedrock/QD part of the system to the surface (surface waters) is strongly influenced by the geometry and the hydrogeological properties of the QD overlying the till. Moreover, there is also an influence on this process of the horizontal extent and the hydrogeological properties of the upper bedrock (the deformation zones) and the high-conductive QD overlying the bedrock in the valleys. Locally, there is a fractionation into groundwater that discharges to the surface and groundwater that flows horizontally along the valley in the upper rock/QD system; groundwater discharge to the surface is facilitated in areas where there are no layers of glacial clay and postglacial sediments above the till.

In summary, there is a good understanding of the hydrological and hydrogeological driving forces and the overall water-flow patterns in the Laxemar-Simpevarp area. Section 6.3.3 summarizes existing knowledge gaps in relation to properties and detailed process descriptions.

6.2.3 Ecosystem models

Based on an overall conceptual model, it was possible to identify pools of carbon and other elements that are of potential relevance to a safety assessment. The element fluxes to and from these pools may vary over time, and accordingly, the pattern of element accumulation in the landscape may also vary. Knowledge of element accumulation in the landscape over time is essential for the identification of potential sinks for contaminants. Any pool of contaminants may be effectively isolated from today’s ecosystem, e.g. by burial in the deeper sediments, but it may also either today or in the future (due to natural or human-induced changes in the landscape) be available to 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, the largest sink for organic matter is the vegetation, but the soil also 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 developed on areas 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 has a high potential for remobilising bioavailable radionuclides and transferring them to humans, especially as this type of land-use is often preceded by ditching. The export of carbon and organic matter from a terrestrial ecosystem is low in comparison with the internal fluxes within the ecosystem.

Lake ecosystems

The most important inflow of elements to lakes is the inflow via water from the terrestrial areas. Similar to most brownwater lakes in Sweden, the lake ecosystems in Laxemar-Simpevarp show much higher respiration than primary production. This means that the energy needs of the lake ecosystem to a large degree are sustained by organic matter produced in the surrounding terrestrial areas. Accordingly, the lakes are important sites for biogeochemical processes in the landscape.

The by far most important outflux of elements from the lake ecosystem is via sediment accumulation. Thereby, there is a large potential for elements entering a lake from the surroundings to be incorporated into the lake food web, and finally to be accumulated in the lake sediments. The sediments may in time perspectives of decades or centuries be regarded as a permanent sink for elements, 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. Thus, present-day lake sediments may in the future be potential sources of radionuclides and other contaminants to humans and biota.

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 instead governed by advective water fluxes. The marine area as a whole is heterotrophic, i.e. more carbon is released than is fixed in biomass. However, some shallow bays in the area with high macrophyte biomass tend to be autotrophic.

Overall, for the whole area, dissolved carbon in the water phase (DIC and DOC) constitutes the major carbon pool. This is true also for most of the individual basins, but in some of the inner, secluded bays, the sediment constitutes the largest carbon pool. The most abundant elements in the marine ecosystem are the major constituents of sea water (Cl, Na, Mg and Ca). The largest amounts of most elements are found in the abiotic components of the ecosystem. However, for some of the non-metals and metalloids, a significant part of the total amount occurs in biota.

6.3 Discussion of uncertainties

As described in this report, the SDM for the surface system at Laxemar-Simpevarp 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 /Strömgren and Brydsten 2008/.

The DEM has a high resolution and the uncertainties in the model must be considered as generally small. However, due 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 quality of the regolith depth and stratigraphy model (RDM) varies within the modelled area, since the geographical density of data varies. That is particularly obvious in the marine areas where some of the lines with a high density of data contrast with surrounding areas with a low density of data (Figure 4-6). There are relatively few data showing the total depth of the regolith in the large valleys. In the RDM, most of the depths in these valleys are calculated from the average thickness of the deposits present in these areas (Table 4-1). Results from drilling indicate, however, that the regolith depth in the large valleys is generally greater than the average values used in the model. It is therefore possible that the total depth of the regolith in the large valleys is generally greater than shown in the model. Moreover, in large parts of the model area, the regolith depths are modelled by use of the QD map. Since the QD map has low reliability in outer parts of the model area, also the RDM has low quality in these areas.

The spatial resolution of the model is 20×20 m. The limited spatial resolution 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. The uncertainties in the regolith depth and stratigraphy model are further discussed in /Nyman et al. 2008, Sohlenius and Hedenström 2008/.

6.3.2 Shoreline displacement and salinity changes in the Baltic

In the Laxemar-Simpevarp area, the latest deglaciation occurred c. 12,000 years BC /Lundqvist and Wohlfarth 2001/. The highest shoreline in the Oskarshamn region is c. 100 metre above sea level /Agrell 1976/, which means that the whole Laxemar-Simpevarp regional model area is situated below the highest shoreline.

The late Weichselian and early Holocene shoreline displacement in the Oskarshamn region has been studied by /Svensson 1989/. The estimated shoreline displacement since the last deglaciation has been reviewed and modified by /Påsse 2001/ (Figure 4-1). According to /Svensson 1989/ shoreline dropped instantaneously c. 25 metres due to drainage of the Baltic Ice Lake 9,500 years BC. The onset of the following Ancylus Lake stage was characterised by a transgression of c. 11 metre. There are no studies from the Oskarshamn area dealing with shoreline displacement during the Littorina

Sea stage. The shoreline displacement curve presented by /Påsse 2001/ shows one transgressive phase during the early part of the Littorina Sea but does not reveal any other transgressive phases. However, detailed stratigraphical studies of sediments from areas north (Södermanland) and south (Blekinge) of the Laxemar-Simpevarp area have shown that three (Södermanland) and six (Blekinge) transgressions occurred during that period /Berglund 1971, Risberg et al. 1991/. It is therefore likely that several transgressions occurred in the Laxemar-Simpevarp area during the Littorina stage. The rate of land uplift during the last 100 years has been c. 1 mm/year /Ekman 1996/.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 open Baltic proper. However, since the Laxemar-Simpevarp area has been situated close to the coast during most of the Littorina stage, it can be assumed that salinity has been generally lower than is 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 hydrogeology

Joint evaluations of meteorological data, surface-water level and discharge data, and groundwater-level/point-water head data have led to an improved understanding of hydrology and near-surface hydrogeology in Laxemar. The presented conceptual model conveys the current understanding of the hydrological and hydrogeological driving forces and the overall water-flow patterns, as wells as knowledge gaps in terms of properties and detailed process descriptions. Specifically, there are some uncertainties associated with the data used for modelling of hydrology and near-surface hydrogeology. Examples of such uncertainties include reliance on non-standard designs and natural sections at surface-discharge gauging stations. This is handled by excluding the uncertain data when developing the conceptual model description (water balances) and calibration of the quantitative water flow model (MIKE SHE).

Generally a larger amount of detailed field investigation data are available from performed in the central parts of the Laxemar local model area, and also on the islands of Ävrö and Hålö and the Simpevarp peninsula. There are less detailed underlying descriptions available for other areas, for which descriptions are primarily based on remote sensing studies.

Characteristic of Laxemar-Simpevarp are the large areas with shallow deposits/exposed rock. Such areas are difficult to parameterize in conceptual models and also to represent properly in quantitative water flow models. There are relatively few hydrogeological monitoring data from the high-altitude areas that can be used to describe the processes of infiltration and groundwater recharge. This bias also relates to the MIKE SHE modelling, as the hydrogeological and hydrological (surface-water discharge) calibration data set primarily includes monitoring data from low-lying areas.

Another characteristic of Laxemar-Simpevarp is the large degree of anthropogenic influence. Of particular interest for hydrology and near-surface hydrogeology is the fact that many areas are affected by land improvement and drainage operations, which has been taken into account by field checks of such operations. Moreover, periods with disturbed groundwater-level and point-water head data have been removed from the data set used for conceptual model development and quantitative model calibration.

6.3.4 Regolith

The evaluation of uncertainties in the description of the regolith can be divided in two parts: spatial distribution 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 are high in these terrestrial parts of the area, whereas the reliability of the map is low in some of the more outer parts of the area /cf. Sohlenius and Hedenström 2008/.

Geophysical methods were used to interpret the distribution of QD in the marine areas. The quality of the marine parts of the map is regarded as high in the deeper parts of the near-shore areas, where the distribution of QD was interpreted by means of sonar recordings of high quality. In the more off-shore areas, sonar recordings were of lower quality and it was sometimes difficult to distinguish till from bedrock outcrops. Other areas with high uncertainties are those situated near the shore and not deep enough to be included in the marine geological mapping programme. In these areas, the distribution of the QD was interpreted from bathymetric information and from the known distribution of QD in the mapped marine and terrestrial areas.

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 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. It is difficult to conclude whether the analysed properties of the different types of regolith are representative of the whole regional model area, since too few analyses have been performed at some of the deposits. For example, only five samples of peat from the same site were analysed for chemical properties.

Some samples from the valleys, classified as till in the field, are surprisingly well sorted with respect to grain size. All these samples were obtained from drillings and were taken beneath thick layers of glacial and postglacial clay. It is possible that the till in these valleys has a grain size composition which is different from the till in other parts of the model area. It is also possible that these samples represent another type of deposit than till, e.g. glaciofluvial sediments. However, the properties of these samples may have been altered by the sampling method. Certain data describing the physical properties of the regolith were taken from the literature. It is not known whether these data are representative for the regolith in the Laxemar-Simpevarp area.

The accumulation rates in marine, coastal, mireand limnic areas have been quantified, but are based on data from a few sites. Thus, the uncertainties 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 characterisations and hydrological measurements 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. 2008/. Much of the report by /Tröjbom et al. 2008/ comprises an explorative evaluation of a vast amount of hydrochemical data from surface waters and shallow groundwater at Laxemar-Simpevarp. 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. 2008/ 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 scentific 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 requires 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 overall and relative magnitudes of amounts and flows in the models are thought to be correct.

7 References

Agrell H, 1976. The highest coastline in south-eastern Sweden. Boreas 5, 143–154.

Almén K-E, Talme O, 1975. Jordartsanalys. Laboratorieanvisningar, del 1. Department of Quaternary Research, Stockholm University, 133 pp.

Andersson J, 2005. Investigation of the amount of dead wood. Oskarshamn site investigation. SKB P-05-87, Svensk Kärnbränslehantering AB.

Andersson M, Nilsson C-A, 1992. Markgeokemiska kartan 3–7, F-H. SGU. Rapporter och meddelanden nr 73. Kartor i skalan 1:1 miljon (in Swedish).

Altman P L, Dittmer D S (eds), 1964. Biology data book. Federation of American Societies for experimental biology, Washington 633 p.

Arnesson A, 2001. Välskötta vallar ger produktiva ekokor. Fakta Jordbruk, nr 14, 2001. Sveriges Lantbruksuniversitet.

Avila R, Kautsky U, Ekström P-A, 2006. Modeling the long-term transport and accumulation of radionuclides in the landscape for derivation of dose conversion factors. Ambio 35, 513–523.

Axheden Å, 2003. Personal communication. Länsstyrelsen i Kalmar län.

Balboa M A, 2005. Biomasa arbórea y estabilidad nutricional de los sistemas forestales de Pinus pinaster Ait., Eucalyptus globulus Labill. y Quercus robur L. en Galicia. Doctoral Thesis. Universidad de Santiago de Compostela, 244 pp.

Berg J, Jansson U, Wästfelt A, 2006. Landscape, history and people in a geographical perspective – studies of land-use, settlement and livelihood in Oskarshamn and Forsmark. SKB Report R-06-37, Svensk Kärnbränslehantering AB.

Berglund B, 1971. Littorina transgressions in Blekinge, South Sweden. A preliminary survey. Geologiska Föreningens i Stockholm Förhandlingar 93, 625–652.

Bergman T, Malmberg Persson K, Persson M, Albrecht J, 2005. Oskarshamn site investigation – Characterisation of bedrock and Quaternary deposits from excavations in the southern part of Laxemar subarea. SKB P-05-47, Svensk Kärnbränslehantering AB.

Bergman T, Sohlenius G, 2007. Oskarshamn site investigation – Petrographic analysis of gravel and boulders in till from the Laxemar area. SKB P-07-30, Svensk Kärnbränslehantering AB.

Blomqvist P, Nilsson E, Brunberg A-K, 2002. Habitat distribution, water chemistry, and biomass and production of pelagic and benthic microbiota in Lake Eckarfjärden, Forsmark. SKB R-02-41, Svensk Kärnbränslehantering AB.

Boresjö Bronge L, Wester K, 2003. Vegetation mapping with satellite data of the Forsmark, Tierp and Oskarshamn regions. SKB P-03-83, Svensk Kärnbränslehantering AB.

Bosson E, Sassner M, Gustafsson L-G, 2008. Numerical modelling of hydrology and near-surface hydrogeology at Laxemar-Simpevarp. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-72, Svensk Kärnbränslehantering AB.

Brunberg A-K, Blomqvist P, 2000. Post-glacial, land rise-induced formation and development of lakes in the Forsmark area, central Sweden. SKB TR-00-02, Svensk Kärnbränslehantering AB.

Brunberg A-K, Carlsson T, Brydsten L, Strömgren M, 2004. Oskarshamn site investigation. Identification of catchments, lake-related drainage parameters and lake habitats. SKB P-04-242, Svensk Kärnbränslehantering AB.

Brydsten L, 2006. A model for landscape development in terms of shoreline displacement, sediment dynamics, lake formation, and lake choke-up processes. SKB TR-06-40, Svensk Kärnbränslehantering AB

Brydsten L, Strömgren M, 2005. Digital elevation models for site investigation programme in Oskarshamn. Site description version 1.2. SKB R-05-38, Svensk Kärnbränslehantering AB.

Chapin F S, Matson P, Mooney H A, 2002. Principles of terrestrial ecosystem ecology. Springer – Verlag, New York, Inc., pp 436.

Crawford J, Sidborn M (eds.), 2009. Bedrock transport properties Laxemar. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-94, Svensk Kärnbränslehantering AB.

Cushing C E, Minshall G W, Newbold J D, 1993. Transport dynamics of fine particulate matter in two Idaho streams. Limnology and Oceanography 38:1101–1115.

Davis J C, 1986. Statistics and data analysis in geology. John Wiley & Sons, New York, p 383–404.

DHI Water & Environment, 2005. MIKE GeoModel – User Guide. DHI Water & Environment, Hörsholm, Denmark.

Drake H, Tullborg E-L, 2008. Oskarshamn site investigation. Detecting the near surface redox front in crystalline rock. Results from drill cores KLX09B-G and KLX11B-F. SKB P-08-44, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, 2009. Fracture mineralogy Laxemar. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-99, Svensk Kärnbränslehantering AB.

Dyson R D, 1978. Cell biology, Allyn & Bacon, Boston 616 pp.

Ekman M, 1996. A consistent map of the postglacial uplift of Fennoscandia. Terra-Nova 8/2, 158–165.

Elhammer A, Sandkvist Å, 2005. Detailed marine geological survey of the sea bottom outside Simpevarp. Oskarshamn site investigation. SKB P-05-35, Svensk Kärnbränslehantering AB.

Elser J J, Urabe J, 1999. The stoichiometry of consumer-driven nutrient recycling: theory, observations, and consequences. Ecology 80(3), 735–751.

Elser J J, Fagan W F, Denno R F, 2000. Nutritional contraints in terrestrial and freshwater food webs. Nature 408: 578–580.

Emeis K C, Struck U, Blanz T, Kohly A, Voss M, 2003. Salinity changes in the central Baltic Sea (NW Europe) over the last 10,000 years. The Holocene 13, 411–421.

Emeis K C, Struck U, Leipe T, Pollehne F, Kunzendorf H, Christiansen C, 2000. Changes in the C, N, P burial rates in some Baltic Sea sediments over the last 150 years-relevance to P regeneration rates and the phosphorus cycle. Marine Geology 167, 43–59.

Engdahl Alf, Ternsell A, Hannu S, 2006. Chemical characterisation of deposits and biota, Oskarshamn site investigation. SKB P-06-320, Svensk Kärnbränslehantering AB.

Engdahl A, Rådén R, Borgiel M, Omberg L-G, 2008. Oskarshamn and Forsmark site investigations. Chemical composition of suspended material, sediment and pore water in lakes and seabays. SKB P-08-81, Svensk Kärmbränslehantering AB.

Follin S, Årebäck M, Axelsson C-L, Stigsson M, Jacks H, 1998. Förstudie Oskarshamn, Grundvattnets rörelse, kemi och långsiktiga förändringar. SKB R-08-55, Svensk Kärnbränslehantering AB.

Follin S, Johansson P-O, Hartley L, Jackson P, Roberts D, Marsic N, 2007. Hydrogeological conceptual model development and numerical modelling using CONNECTFLOW, Forsmark modelling stage 2.2. SKB R-07-49, Svensk Kärnbränslehantering AB.

Fredén C (ed.), 2002. Geology. The Swedish national atlas. Third edition. 208 pp.

Fredriksson R, 2004. Oskarshamn site investigation – Inventory of the soft-bottom macrozoobenthos community in the area around Simpevarp nuclear power plant. SKB P-04-17, Svensk Kärnbränslehantering AB.

Fridriksson G, Öhr J, 2003. Forsmark site investigation – Assessment of plant biomass of the ground, filed and shrub layers of the Forsmark area. SKB P-03-90, Svensk Kärnbränslehantering AB.

Gimeno M J, Auqué L F, Gómez J B, Acero, P, 2008. Water-rock interaction modelling and uncertainties of mixing modelling. Site Descriptive Modelling. SDM-Site Laxemar. SKB R-08-110, Svensk Kärnbränslehantering AB.

Grandia F, Sena C, Arcos D, Molinero J, Duro L, Bruno J, 2007. Quantitative assessment of radionuclide retention in the near-surface system at Forsmark. Development of a reactive transport model using Forsmark 1.2 data. SKB R-07-64, Svensk Kärnbränslehantering AB.

Greger M, 2004. Uptake of nuclides by plants. SKB TR-04-14. Svensk Kärnbränslehantering AB.

Green M, 2005. Bird monitoring in Simpevarp 2002–2004. Oskarshamn site investigation. SKB P-05-42, Svensk Kärnbränslehantering AB.

Grip H, Rodhe A, 1985. Vattnets väg från regn till bäck. Hallgren & Fallgren Studieförlag AB, Uppsala, Sweden (in Swedish).

Gustafsson B, 2004a. Millennial changes of the Baltic Sea salinity. Studies of the sensitivity of the salinity to climate change. SKB TR-04-12, Svensk Kärnbränslehantering AB.

Gustafsson B, 2004b. Sensitivity of the Baltic Sea salinity to large perturbations in climate. Climate Research, 27, 237–251.

Hallbeck L, 2009. Evaluating hydrochemical data from shallow groundwater in Laxemar from a microbiological perspective. SKB R-09-02, Svensk Kärnbränslehantering AB.

Hannu S, Karlsson S, 2006. Chemical characterisation of deposits and biota, Forsmark site investigation. SKB-report P-06-220, Svensk Kärnbränslehantering AB.

Holgersson S, 2009. Oskarshamn site investigation. Batch experiments of I, Cs, Sr, Ni, Eu, U and Np sorption onto soil from the Laxemar area. SKB P-09-29, Svensk Kärnbränslehantering AB.

Ingvarson N H, Palmeby A S L F, Svensson L O, Nilsson K O, Ekfeldt T C I, 2004. Marine survey in shallow coastal waters, Bathymetric and geophysical investigation 2004. Oskarshamn site investigation. SKB P-04-254, Svensk Kärnbränslehantering AB.

Ingvarson N, Palmeby A, Svensson O, Nilsson O, Ekfeldt T, 2004. Marine survey in shallow coastal waters. Bathymetric and geophysical investigation 2004. Oskarshamn site investigation. SKB P-04-204, Svensk Kärnbränslehantering AB.

Isaaks E H, Srivastava R M, 1989. An introduction to applied geostatistics, Oxford University Press, NY, Oxford. ISBN 0-19-505013-4.

Jackson M L, 1958. Soil chemical analysis. Constable & Co Ltd. London. 498 p.

Jansson U, Kautsky U, Miliander S, 2006. Rural landscape, production and human consumption: Past, present and future. Ambio 35, 505–512.

Johansson T, 2000. Biomass equations for determining functions of common and grey alder growing on abandoned farmland and some practical implicatons. Biomass and Bioenergy 18, 147–159.

Johansson T, Adestam L, 2004a. Oskarshamn site investigation. Slug tests in groundwater monitoring wells in soil in the Simpevarp area. SKB P-04-122, Svensk Kärnbränslehantering AB.

Johansson T, Adestam L, 2004b. Oskarshamn site investigation. Drilling and sampling in soil. Installation of groundwater monitoring wells in the Laxemar area. SKB P-04-317, Svensk Kärnbränslehantering AB.

Johansson T, Göransson M, Zetterlund M, Jenkins K, Rönnback K, 2006. Oskarshamn site investigation. Hydrogeological characterization in bogs, lakes and sea bays. SKB P-06-248, Svensk Kärnbränslehantering AB.

Kaislahti Tillman P, Risberg J, 2006. Oskarshamn site investigation – Holocene sedimentary environmental changes at sites PSM002118 and PSM002123 offshore Simpevarp. SKB P-06-250, Svensk Kärnbränslehantering AB.

Kardell L, Eriksson L, 1987. The effect of forest operations on the production of edible mushrooms. Sveriges Skogsvårdsförbunds Tidskrift, 85(2):3–23.

Kjellin B, 2007. Revidering och komplettering av tidigare maringeologiska undersökningar i Simpevarp- och Forsmark-områdena. Utförd inom programmet för Fysisk planering. SGU report (in Swedish).

Knape S, 2001. Natural hydrochemical variations in small catchments with thin soil layers and crystalline bedrock: hydrochemical data from two catchments at Äspö Island and two others in the Lake Gårdsjön area, collected 1997 to 1999. Chalmers University of Technology, Department of Geology, Göteborg, Sweden.

Kumblad L, Gilek M, Naeslund B, Kautsky U, 2003. An ecosystem model of the environmental transport and fate of carbon-14 in a bay of the Baltic sea, Sweden. Ecological Modelling 166, 193–210.

Kumblad L, Kautsky U, Naeslund B, 2006a. Transport and fate of radionuclides in aquatic environments- the use of ecosystem modelling for exposure assessments of nuclear facilities. Journal of Environmental Radioactivity 87, 107–129.

Kumblad L, Söderbäck B, Löfgren A, Lindborg T, Wijnbladh E, Kautsky U, 2006b. Pools and fluxes of organic matter in a boreal landscape: Implications for a safety assessment of a repository for nuclear waste. Ambio 35, 496–504.

Kumblad L, Bradshaw C, 2008. Element composition of biota, water and sediment in the Forsmark area, Baltic Sea. Concentrations, bioconcentration factors and partitioning coefficients (Kd) of 48 elements. SKB TR-08-09, Svensk Kärnbränslehantering AB.

Laaksoharju M, Smellie JAT, Tullborg E-L, Wallin B, Drake H, Gimeno M, Hallbeck L, Molinero J, Nilsson A-C, Waber N, 2009. Bedrock hydrogeochemistry Laxemar, Site descriptive modelling, SDM-Site Laxemar. SKB R-08-93, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, Svantesson S-I, 2006. Oskarshamn site investigation – Searching for evidence of late- or postglacial faulting in the Oskarshamn region. Results from 2005. SKB P-06-160. Svensk kärnbränslehantering AB.

Larsson-McCann S, Karlsson A, Nord M, Sjögren J, Johansson L, Ivarsson M, Kindell S, 2002. Meteorological, hydrological and oceanograpical data for the site investigation program in the community of Oskarshamn. SKB TR-02-03, Svensk Kärnbränslehantering AB.

Lindborg T (ed.), 2005. Description of surface systems. Preliminary site description. Simpevarp sub area – version 1.2. SKB R-05-01, Svensk Kärnbränslehantering AB.

Lindborg T (ed.), 2006. Description of surface systems. Preliminary site description Laxemar subarea – Version 1.2. SKB R-06-11, Svensk Kärnbränslehantering AB.

Lindborg T, Lindborg R, Löfgren A, Söderbäck B, Bradshaw C, Kautsky U, 2006. A strategy for describing the biosphere at candidate sites for repositories of nuclear waste: Linking ecosystem and landscape modeling. Ambio 35, 418–424.

Lindqvist G, 2004a. Oskarshamn site investigation – Refraction seismic measurements in Laxemar. SKB P-04-134. Svensk Kärnbränslehantering AB.

Lindqvist G, 2004b. Oskarshamn site investigation – Refraction seismic measurements in the water outside Simpevarp and Ävrö and on the land on Ävrö. SKB P-04-201. Svensk Kärnbränslehantering AB.

Lindqvist G, 2004c. Oskarshamn site investigation – Refraction seismic measurements in Laxemar autumn 2004. SKB P-04-298. Svensk Kärnbränslehantering AB.

Lindqvist G, 2005. Oskarshamn site investigation – Refraction seismic measurements in Laxemar spring 2005. SKB P-05-155. Svensk Kärnbränslehantering AB.

Lindqvist G, 2006. Oskarshamn site investigation – Refraction seismic measurements in Laxemar spring 2006. SKB P-06-49. Svensk Kärnbränslehantering AB.

Lindqvist G, 2007. Oskarshamn site investigation – Refraction seismic measurements in Laxemar spring 2007. SKB P-07-131. Svensk Kärnbränslehantering AB.

Lindroos H, 2004. Oskarshamn site investigation – The potential for ore, industrial minerals and commercial stones in the Simpevarp area. SKB R-04-72. Svensk Kärnbränslehantering AB.

Lundin L, Björkvald L, Hansson J, Stendahl J, 2004. Surveillance of soils and site types in the Oskarshamn area. Oskarshamn site investigation. SKB P-04-243, Svensk Kärnbränslehantering AB.

Lundin L, Lode E, Stendahl J, Björkvald L, Hansson J, 2005. Oskarshamn site investigation. Soils and site types in the Oskarshamn area. SKB R-05-15. Svensk Kärnbränslehantering AB.

Lundin L, Snäll S, Jonsson E, Hannu S, Selnert E, Engdahl A, 2007. Oskarshamn site investigation. Characterization of soil samples from three valleys in the Laxemar area. SKB P-07-222, Svensk Kärnbränslehantering AB.

Lundqvist J, Wohlfarth B, 2001. Timing and east-west correlation of south Swedish ice marginal lines during the Late Weichselian. Quaternary Science Reviews 20, 1127–1148.

Lundqvist L, 2006. Inledande kulturhistoriska studier i Simpevarpsområdet: Småland, Misterhults socken, Oskarshamn kommun. SKB R-06-65, Svensk Kärnbränslehantering AB. (In Swedish).

Lärke A, Hillgren R, Wern L, Jones J, Aquilonius K, 2005. Hydrological and meteorological monitoring at Oskarshamn during 2003–2004. Oskarshamn site investigation. SKB P-05-227, Svensk Kärnbränslehantering AB.

Löfgren A, 2005. Estimation of biomass and net primary production in field and ground layer, and biomass in litter layer in different vegetation types in Forsmark and Oskarshamn. Oskarshamn/Forsmark site investigation. SKP P-05-80, Svensk Kärnbränslehantering AB.

Löfgren A (ed.), 2008. The terrestrial ecosystems at Forsmark and Laxemar. Site descriptive modelling. SDM-Site. SKB R-08-01, Svensk Kärnbränslehantering AB. Stockholm, Sweden.

Löfgren A, Lindborg T, 2003. A descriptive ecosystem model – a strategy for model development during site investigations. SKB R-03-06, Svensk Kärnbränslehantering AB.

Marklund L G, 1988. Biomassafunktioner för tall, gran och björk i Sverige (In Swedish), Biomass functions for Scots pine, Norway spruce and birch in Sweden. Rapport 45. Department of Forest Survey, Swedish University of Agricultural Sciences, Umeå.

Maxe L, 2003. Bestämning av markmaterialets specifika yta. Resultat från svenska sand-, grus-, morän- och lerprofiler. Institutionen för mark- och vattenteknik. Kungliga tekniska högskolan (in Swedish).

Meyer J L, Likens G E, 1979. Transport and transformation of phosphorus in a forest stream ecosystem, Ecology 60: 1255–1269.

Miliander S, Punakivi M, Kyläkorpi L, Rydgren B, 2004. Human population and activities at Simpevarp. SKB R-04-11, Svensk Kärnbränslehantering AB.

Mjöfors K, Johansson M B, Nilsson Å, Hyvönen R, 2007. Input and turnover of forest tree litter in the Forsmark and Oskarshamn areas. SKB R-07-23, Svensk Kärnbränslehantering AB. 66 pp.

Morosini M, Wass E, 2006. Oskarshamn site investigation. Hydraulic interference and tracer testing of a rock-soil aquifer system between HLX35 and HLX34, SSM000037, SSM000222 and SSM000223 – Subarea Laxemar. SKB P-06-151, Svensk Kärnbränslehantering AB.

Morosini M, Jenkins C, Simson S, Albrecht J, Zetterlund M, 2007. Oskarshamn site investigation. Hydrogeological characterization of deepest valley soil aquifers and soil-rock transition zone at Laxemar, 2006. Subarea Laxemar. SKB P-07-91, Svensk Kärnbränslehantering AB.

Nagy K A, Girard I A, Brown T K, 1999. Energetics of free-ranging mammals, reptiles and birds. Annual Review of Nutrition 19, 247–77.

Naturvårdsverket 2000. Environmental Quality Criteria – Lakes and water courses. Swedish Environmental Protection Agency, Report 5050.

Nilsson G, 2004. Oskarshamn site investigation – Investigation of sediments, peat lands and wetlands. Stratigraphical and analytical data. SKB P-04-273. Svensk Kärnbränslehantering AB.

Nordén S, Andersson E, Söderbäck B, 2008. The limnic ecosystems at Forsmark and Laxemar-Simpevarp. Site descriptive modelling. SDM-Site. SKB R-08-02, Svensk Kärnbränslehantering AB. Stockholm, Sweden.

Nyman H, Sohlenius G, Strömgren M, Brydsten L, 2008. Oskarshamn site investigation – Depth and stratigraphy of regolith SKB R-08-06. Svensk Kärnbränslehantering AB.

Olsson M, Melkerud P A, 1989. Chemical and mineralogical changes during genesis of a podzol from till in southern Sweden. Geoderma 45, 267–287.

Ottosson, P, 2006. Nulägesbeskrivning av rekreation och friluftsliv i Oskarshamn. SKB P-06-114, Svensk Kärnbränslehantering AB.

Persson H, Stadenberg I, 2007a. Distribution of fine roots in forest areas close to the Swedish Forsmark and Oskarshamn nuclear power plants. SKB R-07-01, Svensk Kärnbränslehantering AB.

Påsse T, 2001. An empirical model of glacio-isostatic movements and shore-level displacement in Fennoscandia. SKB R-01-41, Svensk Kärnbränslehantering AB.

Reddy K R, Kadelc R H, Flaig G, Gale P M, 1999. Phosphorus retention in streams andwetlands: a review. Critical reviews in environmental science and technology 29(1): 83–146.

Rhén I, Follin S, Hermanson J, 2003. Hydrogeological site descriptive model – a strategy for its development during site investigations. SKB R-03-08, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Hartley L, Jackson P, Roberts D, Swan D, Gylling B, 2008. Hydrogeological conceptualisation and parameterisation. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-78, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Hartley L, Jackson P, Joyce S, Roberts D, Swift B, Marsic N, Gylling B, 2009. Bedrock hydrogeology: Model testing and synthesis. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-91, Svensk Kärnbränslehantering AB.

Risberg J, Miller U, Brunnberg L, 1991. Deglaciation, Holocene shore displacement and coastal settlements in eastern Svealand, Sweden. Quaternary International 9, 33–39.

Rouwenhorst R J, Jzn F J, Scheffers W A, J P van Dijken, 1991. Determination of protein concentration by total organic carbon analysis, J Biochemical methods 1991, Feb-March 22(2):119–28.

Rudmark L, Malmberg-Persson K, Mikko H, 2005. Oskarshamn site investigation – Investigation of Quaternary deposits 2003–2004. SKB P-05-49. Svensk Kärnbränslehantering AB.

Rühling Å, 1997. Floran i Oskarshamns kommun. Svensk Botanisk Förening, Lund.

SCB, 1998. Markanvändningen i Sverige, tredje utgåvan, table B24. ISBN 91-618-0888-1.

SCB, 2000. Standard yields for yield survey districts, counties and the whole country in 2000. JO 15 SM 0001.

SCB, 2001. Standard yields for yield survey districts, counties and the whole country in 2001. JO 15 SM 0101.

SCB, 2002. Standard yields for yield survey districts, counties and the whole country in 2002. JO 15 SM 0201.

SCB, 2003. Standard yields for yield survey districts, counties and the whole country in 2003. JO 15 SM 0301.

SCB, 2004. Standard yields for yield survey districts, counties and the whole country in 2004. JO 15 SM 0401.

SCB, 2005. Standard yields for yield survey districts, counties and the whole country in 2005. JO 15 SM 0501.

SCB, 2006. Standard yields for yield survey districts, counties and the whole country in 2006. JO 15 SM 0601.

SCB, 2007. Standard yields for yield survey districts, counties and the whole country in 2007. JO 15 SM 0701.

Selnert E, Byegård J, Widestrand H, Carlsten S, Döse C, Tullborg E-L, 2009. Bedrock transport properties. Data evaluation and retardation model. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-100, Svensk Kärnbränslehantering AB.

Sena C, Grandia F, Arcos D, Molinero J, Duro L, 2008. Complementary modelling of radionuclide retention in the near-surface system at Forsmark. Development of a reactive transport model using Forsmark 1.2 data. SKB R-08-107, Svensk Kärnbränslehantering AB.

Sheppard M I, Sheppard S C, Grant C, 2007. Solid/liquid partition coefficients to model trace element critical loads for agricultural soils in Canada. Canadian Journal of Soil Science 87: 189–201.

Sheppard S, Long J, Sanipelli B, Sohlenius G, 2009. Solid/liquid partition coefficients (K_d) for selected soils and sediments at Forsmark and Laxemar-Simpevarp. SKB R-09-27, Svensk Kärnbränslehantering AB.

Sitch S, Smith B, Prentice I C, Arneth A, Bondeau A, Crameer W, Kaplans J O, Levis S, Lucht W, Sykes M T, Thonicke K and Venevsky S, 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Global Vegetation Model. Global Change Biology. 9:161–185.

SKB, 2000. Förstudie Oskarshamn – slutrapport. Svensk Kärnbränslehantering AB (in Swedish).

SKB, 2001. Site investigations. Investigation methods and general execution programme. SKB TR-01-29, Svensk Kärnbränslehantering AB.

SKB, 2002. Simpevarp-site descriptive model version 0. SKB R-02-35, Svensk Kärnbränslehantering AB.

SKB, 2004. Preliminary site description Simpevarp area – version 1.1. SKB R-04-25, Svensk Kärnbränslehantering AB.

SKB, 2006. Long-term safety for KBS-3 repositories at Forsmark and Laxemar. TR-06-09, Svensk Kärnbränslehantering AB.

SKB 2009. Site description of Laxemar at completion of the site investigation phase (SDM-Site Laxemar). SKB TR-09-01, Svensk Kärnbränslehantering AB.

Snäll S, 2004. Kvantitativa bestämningar av mineral i svenska leror. Sveriges geologiska undersökning, Slutrapport FoU-projekt 510031, Sveriges Geologiska Undersökning (in Swedish).

Sohlenius G, Bergman T, Snäll S, Lundin L, Lode E, Stendahl J, Riise A, Nilsson J, Johansson T, Göransson M, 2006. Oskarshamn site investigation. Soils, Quaternary deposits and bedrock in topographic lineaments situated in the Laxemar subarea. SKB P-06-121, Svensk Kärnbränslehantering AB.

Sohlenius G, Hedenström A, 2008. Description of regolith at Laxemar. SKB R-08-05, Svensk Kärnbränslehantering AB.

Sternbeck J, Sohlenius G, 1997. Authigenic sulfide and carbonate mineral formation in Holocene sediments of the Baltic. Chemical Geology 135, 55–73.

Sternbeck J, L, M, Nilsson Ö, 2006. ^{210}Pb and ^{14}C dating of sediments and peat. Accumulation rates of carbon, nitrogen and phosphorus. Oskarshamn and Forsmark site investigations. SKB P-06-301, Svensk kärnsbränslehantering AB.

Strömgren M, Brydsten L, Lindgren F, 2006. Measurements of brook gradients. Oskarshamn site investigation. SKB P-06-05, Svensk Kärnbränslehantering AB.

Strömgren M, Brydsten L, 2008. Digital elevation models of Laxemar-Simpevarp. SDM-Site Laxemar. SKB R-08-63, Svensk Kärnbränslehantering AB.

Svensson N-O, 1989. Late Weichselian and early Holocene shore displacement in the central Baltic, based on stratigraphical and morphological records from eastern Småland and Gotland, Sweden. LUNDQUA 25, 181 pp.

Söderbäck B (ed.), 2008. Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas. SKB R-08-19, Svensk Kärnbränslehantering AB.

Tagesson T, 2006a. Seasonal variation and controlling factors of soil carbon effluxes in six vegetation types in southeast of Sweden. SKB TR-06-28, Svensk Kärnbränslehantering AB.

Tagesson T, 2006b. Indirect estimations and spatial variation in leaf area index of coniferous, deciduous and mixed forest stands in Forsmark and Simpevarp. SKB TR-06-29. Svensk Kärnbränslehantering AB.

Tagesson T, 2007. Soil carbon effluxes in ecosystems of Forsmark and Simpevarp. SKB TR-07-13, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, 2006. Chemical characteristics of surface systems in the Simpevarp area. Visualisation and statistical evaluation of data from surface water, shallow groundwater, precipitation and regolith. SKB R-06-18, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, Johansson P-O, 2007. Hydrochemistry in surface water and shallow groundwater. Site descriptive modelling SDM-Site Forsmark. SKB R-07-55, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, Kalinowski B, 2008. Hydrochemistry of surface water and shallow groundwater. Site descriptive modelling. SDM-Site Laxemar. SKB R-08-46, Svensk Kärnbränslehantering AB.

Thunehed H, Triumf C-A, 2005. Oskarshamn site investigation – Detailed ground geophysical survey at Laxemar. Magnetic total field and resistivity. SKB P-05-188. Svensk Kärnbränslehantering AB.

Thunehed H, Triumf C-A, 2006. Oskarshamn site investigation – Detailed ground geophysics at Laxemar, autumn/winter 2005/2006. Magnetic total field and resistivity. SKB P-06-137. Svensk Kärnbränslehantering AB.

Turunen J, Tomppo E, Tolonen K, Reinikainen A, 2002. Estimating carbon accumulation rates of undrained mires in Finland-application to boreal and subarctic regions. The Holocene 12, 69–80.

Truvé J, 2007. Surveys of mammal populations in the areas adjacent to Forsmark and Oskarshamn. Results from 2007, compared with results from 2002/2003. Oskarshamn and Forsmark site investigation. SKB P-07-122, Svensk Kärnbränslehantering AB.

Truvé J, Cederlund G, 2005. Mammals in the areas adjacent to Forsmark and Oskarshamn – Population density, ecological data and carbon budget. SKB R-05-36, Svensk Kärnbränslehantering AB.

Ulén B, Snäll S, 1998. Biogeochemistry and weathering in a forest catchment and an arable field in central Sweden. Acta Agric. Scand., Sect. B, Soil and Plant Sci. 48 201–211.

UNESCO, 1992. International Glossary of Hydrology. UNESCO, Paris.

Wahlgren C-H, Curtis P, Hermanson J, Forssberg O, Öhman J, Fox A, La Pointe P, Drake H, Triumf C-A, Mattsson H, Thunehed H, Juhlin C, 2008. Geology Laxemar. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-54, Svensk Kärnbränslehantering AB.

Wallander H, Göransson H, Rosengren U, 2004. Production, standing biomass and natural abundance of 15N and 13C in ectomycorrhizal mycelia collected at different soil depths in two forest types. Oecologia 139, 89–97.

Werner K, 2008. Description of surface hydrology and near-surface hydrogeology at Laxemar-Simpevarp. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-71, Svensk Kärnbränslehantering AB.

Werner K, Bosson E, Berglund S, 2006. Analysis of water flow paths: Methodology and example calculations for a potential geological repository in Sweden. Ambio 35: 425–434.

Werner K, Bosson E, Berglund S, 2007. Flow and radionuclide transport from rock to surface systems: Characterization and modelling of potential repository sites in Sweden. In: Proceedings of ICEM '07, the 11th international conference on environmental remediation and radioactive waste management, Bruges, Belgium, 2–6 September 2007.

Werner K, Öhman J, Holgersson B, Rönnback K, Marelius F, 2008. Meteorological, hydrological and hydrogeological monitoring data and near-surface hydrogeological properties data from Laxemar-Simpevarp. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-73, Svensk Kärnbränslehantering AB.

Westman P, Wastegård S, Schoning K, Gustafsson B, 1999. Salinity change in the Baltic Sea during the last 8 500 years: evidence causes and models. SKB TR 99-38, Svensk Kärnbränslehantering AB.

Wijnbladh E, Aquilonius K, Floderus S, 2008. The marine ecosystems at Forsmark and Laxemar-Simpevarp, Site descriptive modelling. SDM-Site. SKB R-08-03, Svensk Kärnbränslehantering AB. Stockholm, Sweden.

Wiklund, 2002. Digitala ortofoton och höjdmodeller. Redovisning av metodik för platsundersökningsområdena Oskarshamn och Forsmark samt förstudieområdet Tierp Norra. SKB P-02-02, Svensk Kärnbränslehantering AB.

WRB, 1998. World Reference Base for Soil Resources World Soil Resources Reports 84. Food and Agriculture Organisation of the United Nations, Rome 1998. 88pp.

Åström M, Björklund A, 1995. Impact of acid sulfate soils on stream water geochemistry in western Finland. Journal of Geochemical Exploration 55, 163–170.

www-references

SGU, 2007. www. Brunnsarkivet [Web]. http://www.sgu.se/sgu/sv/samhalle/grundvatten/brunnar/brunns_arkiv.htm [Accessed 2007-02-27].

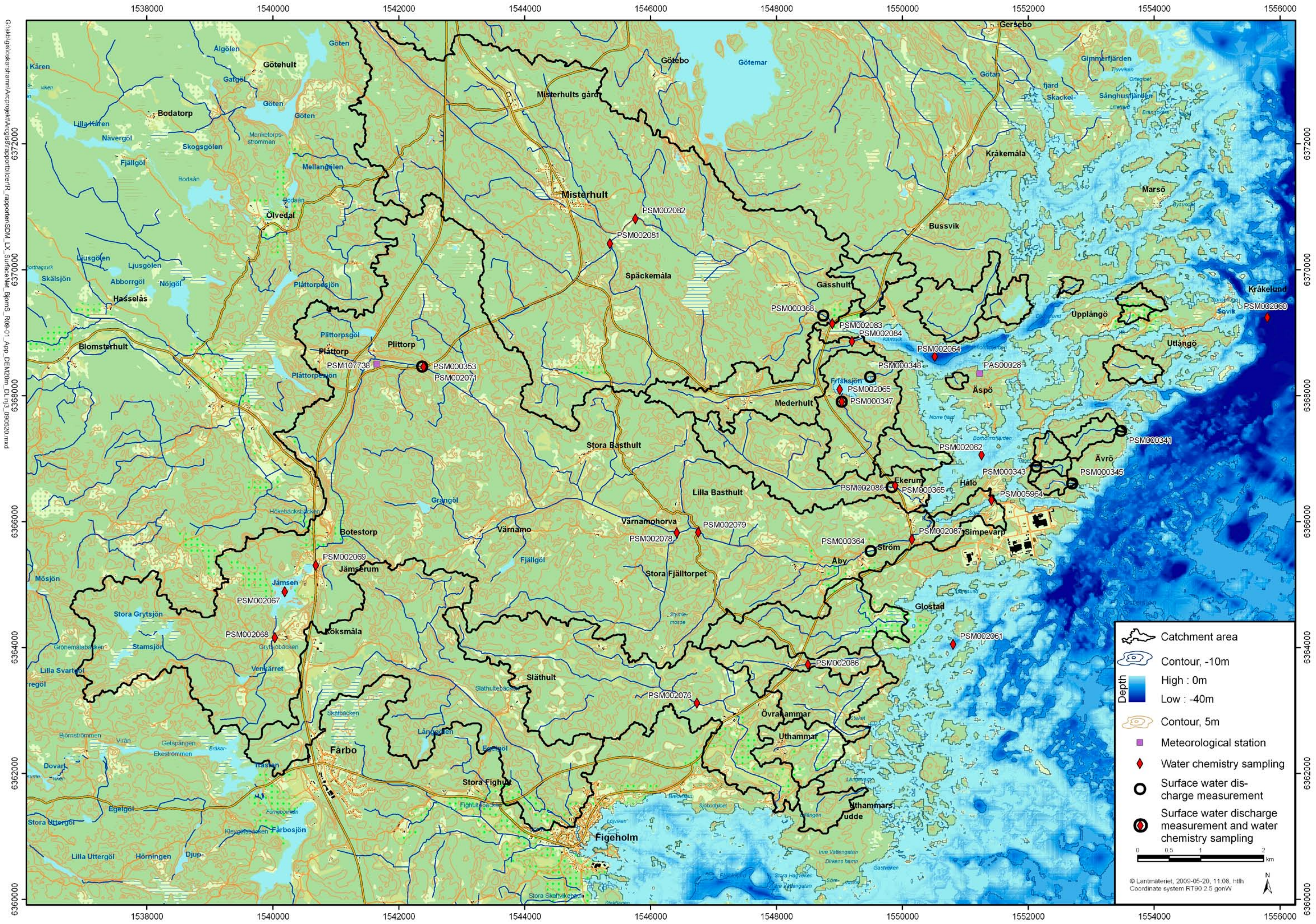
SMHI, 2003. www. Nordklim [Web] http://www.smhi.se/hfa_coord/nordklim/index.php?page=dataset [Accessed 2006-09-01].

Swedish Dairy Association, 2007. www. Statistisk foderstat från Svensk Mjölks IndividRAM Statistik. 623 besättningar mellan 2005–09 och 2006–08.

USDA (United States Department of Agriculture), 2007. www. USDA National Nutrient Database, Release 18 [Web]. http://www.usda.gov/wps/portal/usdahome. [Accessed 2007-12-17].

Appendix

Map of the Laxemar-Simpevarp area.


Catchment area
Contour, -10m
Depth
High : 0m
Low : -40m
Contour, 5m
Meteorological station
Water chemistry sampling
Surface water discharge measurement
Surface water discharge measurement and water chemistry sampling
© Lantmäteriet, 2009-05-20, 11:08, htfh
Coordinate system RT90 2.5 gonW
Misterhult
Misterhults gård
Götebo
Götemar
Götehult
Bodatorp
Ölvedal
Hasselås
Blomsterhult
Plittorp
Plattorp
Späckemåla
Gässhult
Mederhult
Äspö
Stora Basthult
Lilla Basthult
Värnamo
Värnamohorva
Botestorp
Jämserum
Koksmåla
Stora Fjälltorpet
Ekerum
Halö
Simpevarp
Ström
Åby
Glostad
Släthult
Övrahammar
Uthammar
Färbo
Figeholm
Stora Fighult
Bussvik
Kråkemåla
Marsö
Upplångö
Utlängö
Kråkelund
Ävrö
Gersebo
PSM002082
PSM002081
PSM000368
PSM002083
PSM002084
PSM002064
PSM002060
PSM107738
PSM000353
PSM002071
PSM000348
PAS00028
PSM002065
PSM000347
PSM000341
PSM002062
PSM000343
PSM000345
PSM002085
PSM000365
PSM005964
PSM002079
PSM002078
PSM000364
PSM002087
PSM002069
PSM002067
PSM002068
PSM002061
PSM002086
PSM002076
1538000
1540000
1542000
1544000
1546000
1548000
1550000
1552000
1554000
1556000
6360000
6362000
6364000
6366000
6368000
6370000
6372000