R-05-03

Description of surface systems

Preliminary site description
Forsmark area – version 1.2

Tobias Lindborg (editor)
Svensk Kärnbränslehantering AB

June 2005

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Preface

SKB started site investigations for a deep repository for spent nuclear fuel in 2002 at two different sites in Sweden, Forsmark and Oskarshamn. The investigations should provide necessary information for a license application aimed at starting underground exploration. For this reason, ecosystem data need to be interpreted and assessed into site descriptive models, which in turn are used for safety assessment studies and for environmental impact assessment. Descriptions of the surface system are also needed for further planning of the site investigations.

This report describes the surface ecosystems of the Forsmark site (e.g. hydrology, Quaternary deposits, chemistry, vegetation, animals and the human land use). The ecosystem description is an integration of the site and its regional setting, covering the current state of the biosphere as well as the ongoing natural processes affecting the long-term development. Improving the descriptions is important during both the initial and the complete site investigation phase. Before starting of the initial phase in Forsmark, version 0 of the site descriptive model was developed. The results of the initial site investigation phase is compiled into a preliminary site description of Forsmark (version 1.2) in June 2005. This report provides the major input and background to the biosphere description, in the 1.2 version of the Forsmark site description.

The basis for this interim version is quality-assured field data from the Forsmark sub area and regional area, available in the SKB SICADA, and GIS data bases as of July 31th 2004 as well as version 1.1 of the Site Descriptive Model.

To achieve an ecosystem site description there is a need to develop discipline-specific models by interpreting and analysing primary data. The different discipline-specific models are then integrated into a system describing interactions and flows and stocks of matter between and within functional units in the biosphere. Methodologies for developing descriptive- and ecosystem models are only described briefly in this report, but for thorough methodology descriptions see references.

The work has been conducted by the project group SurfaceNet together with other discipline-specific collaborators, engaged by members of the project group. The members of the project group represent the disciplines ecology, hydrology, Quaternary geology, soil science, limnology, oceanography, hydrogeology, hydrogeochemistry, environmental science, physical geography and human geography. In addition, some group members have specific qualifications of importance, e.g. experts in GIS modelling and in statistical data analysis.

The following persons contributed to the project and/or to the report:

Gustav Sohlenius, Anna Hedenström, (Geological Survey of Sweden, SGU) – regolith, overburden, soil, Quaternary deposits, descriptions and models,

Ulf Jansson, (Dept of human geography, Stockholm univ) – historical description, land use and human population,

Lars Brydsten, Mårten Strömgren (Dept of ecology and environmental science, Umeå univ) – landscape geometry, topography, bathymetry, DEM-model, Sten Berglund, Emma Bosson, (SKB) Per Olov Johansson (Artesia Grundvattenkonsult AB), Kent Werner (Golder Associates AB) – hydrology description, hydrology models, transport properties, climate description, wells,

Anders Engqvist, (Dept of system ecology, Stockholm univ) – oceanographic descriptions and modelling.

Björn Söderbäck, Sara Karlsson (SKB) – limnic description, limnic ecosystem, surface water chemistry,

Anders Löfgren (EcoAnalytica), Lasse Kyläkorpi, Sofia Miliander (Swedpower AB) – terrestrial description, terrestrial ecosystem, human description,

Linda Kumblad (Dept of System Ecology, Stockholm University), Erik Wijnbladh (SKB) – marine description, marine ecosystem.

Per Erik Jansson, David Gustafsson (Royal Institute of Technology, KTH) – terrestrial ecosystem modelling (Coup model),

Ulrik Kautsky, Jacob Jones (SKB) – safety assessment and dose modelling,

Johan Carlsson (SKB) – project administration,

Helena Nyman (SWECO Position) – Geographical Information System (GIS-modelling).

Tobias Lindborg (SKB) – project leader and editor.

Stockholm, June 2005

Tobias Lindborg

Site Investigations – Analysis

Contents

1 Introduction

1.1 Background

The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site characterisation at two different locations, the Forsmark and the Simpevarp area, with the objective of siting a geological repository for spent nuclear fuel. The characterisation work is divided into an initial site investigation phase and a complete site investigation phase /SKB, 2001/. The results of the initial investigation phase will be used as a basis for deciding on a subsequent complete investigation phase. On the basis of the complete site investigation, a decision will be made whether detailed characterisation will be performed (including sinking of a shaft).

An integrated component in the characterisation work is the development of a site descriptive model that constitutes an integrated description of the site and its regional setting, covering the current state of the geosphere and the biosphere, as well as the ongoing natural processes that affect long-term developement. The site description includes two main components:

- A written synthesis of the site summarising the current state of knowledge as well as describing ongoing natural processes which affect long-term development.
- One or several site descriptive models, in which the collected data are interpreted and presented in a form which can be used in numerical models for rock engineering, environmental impact and long-term safety assessments.

More information about the general principles for site descriptive modelling and its role in the site investigation programme can be found in the general execution programme for the site investigations /SKB, 2001/.

1.2 Objectives

This report is developed within the frame of the SurfaceNet project, with the main objective to produce a detailed description of the surface systems, based on available data from the Forsmark area, and it is a supporting report to the site description project. The specific objectives of the work are to:

- describe the functional units (abiotic and biotic) in the ecosystem,
- develop descriptive models of these units,
- construct ecosystem models of land, lakes and sea,
- give examples of how Safety Analyses can use the site description in dose modelling and in descriptions of the site development in the near and far future, and
- show how the site models can be used to support simplifications and assumptions in the overall safety assessment in Forsmark.

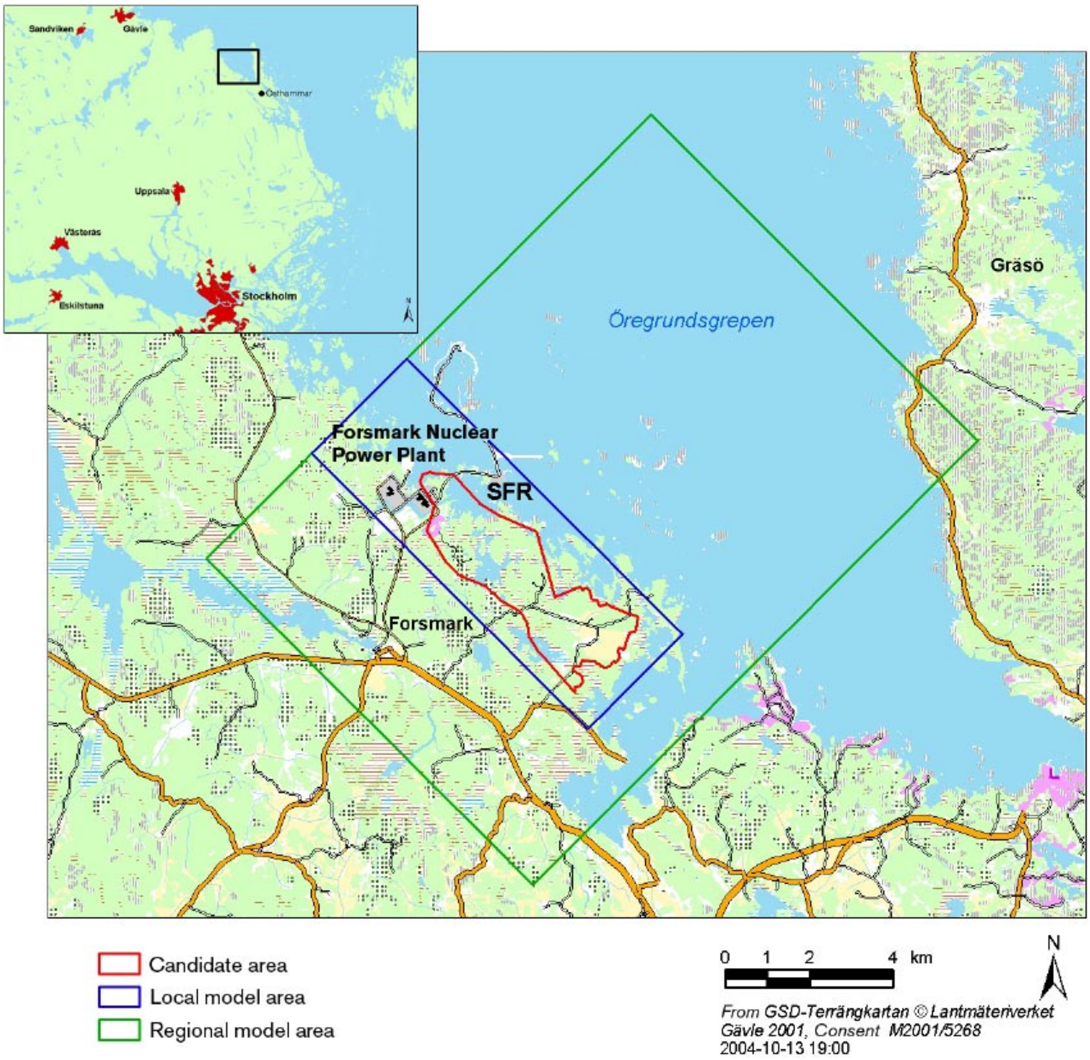

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Figure 1-1. *Overview of the Forsmark area and identification of regional model area.*

1.3 The site location

The Forsmark area is located in the province of Uppland (County of Uppsala), within the municipality of Östhammar, see Figure 1-1 and Appendix 2. The site is characterised by a relatively low topography situated on the coastline of the Baltic Sea. The major settlements in the region are Uppsala and Östhammar, located 73 km and 19 km, respectively from the site.

1.4 This report

This report consists of a number of descriptions representing different disciplines that together constitute the surface system. These descriptions cover the most important discipline specific patterns and processes at various spatial and temporal scales, e.g. temperature is affecting both temporal patterns such as production, and spatial patterns such as frost in the ground. Each description should be considered independent, aiming at a deepened understanding of the pattern and processes at the site. The different disciplines do also contribute with necessary information to the overall descriptive ecosystem models (Chapter 4), which together will be used to estimate and predict flow and accumulation of matter at a landscape scale in the safety assessment.

Below is a brief overview of the major headings and their content. If a specific reference has served as a major foundation for the chapter it is noted. The overview serves as guidance for the reader and provides a short presentation of the different disciplines that together constitute the surface system.

The report starts with an introductory chapter, covering the background, objectives, how the work behind this report was organised, and the strategy of developing ecosystem descriptions /Löfgren and Lindborg, 2003/.

Chapter 2 describes the site investigation and the types of data that are used.

Chapter 3 contains the disciplinary descriptions and is divided into sections in accordance with the disciplines. Below follows a short description of the sections and their major content:

Historical description consists of three parts: (i) shoreline displacement describing the formation of virgin land /Brydsten, 1999/, (ii) post glacial succession of ecosystems that handles the temporal changes in ecosystems during historical time, and (iii) humans and land use describing the historical land-use, the changes in settlement and how people used the landscape during the last centuries /Jansson et al. 2004/. These descriptions are a base for the predictions of future scenarios in the safety assessment.

Geometry presents a descriptive model for altitude and depth data covering the site, which is important input data for e.g. surface hydrological calculations and lake and sea descriptions.

Regolith/overburden describes the geomorphological conditions at the site important for estimating transport of mater and carbon in the soil. It is also an important predictor of the vegetation types at the site.

Climate describes a number of climate properties at the site, such as temperature and precipitation /Johansson et al. 2005/. Climatic data sets the frame work for many processes and serves as important input for the surface hydrological modelling.

Hydrology describes the surface hydrology using measured properties as well as properties quantified using modelling tools /Johansson et al. 2005/. Water is the main transport medium in the system models and hydrological properties are therefore an important input to e.g. the terrestrial ecosystem model.

Oceanography describes a numerical model that quantifies water retention time in the marine basins outside the site, which is input data to the marine ecosystem model.

Chemical properties compile chemical data describing for example precipitation, surface water and soil. This section supports the limnic and marine ecosystem models with data describing the water chemistry.

Terrestrial biota is a compilation of data describing the primary producers and the consumers in terrestrial environments. It includes both a general description of the biota and information of biomass, production, and turnover of tissue, and carbon content, used in the terrestrial ecosystem model.

Marine biota is a compilation of data describing the primary producers and the consumers in marine environments. It includes both a general description of the biota and information of biomass, production, and turnover of tissue and carbon content, used in the marine ecosystem model.

Limnic biota is a compilation of data describing the primary producers and the consumers in aquatic environments, such as lakes and streams. It includes both a general description of the biota and information of biomass, production, and turnover of tissue and carbon content, used in the limnic ecosystem model.

Human description presents data related to the human population at the site, their activities and current land use /Miliander et al. 2004/. This data is of major importance for identifying links between humans and different properties of the site, which supports the safety assessment to identify potential sources of exposure of radionuclides to humans.

Chapter 4 describes the construction of descriptive ecosystem models using data from Chapter 3. The overall aims are to describe the carbon cycle, both as a conceptual model and by using quantitative data presenting a carbon budget for a catchment area, one lake and three marine basins. The chapter is subdivided in the following sections:

- The terrestrial ecosystem presents the descriptive model for the terrestrial area in a catchment area.
- The limnic ecosystem presents the descriptive model for the lake.
- The marine ecosystem presents the descriptive model for the marine basins.
- An integrated ecosystem description connecting the terrestrial and aquatic ecosystems and the pools and fluxes between them. Data from the ecosystem models are here put together into an integrated ecosystem model, aiming at describing the major stocks and flows of matter within a landscape consisting of land, lakes and sea.

Appendix 1 is a map over the Forsmark site.

Appendix 2 describes the strategy of the safety assessment of the potential deep repository and how this can be applied using hypothetical data from Chapter 3 and 4. The strategy covers spatial perspectives from a single catchment area up to a landscape level, as well as temporal perspectives ranging from 1,000 years to glacial cycles. Methods and tools of potential interest for dose modelling and exposure to biota and humans are briefly presented here.

1.5 Development of ecosystem models

The building of a descriptive surface system model can be described in the following three steps Figure 1-2:

- Building a general conceptual model that describes stocks and flows of matter, using functional groups of organism where it is possible. This demands a categorisation of the ecosystem into suitable units of resolution.
- Collecting site specific data to adapt the conceptual model to the specific site, resulting in a descriptive model describing stocks and flows of matter at the site for the suitable units of resolution. The data is presented in a GIS.
- Describing processes affecting the transfer and accumulation of matter within and between units in a landscape.

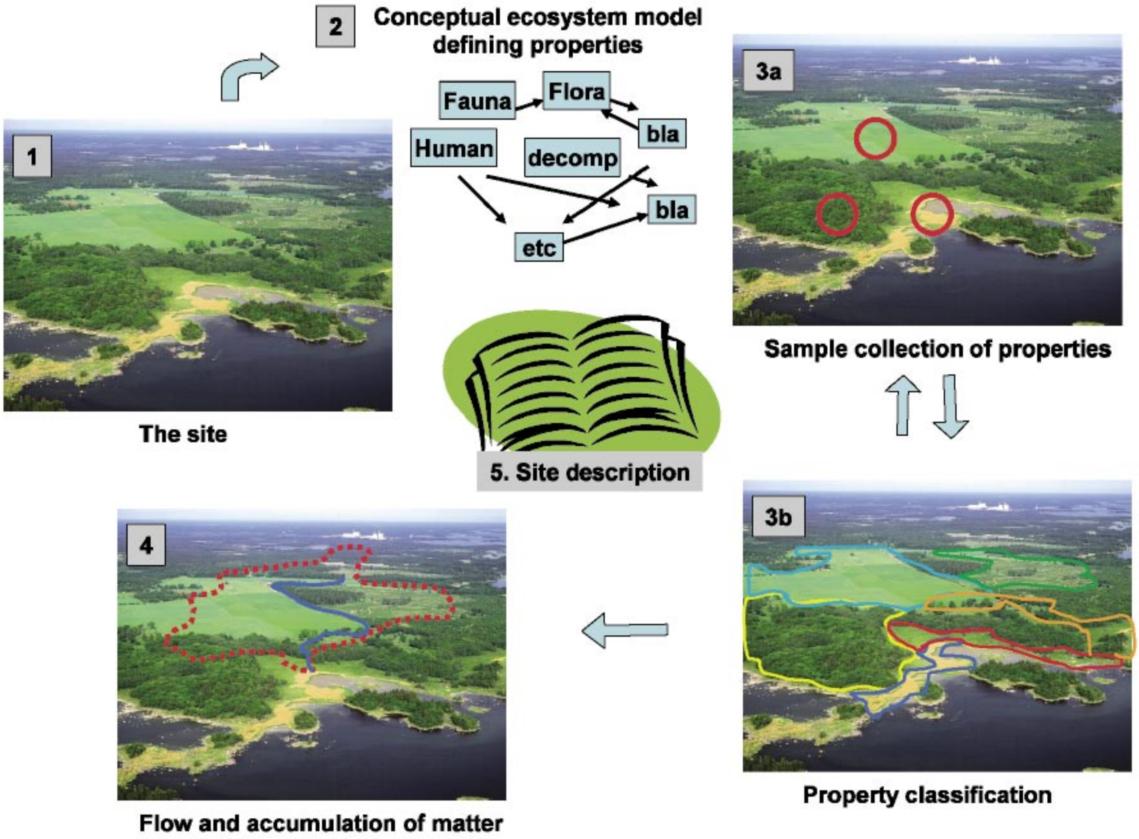

Figure 1-2. *The process of building a site descriptive ecosystem model. The site (1) is defined. A conceptual model (2) is produced describing functional units, properties and the fluxes between them. Samples are collected at the site (3a) using quantitative statistics to describe the biotic and abiotic properties in the conceptual model. The landscape is divided into a number of distributed models 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.*

1.5.1 A conceptual model

A conceptual model is necessary as a starting point when identifying different properties affecting the stocks and flows of matter in the ecosystem 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 step is the starting point for planning of field surveys, necessary for collecting the site-specific data in the next step (see conceptual models in Chapter 4).

The general conceptual model can, after site specific data are collected, be adjusted to a site specific conceptual model. Thus, new information may be added or existing data omitted, i.e. a functional group needs to be re-considered or a biomass unit is too small to be relevant. One of the more difficult tasks is to find a suitable categorisation and classification of the landscape into more easily handled units. In this report, the landscape was divided into three large-scale units: terrestrial, limnic and marine ecosystems. Further classification was done using units which potentially constitutes a base for budget calculation of organic matter. The units were then further divided using functional groups within the food web.

The spatial resolution of the gathered data is of course context dependent. However, the resolution of the terrestrial landscape has in our case been a function of the resolution of satellite classification techniques and the diversity of major vegetation types. Similarly, the spatial resolution of lakes has been set by the possibilities to monitor each lake separately and the categorization of lake habitats is done using a recently developed classification system of habitats /Brunberg et al. 2004/. The budgets of organic matter in terrestrial systems are described by means of biomass, primary production, secondary production, decomposition, mineralization and soil chemistry. The budgets of organic matter in lake and sea ecosystems are described by means 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 ground water movement.

1.5.2 Site specific data

The two Swedish sites considered as potential sites for a future repository of spent nuclear fuel are both situated at the coast and do both include a large number of different ecosystems such as forests, agriculture land, wetlands, lakes and sea. In this step, the starting point was the conceptual model and we use site specific data to establish local budgets of standing stocks and flow of matter for the different units of resolution. The site-specific data is presented in a GIS covering the specific area in a large database. This makes it possible to use over-layering techniques when merging data, e.g. making spatial explicit estimates of standing organic matter from different functional groups such as tree layer, shrub layer, field layer and ground layer.

1.5.3 Transfer and accumulation processes in the landscape

Carbon, energy, and biomass have been used interchangeable as currencies of the carbon and energy dynamics of ecosystems, because of the relative constancy of carbon and energy contents of organic matter /Chapin et al. 2002/. The proportions between carbon, nitrogen and phosphorous are often very constant within system, 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. 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. human starts to plough old lake beds or harvest peat. In the long-term cycling, matter is leaching from the terrestrial ecosystem into streams, following watercourses into lakes and in the end discharging into the sea. Some matter is accumulated along this way, for example in lake beds. The intention of this work is to construct a spatially explicit ecosystem model that will be able to describe these processes in the landscape.

The first step is to connect the different units by quantifying flows of matter between units within the ecosystem. Surface hydrology is considered the most important component determining transport of matter /e.g. Blomqvist et al. 2002/, and is thus subjected to quantitative modelling and simulation using site specific data in order to understand vertical and horizontal movement 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 1-3. This provides a tool to separate or link different subareas and ecosystem within the landscape. Moreover, together with hydrology models it is possible to calculate turnover time for any chosen part of the site.

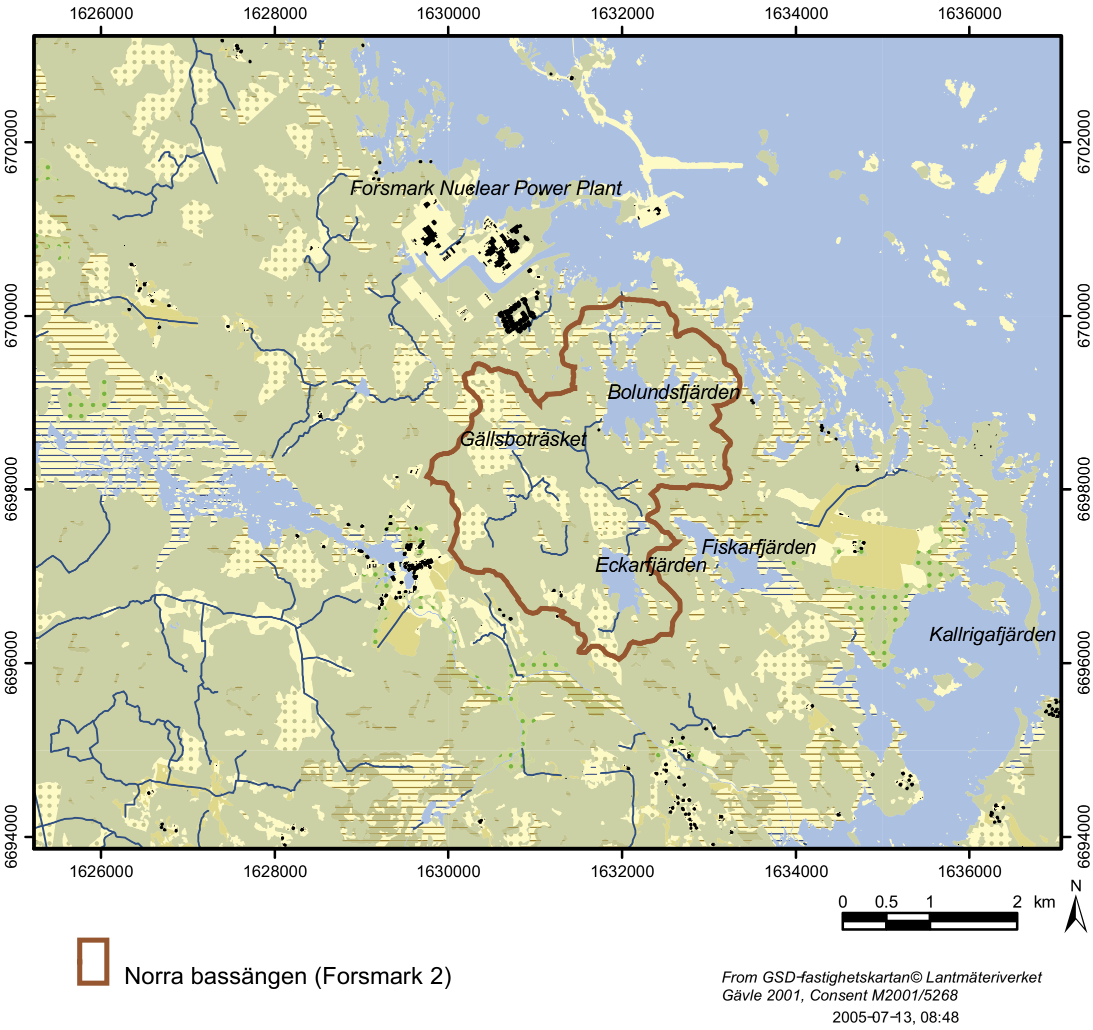

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Figure 1-3. *Example of a model area in Forsmark. The drainage area Norra Bassängen (Forsmark 2) with the water shed as the model boundary.*

The aquatic systems are important for transport of matter, but also for accumulation in the lake or sea bed. Budget calculations describing the flows of matter at the level of 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 in the lake. Matter transport in streams shows the actual leakage from the terrestrial systems, making it possible to compare estimated leakage and actual leakage from terrestrial systems.

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

In the last step, the model is transformed into a numerical model to predict how and where matter is accumulated. During this step the uncertainty of the model is evaluated.

In the risk assessment of radionuclides, the focus has, until recently, been the protection of humans and thus the pathways leading to human consumption /e.g. Strand and Larsson, 2001; Copplestone et al. 2004/. Consequently, ecological components have been omitted or incompletely described /e.g. IAEA, 1999; Vieno and Nordman, 1999/. This approach has been increasingly questioned and new regulations require that effects on ecosystem should be considered /e.g. IAEA, 1999; SSI, 1998/. The suggested method is based on an ecosystem approach where ecosystems are delimited and described and later put together into a spatially explicit ecosystem model covering a landscape. This requires an interdisciplinary work incorporating several scientific disciplines.

One of the great challenges will be to integrate all data. During this integration, a number of simplifying assumptions have to be made. However, it will always be possible to back-track the information in larger details, if necessary, due to the extensive site-specific database. This approach ensures that many of the simplifying assumptions made going from step 2 to 3, Figure 1-2, may be modelled and tested. A mass-balanced ecosystem model with food webs provide a way of analysing how matter are linked to different ecosystem components through fluxes of e.g. carbon.

The balance of nutrients required to support maximal growth for terrestrial plants is general, and the nutrient that most strongly limits growth determines cycling rates of all 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 the vegetation, to facilitate mass-calculations of other nutrients or radionuclides from established carbon masses. Moreover, by estimating inflow and outflow of matter in the ecosystem units, it is possible to reduce the potential variation by setting the physical and biological limits for estimations of e.g. carbon accumulation in a lake bed. We therefore strongly believe that the ecosystem modelling approach, combined with the use of site-specific data, will result in more accurate and precise estimations of flow and accumulation of matter because of the site specific limitations that are introduced.

If we describe standing stocks and flow of matter accurately, we will have a baseline for making predictions of dispersal and accumulation of chemical elements or substances, such as radionuclides, released in the area. Thus, 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 dose to humans at the specific site, see Figure 1-4, /Kumblad et al. 2003/. By adding the historical perspective on the landscape, we will also be able to predict transport and accumulation of matter during succession and different management regimes.

Figure 1-4. Picture of Bolundsfjärden, Forsmark area, heading west.

2 Site investigations and overview of available data

2.1 Overview of site investigations

This section presents a summary of the investigations made between data freezes 1.1 and 1.2. The majority of the surface investigations were performed during the period May 1st 2003–July 31st 2004, and comprises the following major components:

- Airborne photography.
- Airborne and surface geophysical investigations.
- Lithological mapping of the rock surface.
- Mapping of catchments areas and lake morphometry.
- Mapping of Quaternary deposits and soils.
- Marine geological investigations.
- Hydrogeochemical sampling and analysis of surface waters.
- Vegetation inventories in land, lakes and sea.
- Mammal inventories in land, lakes and sea.
- Monitoring boreholes that were established in the regolith/overburden.

All data are stored in the SKB databases SICADA and SKB GIS. The basic primary data are also described in the SKB P-series of reports.

2.2 Site-specific data

This section summarises data available at the time of the site description and distinguishes data that were used and not used in the modelling. The data are presented in two tables (Table 2-1 and 2-2) divided into abiotic and biotic input data. In each table, the first two columns show where the data are available, columns 3 and 4 identify the data that were actually used for modelling, and column 5 shows data that were not used for modelling and presents arguments why they were excluded from the modelling.

Table 2-1. Available abiotic data for the surface system and their handling in Forsmark model version 1.2. Report numbers in italics show data available already at data freeze 1.1.

Available data/data specification	Reference, for complete list see Chapter 5	Usage in this work, analysis/modelling	Section in report	Not utilised in this work, arguments/ comment
Geometrical and topographical data				
Geometry, topography, bathymetry, Digital Elevation Model (DEM)	P-04-25 P-04-125 R-04-70	Basic input to flow and transport models.	4.3, 4.4	
Geological data				
Geological maps, Quaternary deposit descriptions	P-03-11 R-04-39 SKB GIS	Conceptual model, distribution of Quaternary deposits, 2D model and input to 3D soil-depth model.	4.3	
Marine geological map	P-03-101 SKB GIS	Conceptual model, distribution of Quaternary deposits, 2D model.	4.3	
Soil type map	R-04-08 SKB GIS	Conceptual and quantitative model, input to 3D soil-depth model.	4.3	
Stratigraphical and analytical data from boreholes (HFM, SFM, PFM)	P-03-14 *P-03-64* P-04-111 P-04-138 P-04-139 P-04-140 P-04-148	Stratigraphical distribution and characterisation of Quaternary deposits. Depth to bedrock. Input to 3D soil-depth model.	4.3	
Peatland investigations	R-01-12 P-04-127	Chemical properties and distribution of organic deposits in two mires. Conceptual model.	4.3	
Mapping of marine and lacustrine sediment	P-03-24 P-04-86 *TR-03-17* *R-01-12*	Description of stratigraphical distribution and characteristics of sediments in lakes. Input to 3D soil-depth model.	4.3	
Stratigraphical data from machine-cut trenches	P-04-34	Depth and stratigraphical distribution of Quaternary deposits. Conceptual model, input to 3D soil-depth model.	4.3	
Investigation of evidence of neotectonic movements	P-03-76 P-04-123	Conceptual understanding.	3.2 4.3	
Textural composition	P-03-14 P-04-34 P-04-86 P-04-111 P-04-148 R-04-08	Conceptual model, input to quantitative modelling of hydraulic properties.	4.3	
Chemical analyses of glacial and post-glacial sediments	P-03-14 *TR-03-17* P-04-34 P-04-86 P-04-111 P-04-148 R-04-08	Conceptual model, input to quantitative model of chemical properties.	4.4	
Peat chemistry	P-04-127			
Pollen composition in glacial sediments	P-04-110	Conceptual understanding, glacial/interglacial history.	4.3	
Helicopter-borne survey data	P-03-41			Not yet utilised.

Available data/data specification	**Reference, for complete list see Chapter 5**	**Usage in this work, analysis/modelling**	**Section in report**	**Not utilised in this work, arguments/ comment**
Ground penetrating radar	P-04-78 P-04-156	Conceptual model and 3D model of soil depth.	4.3	
Reflection seismics	P-04-99			
Meteorological data				
Regional meteoro-logical data up to 2003	R-99-70 *TR-02-02* SICADA	General description and quantitative modelling of groundwater and surface water flows.	4.4	
Data from meteoro-logical stations at Högmasten and Storskäret June 2003 to July 2004	SICADA	Comparison with regional meteorological data.	4.4	
Snow depth, ground frost and ice cover	P-03-117 P-04-137	Validation of snow routine in quantitative modelling.	4.4	
Hydrological data				
Catchment charac-teristics – regional data	SKB GIS	Delineation of catchment areas.	4.4	
Regional discharge data	R-99-70 TR-02-02	Specific discharge in conceptual and quantitative modelling.	4.4	
Geometric data on catchment areas, lakes and water courses	P-04-25 SKB GIS	Delineation and characteristics of catchment areas and lakes.	4.4	
Automatic discharge measurements	SICADA		4.4	Only < 3 months time series at one station.
Simple discharge measurements in water courses	SICADA *P-03-27* P-04-146	General description of temporal variability in surface water discharge.	4.4	
Installation of surface water level gauges	P-03-64 P-04-139	Surface water – groundwater level relations, test of quantitative modelling with MIKE SHE.	4.4	
Level measurements in lakes and the sea	SICADA P-04-313			
Hydrogeological data				
Inventory of private wells	R-02-17	Description of available hydro-geological information.	4.4	No attempt is made to infer hydraulic para-meters from capacity data.
Data on installed groundwater monitoring wells, abstraction wells and BAT filter tips	P-03-64 P-04-136 P-04-138 P-04-139	Description of soil depth, basis for groundwater level measurements and hydraulic tests.	4.4	
Hydraulic conductivity of Quaternary deposits	P-03-65 P-04-136 P-04-138 P-04-140 P-04-142	Basis for assigning hydraulic conductivity of Quaternary deposits in conceptual and quantitative models.	4.4	
Groundwater levels in Quaternary deposits	P-04-313	General description, conceptual and quantitative modelling.	4.4	
Oceanographic data				
Regional oceano-graphic data	TR-02-02 TR-99-11	Quantitative modelling (see /Lindborg, 2005/	-	
Chemistry data				
Surface water sampling	P-03-27	Description.	4.5	
Groundwater sampling	P-03-47 P-03-48	Description.	4.5	

Table 2-2. Available biotic data for the surface system and their handling in Forsmark model version 1.2. Report numbers in italics show data available already at data freeze 1.1.

Available data/data specification	Reference, for complete list see Chapter 5	Usage in this work, analysis/modelling	Section in raport	Not utilised in this work, arguments/ comment
Terrestrial biota				
Compilation of existing information 2002	R-02-08	Description.	4.6, 4.8	
Bird population survey	P-03-10 P-04-30	Description.	4.6, 4.8	
Mammal population survey	P-04-04	Description, modelling.	4.6, 4.8	
Amphibians and reptiles	P-04-07	Description, modelling.	4.6, 4.8	
Vegetation inventory	P-03-81	Description.	4.6, 4.8	
Vegetation mapping	R-02-06	Description, modelling.	4.6, 4.8	
Biomass of the dead organic material	P-03-90 P-04-124	Modelling.	4.6, 4.8	
Data from soil mapping	R-04-08	Description, modelling.	4.6, 4.8	
Limnic biota				
Habitat borders	P-04-25	Description.	4.6, 4.8	
Limnic producers	R-02-41 R-03-27	Description, modelling.	4.6, 4.8	
Limnic consumers	R-03-27 P-04-05	Description, modelling.	4.6, 4.8	
Marine biota				
Light penetration depth	SICADA	Description.	4.6, 4.8	
Phytoplankton	SICADA	Description, modelling.	4.6, 4.8	
Zooplankton	SICADA	Description, modelling.	4.6, 4.8	
Macrophyte communi-ties	R-99-69	Description, modelling.	4.6, 4.8	
Macrofauna	R-99-69	Description, modelling.	4.6, 4.8	
Bird population survey	P-03-10 P-04-30	Description.	4.6, 4.8	
Humans and land use				
Humans and land use	R-04-10	Description, modelling.	4.7	

3 Descriptive models

3.1 Historical description

3.1.1 Geological development during the Quaternary period

Quaternary development of Sweden

The Quaternary is the present geological period and is characterised by alternating cold glacial and warm interglacial stages. The glacial stages are further subdivided into cold phases, stadials and relatively warm phases, interstadials (Figure 3-1). A combination of climatic oscillations with a high amplitude, together with the intensity of the colder periods is characteristic of the Quaternary period. At the Geological Congress in London, 1948 the age of the Tertiary/Quaternary transition, as used here, was determined to be 1.65 million years. More recent research, however, suggests that the Quaternary period started c 2.4 million years ago /e.g. Ŝibrava, 1992; Shackelton, 1997/. The Quaternary period is subdivided into two epochs: the Pleistocene and the Holocene. The latter represents the present interglacial, starting c 11,500 years ago (Figure 3-1).

Results from studies of deep-sea sediment cores suggest as many as fifty glacial/interglacial cycles during the Quaternary /Shackelton et al. 1990/. The climate during the past c 900,000 years has been characterised by 100,000 years long glacial periods interrupted by interglacials lasting for approximately 10,000–15,000 years. The coldest climate, and largest ice sheets, occurred toward the end of each of the glacial periods. Most research indicates that the long-term climate changes (> 10,000 years) are trigged by variations in the earth's orbital parameters. However, there is not a universal agreement on this point. The warm interglacials are relatively short compared to the glacial periods. It is therefore likely that the present interglacial Holocene will be followed by a long period of colder climate and Scandinavia will probably be covered by ice once more. Quaternary climatic conditions, with focus on Sweden, have been reviewed by /e.g. Morén and Påsse, 2001/.

The most complete stratigraphies used in Quaternary studies are from the well-dated sediment cores retrieved from the deep sea, which have been used for studies of e.g. oxygen isotopes /e.g. Shackelton et al. 1990/. The marine record has been subdivided into different Marine Isotope Stages (MIS), which are defined based on changes in the global climatic record. Quaternary stratigraphies covering the time before the Last Glacial Maximum (LGM) are sparse in areas that have been repeatedly glaciated, such as Sweden. Furthermore, these stratigraphies are often disturbed by erosion and are difficult to date absolutely. Our knowledge of pre-LGM Quaternary history of Sweden is, therefore, to a large extent based on indirect evidence from non-glaciated areas.

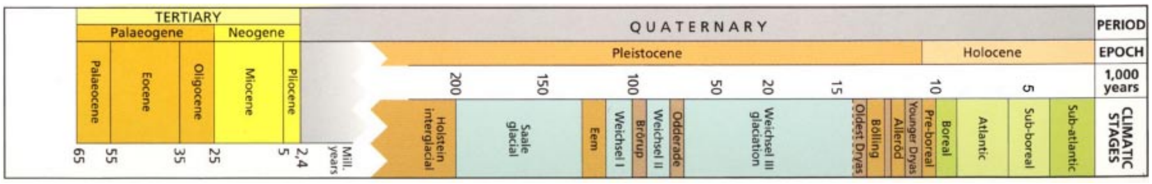

Figure 3-1. *The geological timescale showing the subdivision of the late Quaternary period with climatic stages from /Fredén, 2002/. The ages are approximate and given in calendar years before present (Sveriges Nationalatlas, www.sna.se)*

In most parts of Sweden, the relief of the bedrock is mainly of Pre-Quaternary age and has only been slightly modified by glacial erosion /Lidmar-Bergström et al. 1997/. The magnitude of the glacial erosion seems, however, to vary considerably geographically. Pre- Quaternary deep weathered bedrock occurs in areas such as the inland of eastern Småland, southern Östergötland and the inner parts of northernmost Sweden /Lundqvist, 1985; Lidmar-Bergström et al. 1997/. The occurrence of saprolites indicates that these areas have only been affected to a small extent by glacial erosion.

In some areas, such as in large parts of inner northern Sweden, deposits from older glaciations have been preserved, indicating that the subsequent glaciations have had a low erosional capacity /e.g. Hättestrand and Stroeven, 2002; Lagerbäck and Robertsson, 1988/. However, such deposits occur also in areas, e.g. Skåne, which have been glaciated during a relatively short period of time.

The Pleistocene

The global oxygen isotope record indicates numerous glaciations during the Quaternary period. Several of these glaciations have probably affected Sweden. It is, however, at present impossible to state the total number of Quaternary glaciations in Sweden. Here, the preserved geological information from Pleistocene is, as mentioned above, fragmentary. Pleistocene deposits have mainly been found in areas, which have been subjected to glaciations during a short period of time, or where the glacial erosion has been low due to cold-based ice conditions. It has been suggested that these latter conditions occurred in the inner pats of northern Sweden during the middle and late parts of the latest glaciation, the Weichselian. Most Pleistocene deposits have been correlated with the stadials and interstadials, which took place during the latest glaciation. There are, however, a few sites with older Pleistocene deposits. Inorganic deposits such as glacial till have not been dated with absolute methods and such deposits from early stages of the Quaternary period may therefore exist.

There are traces of three large glaciations, Elster (MIS 8), Saale (MIS 6) and Weichsel (MIS2-5d), that reached as far south as northern Poland and Germany. /e.g. Fredén, 2002/. Saale had the largest maximum extension of any known Quaternary ice sheet. There were two interstadials, Holstein and Eem, between theses three glacials. The oldest interglacial deposits in Sweden, dated by fossil composition, was probably deposited during the Holstein interglacial (MIS 7, c 230,000 years ago) /e.g. Ambrosiani, 1990/. The till underlying the Holsteinian deposits may have been deposited during Elster and is the oldest known Quaternary deposit in Sweden.

Deposits from the Eemian interglacial (MIS 5e, 130,000–115,000 years ago) are known from several widely spread sites in Sweden /e.g. Robertsson et al. 1997/. The climate was periodically milder than during the present interglacial, Holocene. The sea level was, at least periodically, higher then current large parts of the Swedish lowland, and probably covered with brackish or marine water.

The latest glacial, the Weichselian started c 115,000 years ago. It is characterised by colder phases, stadials, interrupted by milder interstadials. Numerous sites with deposits from the early part of Weichsel are known from the inner parts of northern Sweden. The model presented by /e.g. Fredén, 2002; Lundqvist, 1992/ is often used to illustrate the history of Weichsel (Figure 3-2). Two interstadials took place during the early part of Weichsel, approximately 100,000–90,000 (MIS 5c) and 80,000–70,000 years ago (MIS 5a). Most of Sweden was free of ice during these interstadials, but the climate was considerably colder than today and tundra climate with shrub vegetation probably characterised northern Sweden.

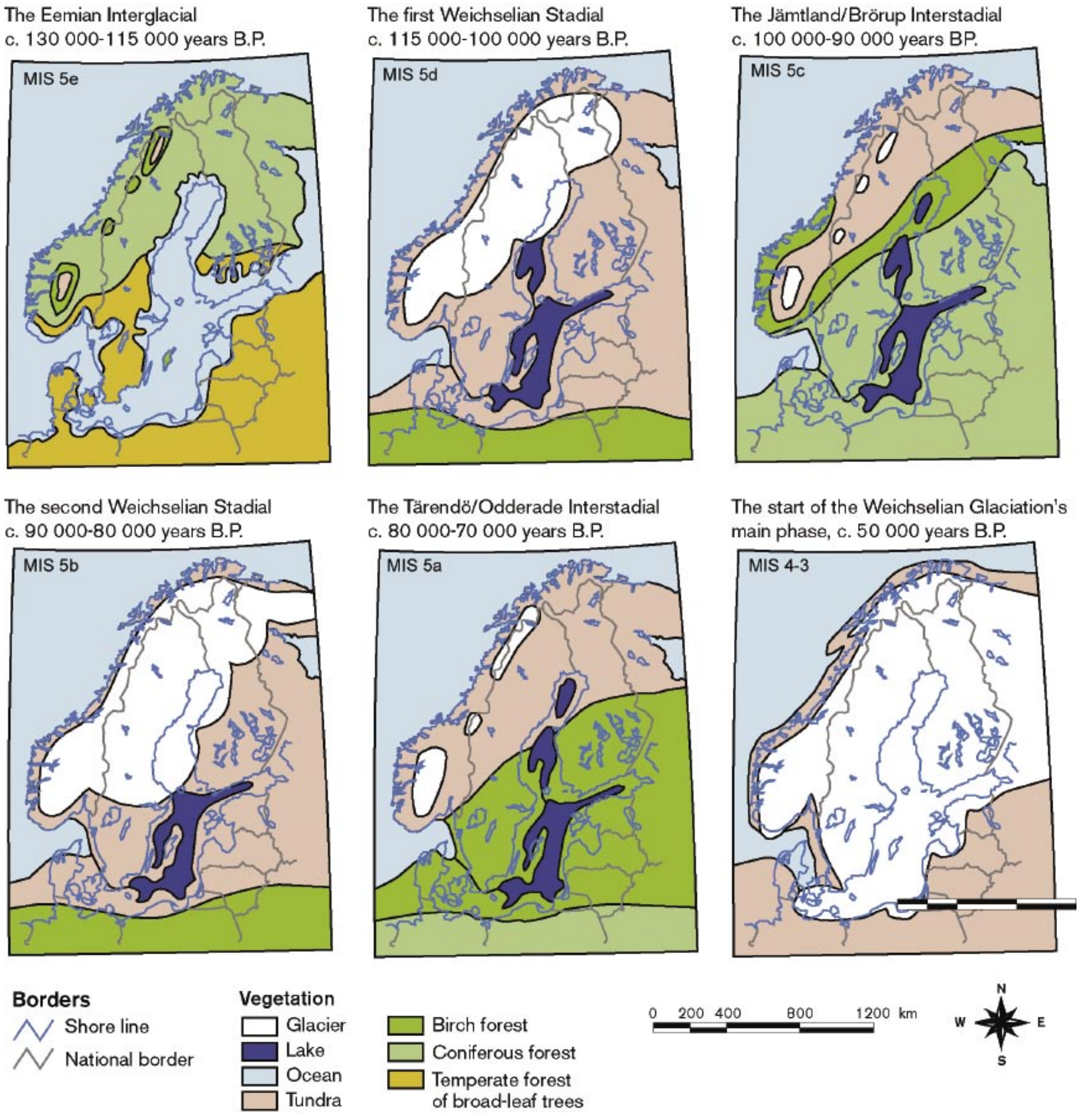

Figure 3-2. The development of vegetation and ice cover in northern Europe during the latest interglacial (Eem) and first half of the last ice age (Weichsel). The different periods have been correlated with the Major Isotope stages (MIS). The maps should be regarded as hypothetical due to the lack of well dated deposits from the different stages (Sveriges Nationalatlas, www.sna.se).

Southern Sweden was covered with coniferous forests during the first of these interstadials.

The second interstadial (correlated with MIS 5a) was colder and the vegetation in southern Sweden was probably characterised by a sparse birch forest. Most researchers agrees that the ice did not reach further south than the Mälaren Valley during the Early Weichselian stadials. The ice advanced south and covered southern Sweden first during Mid Weichselian (c 70,000 years ago). Most of Sweden was thereafter covered by ice until the deglaciation at around 12,000 years BP. Parts of Skåne were, however, free of ice until a few thousand years before LGM.

The model presented by /Fredén, 2002; Lundqvist, 1992/ have been questioned (Figure 3-3). Most researchers agree that at least two interstadials, with ice-free conditions, did occur during the Weichselian glaciation. However, since the dating of such old deposits is problematic, the timing of these interstadials is uncertain. Investigations from both Finland and Norway suggest that most of the Nordic countries were free of ice during parts of Mid Weichselian (MIS 3-4) /e.g. Olsen et al. 1996; Ukkonen et al. 1999/. That may imply that one of the interstadials attributed to Early Weichselian by /Fredén, 2002/ may have occurred during Mid Weichsel. In large parts of Sweden, the total time of ice cover during Weichsel may therefore have been considerably shorter than previously has been suggested by /e.g. Fredén, 2002/.

During the last glacial maximum (LGM), c 20,000 years ago (MIS 2), the continental ice reached its southernmost extent (Figure 3-3). The Weichselian ice sheet reached as far south as the present Berlin, but had a smaller maximal extent than the two preceding glacials (Saale and Elster).

The latest deglaciation

A marked improvement in climate took place about 18,000 years ago, shortly after LGM and the ice started to withdraw, a process that was completed after some 10,000 years.

The timing of the deglaciation of Sweden has been determined with ^{14}C dates and clay-varve chronology. The deglaciation of eastern Sweden, including the Simpevarp and Forsmark areas, has mainly been studied by using clay-varve chronologies /Kristiansson, 1986; Strömberg, 1989; Brunnberg, 1995; Ringberg et al. 2002/, whereas the timing of the deglaciation in other parts of Sweden has been determined with ^{14}C dates. These two chronologies have recently been calibrated to calendar years /e.g. Fredén, 2002; Lundqvist and Wohlfarth, 2001/.

There were several standstills and even readvances of the ice front during the deglaciation of southern Sweden. In western Sweden, zones with end moraines reflect these occasions. The correlations of ice marginal zones across Sweden are, however, problematic. In

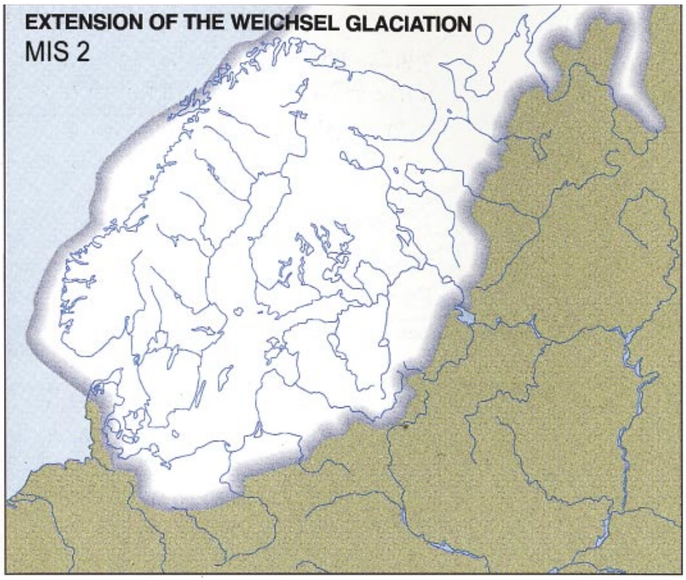

Figure 3-3. The maximum extent of the Weichselian ice sheet during MIS 2 approximately 20,000 years ago (Sveriges Nationalatlas, www.sna.se).

southeastern Sweden few end moraines developed because a lot of stagnant ice remained in front of the retreating ice sheet. There was a major standstill and in some area readvances of the ice front during a cold period called Younger Dryas (c 13,000–11,500 years ago). The ice front then had an east west extension across Västergötland and Östergötland (Figure 3-4). The end of Younger Dryas marks the onset of the present interglacial the Holocene. The ice retreated more or less continuous during the early part of the Holocen.

Climate and vegetation after the latest deglaciation

Pollen investigations from southern Sweden have shown that a sparse *Betula* (birch) forest covered the area soon after the deglaciation /e.g. Björck, 1999/. There was a decrease in temperature during a cold period called the Younger Dryas (c 13,000–11,500 years ago) and the deglaciated parts of Sweden were consequently covered by a herb tundra. At the beginning of the Holocene c 11,500 years ago the temperature increased and southern Sweden was first covered by forests dominated *Betula* and later by forests dominated by *Pinus* (pine) and *Corylus* (hazel). The timing and climatic development of the transition between the Pleistocene and the Holocene has been discussed by /e.g. Björck et al. 1996; Andrén et al. 1999/. Northern Sweden was deglaciated during the early part of Holocene when the climate was relatively warm. These areas were therefore covered by forest, mainly birch and pine, shortly after deglaciation.

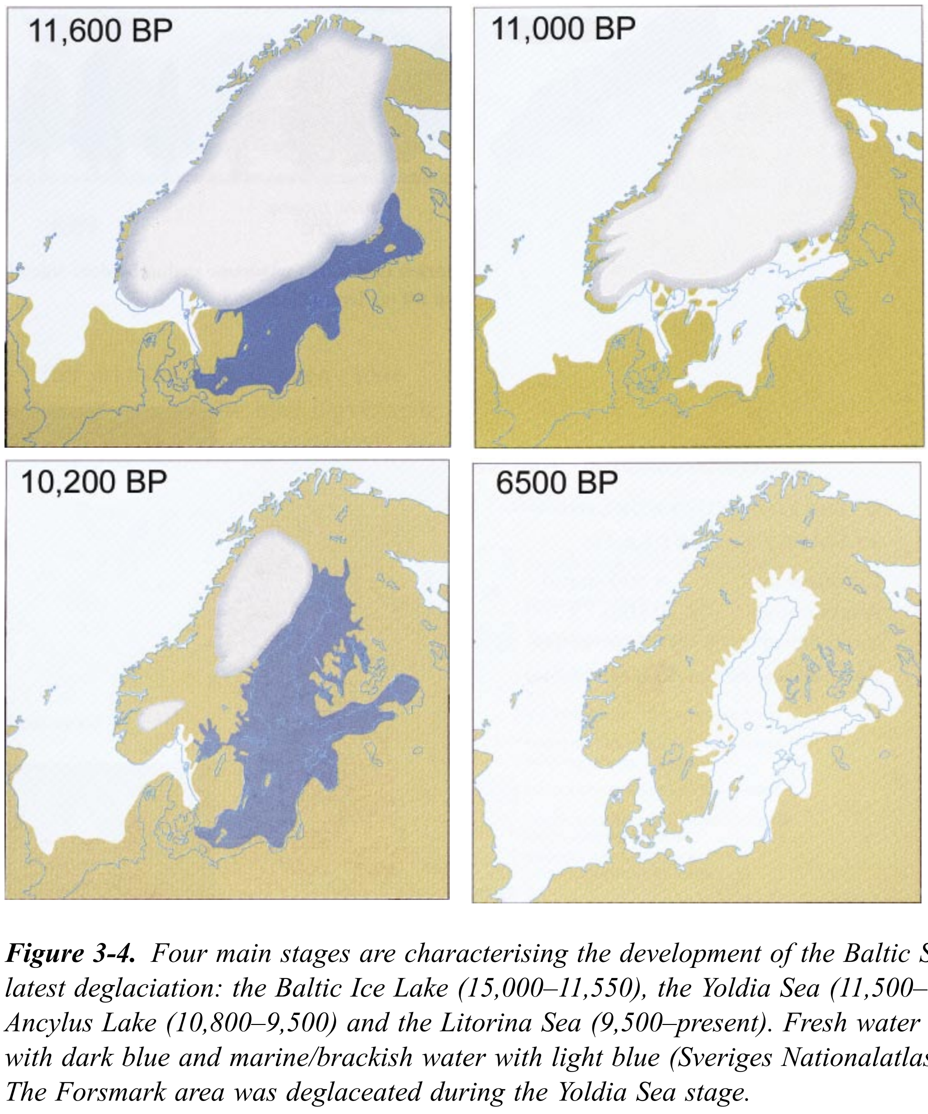

Figure 3-4. *Four main stages are characterising the development of the Baltic Sea since the latest deglaciation: the Baltic Ice Lake (15,000–11,550), the Yoldia Sea (11,500–10,800), the Ancylus Lake (10,800–9,500) and the Litorina Sea (9,500–present). Fresh water is symbolised with dark blue and marine/brackish water with light blue (Sveriges Nationalatlas, www.sna.se). The Forsmark area was deglaceated during the Yoldia Sea stage.*

Between 9,000 and 6,000 years ago the summer temperature was approximately 2°C warmer than at present and forests with *Tilia* (lime), *Querus* (oak) and *Ulmus* (elm) covered large parts of southern Sweden. These trees then had a much more northerly distribution than the present. The temperature has subsequently decreased, after this warm period, and the forests became successively more dominated by coniferous trees. During the Holocene *Picea* (spruce) has spread successively from northernmost Sweden towards south. This tree has not yet spread to Skåne and the Swedish west coast. The composition of vegetation has changed during the last few thousand years due to human activities, which have decreased the areas covered by forest. The vegetation development in Sweden during the last 15,000 years has been reviewed by /e.g. Berglund et al. 1996/.

Development of the Baltic Sea after the latest deglaciation

A major crustal phenomenon that has affected and continues to affect northern Europe, following melting of the latest continental ice, is the interplay between isostatic recovery on the one hand and eustatic sea level variations on the other. During the latest glaciation, the global sea level was in the order of 120 m lower than the present, due to the large amounts of water stored in ice /Fairbanks, 1989/.

In northern Sweden the heavy continental ice depressed the Earth's crust by as much as 800 m below its present altitude. As soon as the pressure started to decrease, due to thinner ice coverage, the crust started to rise (isostatic land uplift). This uplift started before the final deglaciation and is still an active process in most parts of Sweden. In Sweden the highest identified level of the Baltic Sea or the West Sea is called the highest shoreline. This shoreline is situated at different altitudes throughout Sweden depending on how much the crust had been depressed. The highest levels, nearly 300 m, are found along the coast of northern Sweden and sinks to levels below 20 m in southernmost Sweden.

Premises for surface water evolution

As shown in Figure 3-4, almost the whole regional model area was covered by sea water until 2,500 years ago. There are no direct records from the site which can be used to depict past salinity. The past salinity in the Baltic Proper since the onset of the Litorina period has been reviewed by /Westman et al. 1999/ and /Gustafsson, 2004a/. From proxy data they estimated a range within which the salinity of the Baltic Proper can be described over time. They also showed a model which uses knowledge of the sills in the southern Baltic Sea together with river runoff to the Baltic Sea to estimate past and future salinity changes in the Baltic Sea, and which also can be used to evaluate differences in salinity between the different basins of the Baltic Sea /Gustafsson, 2004a,b/.

The model by /Gustafsson, 2004a,b/ has, together with proxy records of salinity in the Baltic proper, been used here to make a rough estimation of the likely range of past salinity in the Bothnian Sea, i.e. the basin where the Forsmark area is situated (Figure 3-5). The difference in estimated salinity between he Baltic Proper and the Bothnian Sea back in time is generally low (< 1 ppt), due to the wide sill in Ålands hav.

Late Quaternary history of the Forsmark area

The marine isotope record suggests numerous glaciations during the Quaternary period. The number of glaciations covering the Forsmark area is, however, unknown. End moraines from three glaciations are known from northern Poland and Germany. It can therefore be concluded that the Forsmark area has been glaciated at least three times,

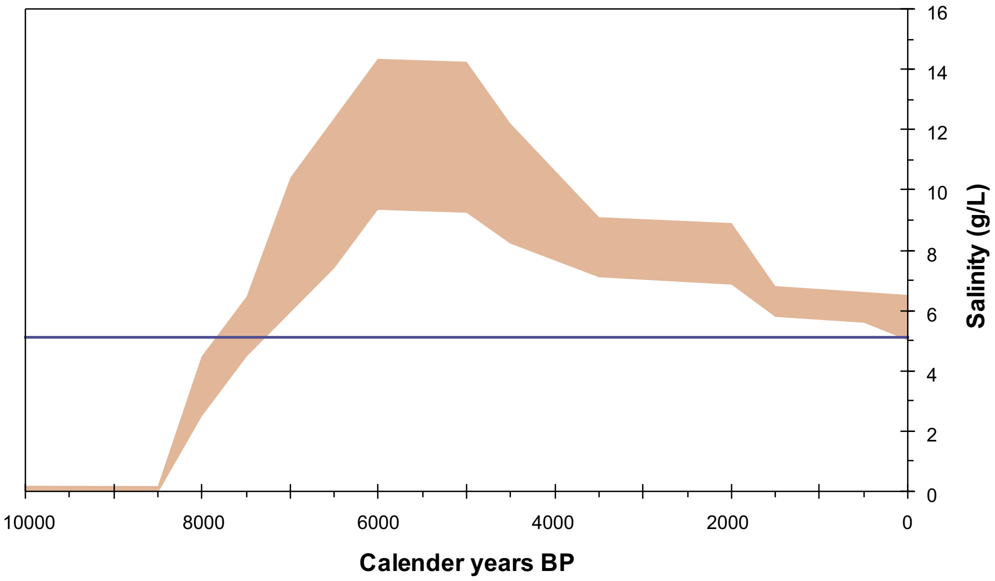

***Figure 3-5.** Estimated range for the salinity of Baltic Sea water in the Forsmark area from the onset of the Litorina period until today. Maximum and minimum estimates are derived from /Westman et al. 1999/ and /Gustafsson, 2004a,b/. The present salinity in the area is shown as a horizontal reference line.*

but probably more, during the Quaternary period. During the last interglacial, the Eemian (MIS 5e, 130,000–115,000 years ago), the Baltic Sea level was higher than at present interglacial and it is therefore likely that the Forsmark area was covered with brackish water during a substantial part of that interglacial /Robertsson et al. 1997/.

The area was probably free of ice during the first Weichselian stadial and interstadials. The inland ice during the second Weichselian stadial probably reached as far south as the Stockholm region, thus covering the Forsmark area (Figure 3-3). It has been assumed that tundra conditions prevailed during the stadials /Fredén, 2002/. The vegetation during the first Weichselian interstadial was probably dominated by coniferous forest whereas the second interstadial was colder, the forest sparse and dominated by *Betula* (birch). The exact timing of the Mid Weichselian glaciation is, however, unknown and there are indications of ice free condition in large parts of Fennoscandia during parts of Mid Weichsel /Ukkonen et al. 1999/. The total time of ice coverage in the Forsmark area may therefore have been considerably shorter than in the model presented by /Fredén, 2002/.

According to mathematical and glaciological models, the maximum thickness of the ice cover in the Forsmark region was more than 1.5 km at 18,000 years BP /Näslund et al. 2003/.

Glacial striae on bedrock outcrops are formed at different stages of the glaciations, thus several generations of striae may be identified. The oldest glacial striae observed in north-eastern Uppland are orientated from the north-west, a younger system from the north-north west and the youngest striae are formed by an ice moving approximately from the north /Persson, 1992/. All known overburden in the Forsmark regional model area has been deposited during, or after, the Weichselian glaciation.

Table 3-1. Summary of the stages of the Baltic Sea, years before present /Fredén, 2002; Westman et al. 1999/. Note that the Litorina Sea stage is based on the palaeogeography in the threshold areas and includes e.g the Mastogoia Sea stage and the present Baltic conditions. Note also that the altitudes and ages are approximate values, based on regional extra- and interpolations.

Baltic stage	Calender year BP	Salinity	Environment in Forsmark
Baltic Ice Lake not applicable in Forsmark	15,000–11,550 not applicable in Forsmark	Glacio-lacustrine not applicable in Forsmark	Covered by inland ice.
Yoldia Sea	11,500–10,800	Lacustrine/Brackish /Lacustrine	Deglaciation, regressive shoreline from c 150 m a s l. Minor (or no) influence of brackish water.
Ancylus Lake	10,800–9,500	Lacustrine	Regressive shoreline from c140–75 m a s l.
Litorina Sea sensu lato	9,500–present	Brackish	Regressive shoreline from 75–0 m a s l. Most saline period 6,500–5,000 calendar years BP. Present Baltic Sea during approximately the last 2,000 years.

Shore displacement

The latest deglaciation in Forsmark took place during the Preboreal climatic stage, c 10,800 years ago /Fredén, 2002; Persson, 1992; Strömberg, 1989/. The closest shore/land area at that time was situated c 80 km to the west of Forsmark. The Forsmark area was initially covered with approximately 150 m of Yoldia Sea water.

The Holocene shoreline displacement in northern Uppland has been studied with stratigraphical methods by /e.g. Robertsson and Persson, 1989; Hedenström and Risberg, 2003; Risberg and Arnberg, in press/. Påsse has made a mathematical model of the shoreline displacement. The modelled curve, together with the results from dated isolation events of lakes and mires are presented together in Figure 3-6. Påsse's curve is similar to the curve presented by /Hedenström and Risberg, 2003/. Påsse's mathematical model, however, continues back to the deglaciation whereas the stratigraphical investigations only cover the last 6,500 years. The ages given in the curve are calendar years before AD 2,000.

The curve in Figure 3-6 shows that the shoreline in Forsmark has been continuously regressive since the deglaciation. The brackish water phase of the Yoldia Sea lasted c 120 years, as recorded e.g. by ostracods and foraminifers in varved clay from central Sweden /Wastegård et al. 1995; Schoning, 2001/. Marine water entered the Baltic basin through the topographic lowland in Närke, known as the Närke Strait. The short durance of the brackish phase, the late deglaciation together with freshwater supply from the melting ice probably resulted in only minor, if any, influence of saline water in north-eastern Uppland during this stage.

The next Baltic stage, the Ancylus Lake, was lacustrine with initial outlet through Lake Vänern basin. The isostatic uplift was faster in the north, resulting in the Ancylus transgression flooding regions situated south of the outlet, for example the Oskarshamn area /e.g. Svensson, 1989/. During the first c 2,000 years after the deglaciation, i.e. during the Yolida Sea and Ancylus Lake stages of the Baltic, the regression rate in Forsmark was fast, in the order of 3.5 m/100 years.

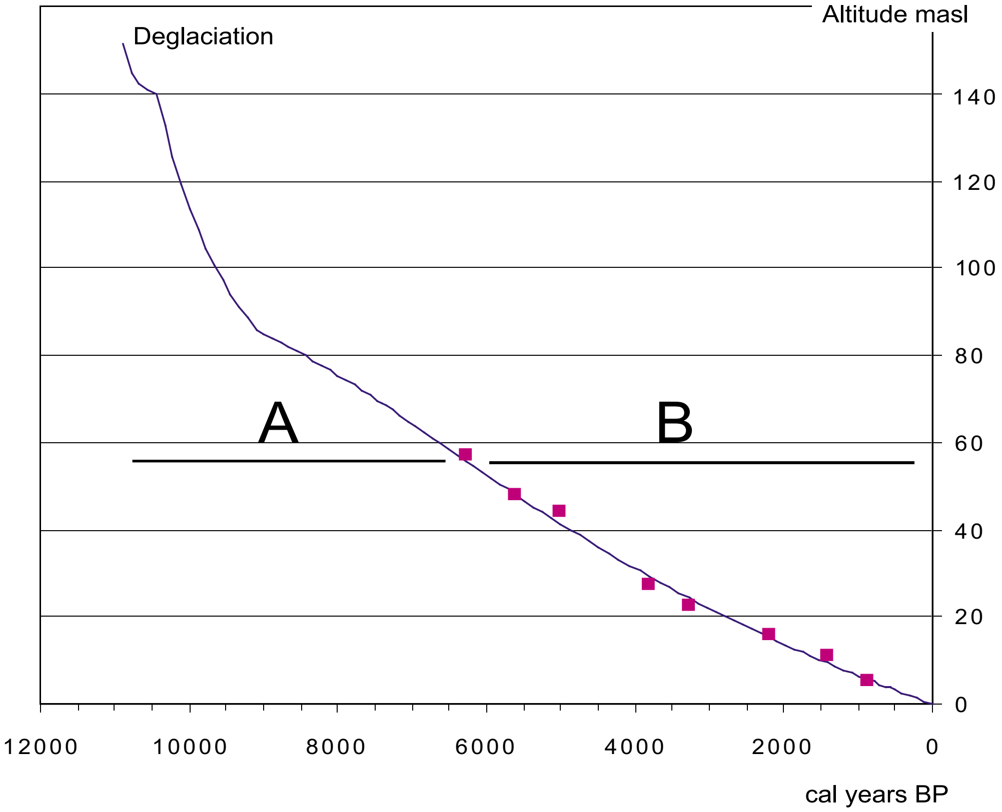

***Figure 3-6.** Shore displacement curve for Forsmark. The purple squares are ages and altitude of dated isolation basins /Hedenström and Risberg 2003; Risberg and Arnber, in press/. The solid black line is the mathematically modelled shore displacement /Påsse, 1997/. The older part of the curve, marked with A, has a larger uncertainty than the younger part, marked with B.*

Global eustatic sea level rise, in combination with a reduced isostatic rebound in the southern Baltic basin enabled marine water to enter the Baltic basin through the Danish straits, marking the onset of the Litorina Sea *sensu lato*. This stage includes an initial phase when the salinity was stable and low, the Mastogloia Sea, that lasted for approximately 1,000 years in Southern Uppland before the onset of the brackish water Litorina sensu stricto /Hedenström, 2003/. The variations in salinity in the Baltic is summerized by /Westman et al. 1999/ with updated chronology in /Fredén, 2002/. In this model version, the regional stratigraphical data is restricted to the last 6,500 years. During the last c 9,000 years the regression rate is slower, in the order of 0.9 m/100 year (Figure 3-6). The present land uplift in Forsmark is c 6 mm/year /Ekman, 1996/.

Comments on the uncertainties

The beginning of the curve (10,800 years ago/151 m a s l) represents the deglaciation of Forsmark, according to the regional compilation in /Fredén, 2002/. The age of the deglaciation is based on clay varve chronology that has an uncertainty of at least ± 200 years. The compilation of the highest coastline (HK) presented in /Fredén, 2002/ imply an elevation of 190 m a s l for northern Uppland. This altitude is based on a long distance interpolation between Kilsbergen area (Närke) and Borlänge (Dalarna). The new model for Forsmark indicates that HK in the area was located at approximately 40 m lower, i.e c 150 m a s l. This lower altitude is probably a more accurate level than the interpolated level. The altitude is determined in the diagram, based on the time for deglaciation. The uncertainty in the age of deglaciation is thus inherited to the altitude of HK. It should be noted however, that there were no land areas in the Forsmark area at that time. What the new curve shows is that the water depth during deglaciation was approximately between c 150 and 130 m in the areas presently above the sea level.

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

Furthermore, it should be pointed out that the part of the curve that is extrapolated beyond the oldest empirical data is therefore affected with a higher uncertainty than the more recent part of the curve, based on interpolation. The relatively large number of empirical data (8 sites), and the fact that a long time period is covered (6,500 years), however gives a relatively high precision also in the extrapolated part of the curve (Påsse, pers comm).

Based on the variation in data, the curve can be divided into two intervals with different precision:

A: Deglaciation to 6,500 years ago

B: 6,500 – recent conditions

It is not possible to quantify the uncertainties (in age) at this point.

Palaeogeographical effects of the Shore displacement

Within northern Uppland, the first land areas emerged c 6,500 years ago /Robertsson and Persson, 1989; Bergström, 2001; Hedenström and Risberg, 2003/, i.e. during the most saline phase of the Litorina Sea, correlated with the Holocene climatic optimum during the Atlantic climatic stage /Westman et al. 1999/. In Forsmark, however, it took some additional 3,000 years before the first islands started to form. The flat upper surface, in combination with the relatively fast land upheaval (6 mm/year), has resulted in rapid growth of new land areas and major geographical changes over time. An effect of the continuous regressive shoreline displacement is that the new land areas and lakes have not been flooded after emerging from the Baltic.

The major part of the Forsmark regional model area was still covered by water until c 2,500 years ago. A few scattered islands, situated close to the church of Forsmark, are the first land areas to emerge from the Baltic, 500 BC. The surface of the islands was covered by sandy till and exposed bedrock, similar to the present situation on the islands within the regional model area. Palaeo-ecological studies from the Florarna mire complex, situated c 30 km west of the regional model area, indicated local humid and cold climate at approximately this time /Ingmar, 1963/.

At 450 AD, the Baltic still covered the Forsmark candidate area (Figure 3-7). In more elevated areas in the south-western part of the map, land-areas presently covered by peat had emerged. At that time, these sedimentary basins were newly isolated from the Baltic and most probably a number of very small and shallow freshwater lakes/ponds existed. At the same time the isolation process of the first larger lake, Lake Bruksdammen started, west of the map. A grave mound, the oldest known archaeological site in the area, is located on the crest of an island situated c 1 km east of the church of Forsmark.

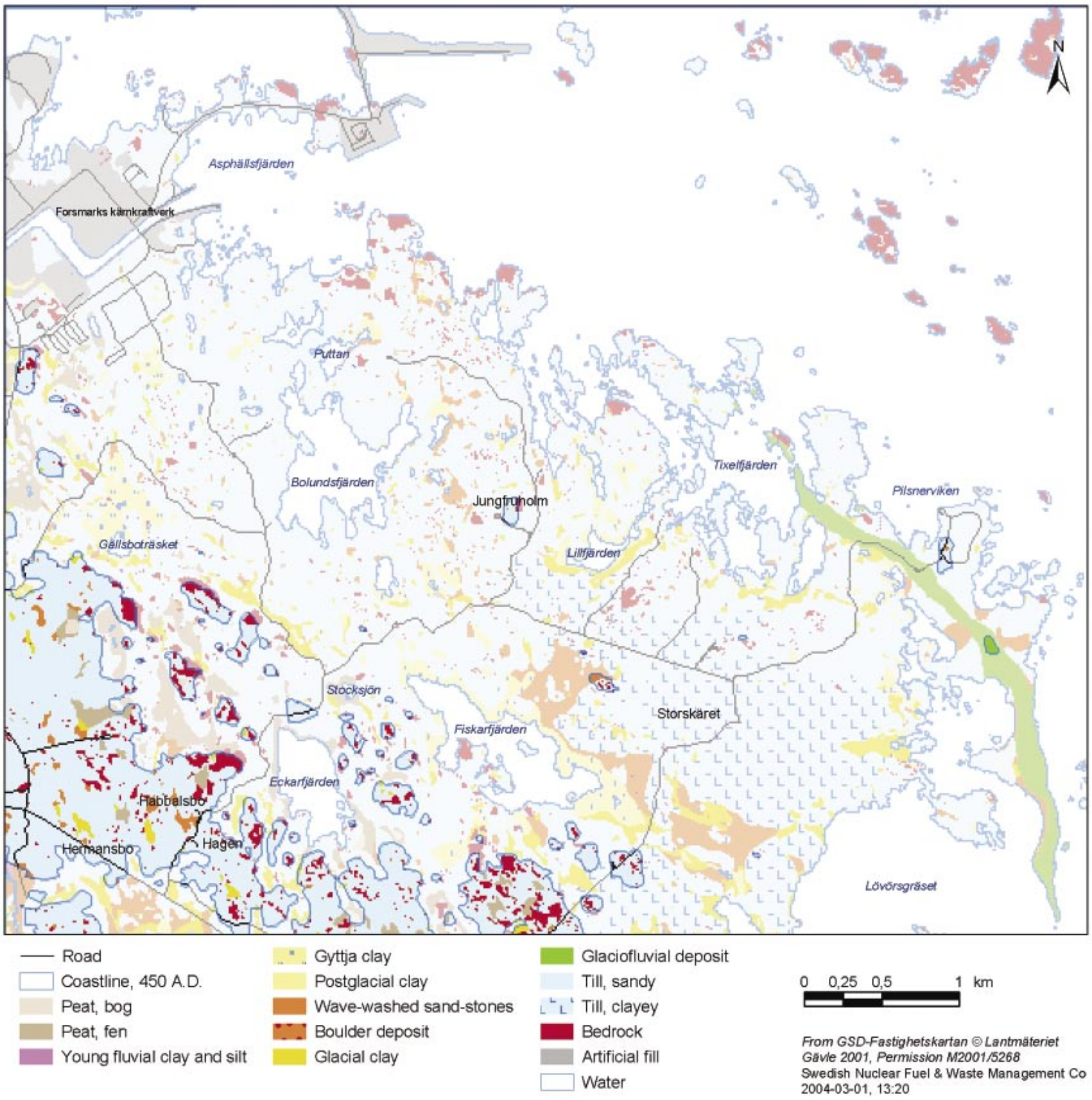

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Figure 3-7. *450 AD, the Forsmark candidate area is still covered by the Baltic. In the most elevated parts of the investigated area, land areas have emerged and are part of the outer archipelago.*

Figure 3-8 shows the distribution land and sea at AD 950. The isolation process at Lake Eckarfjärden is initiated with open connection to the Baltic trhough the threshold area at the north /cf Hedenström and Risberg, 2003/. The short lake phase of the Stenrödsmossen basin is probably succeeded by infilling of reed /cf Fredriksson, 2004/. The Börstilåsen esker constitutes some small islands in the east, exposed to wave action and erosion.

At 1,450 AD (Figure 3-9) a considerable part of the candidate area had emerged and several freshwater lakes were isolated from the Baltic, e.g. Eckarfjärden, Gällsboträsket and Djupträsket. In the areas covered by water in Figure 4, no surfaces with > 0.5 m peat has been identified. Instead, the wetlands in the lowest parts are covered by gyttja clay, sometimes with a thin peat cover. The area covered by clayey till at Storskäret formed a large island, partly protected from wave actions by the Börstilåsen.

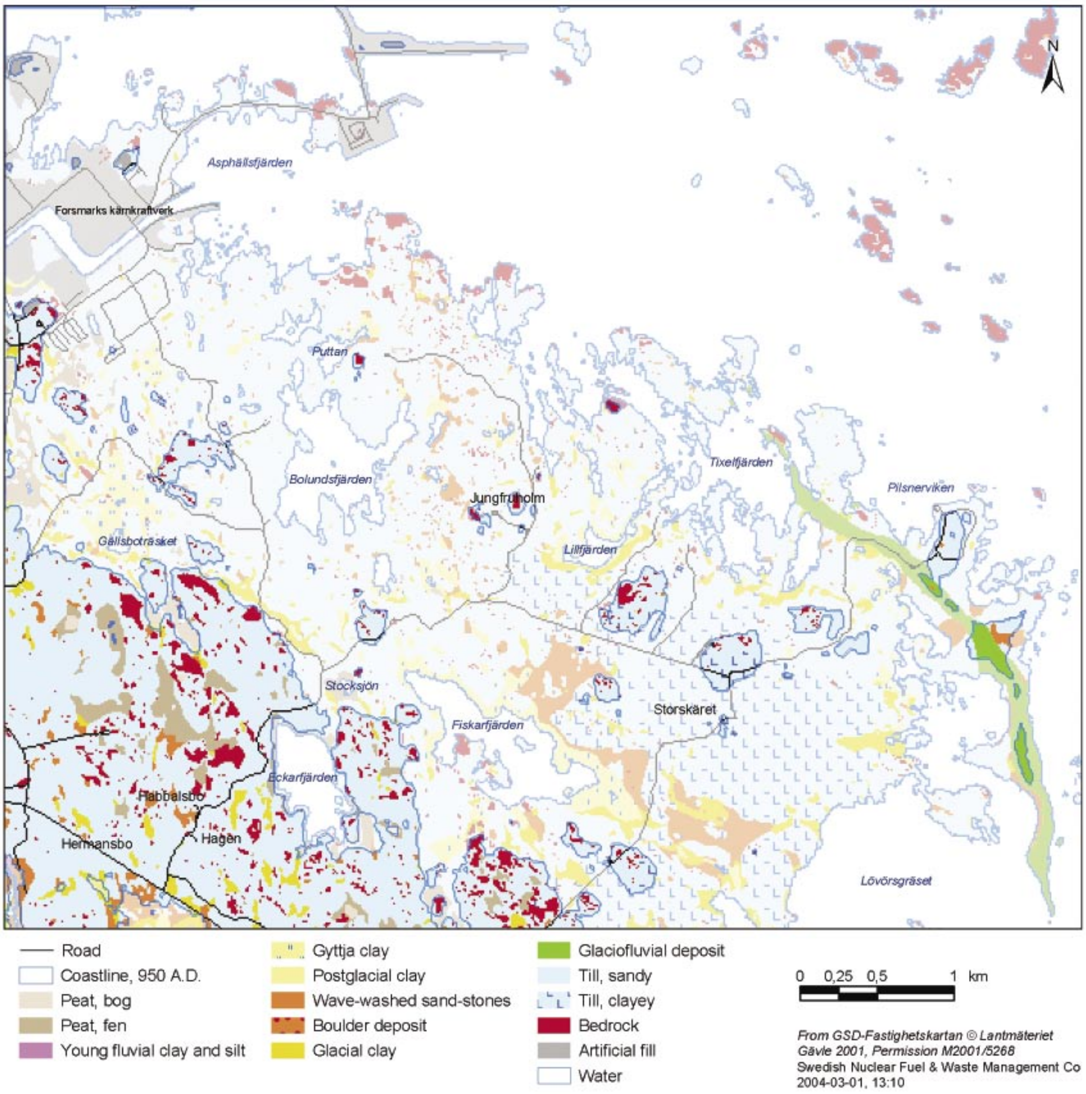

Figure 3-8. *950 AD, the isolation process of Lake Eckarfjärden is initiated with open connection to the Baltic through the threshold area at the north.*

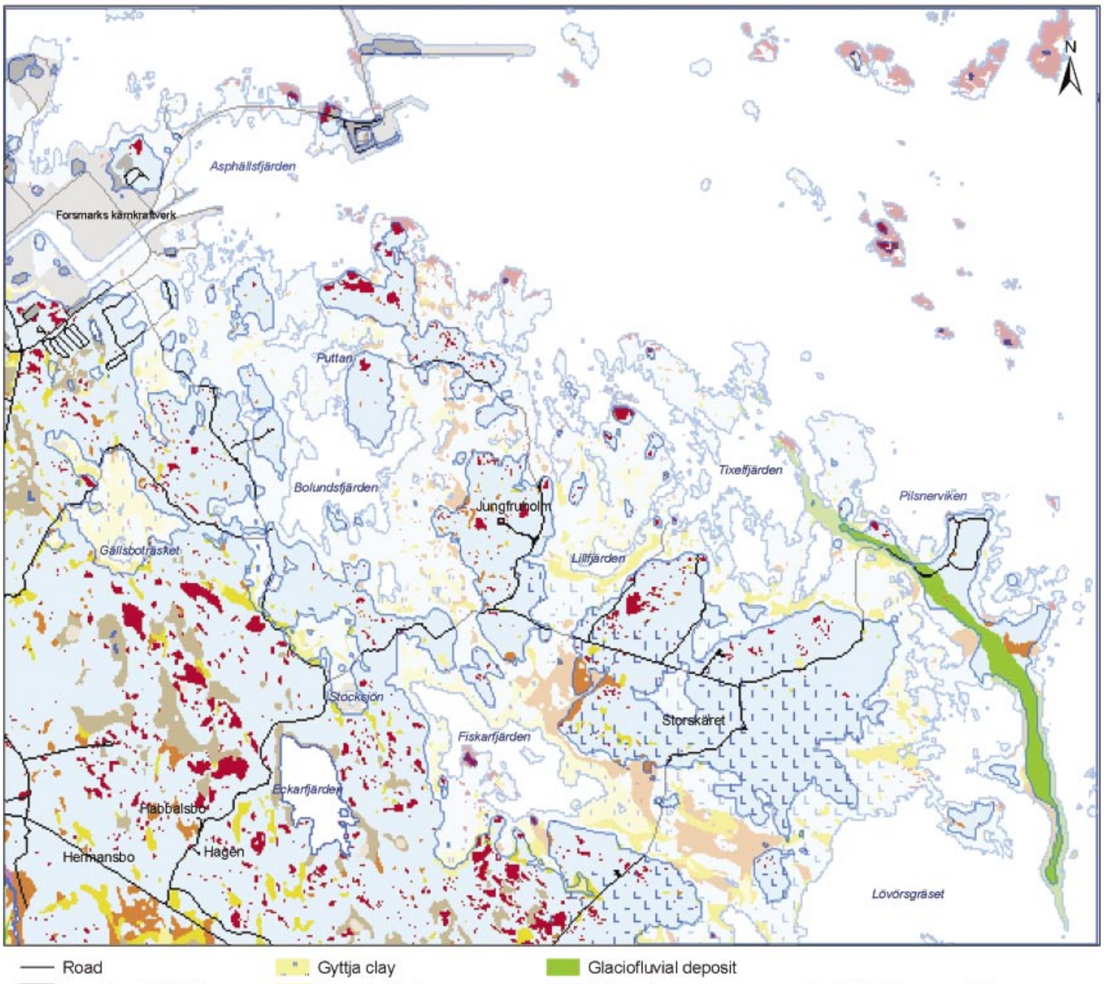

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Figure 3-9. *1,450 AD, several freshwater lakes has formed and the landareas are growing. Stoskäret in the east however, is still part of an island.*

In the last map (Figure 3-10), the distribution of land and sea at 1,700 AD is shown. The major part of the candidate area is situated above sea level. The Lake Bolundsfjärden is still in contact with the Baltic through the exposed strait at Puttan. The land area north of Lake Fiskarfjärden has emerged and transformed the lake basin into a sheltered position, favouring sedimentation.

The ongoing change in the distribution of land and sea continues with the emergence of new land areas, forming new and larger island. The distribution of minerogenic Quaternary deposits is affected by soil forming processes in the surface, but no major redistribution takes place after the area has been isolated from the Baltic. The most notable change will be observed in the distribution of organic soils, for example the sedimentation of gyttja in the lakes and the formation of peat in the wetlands.

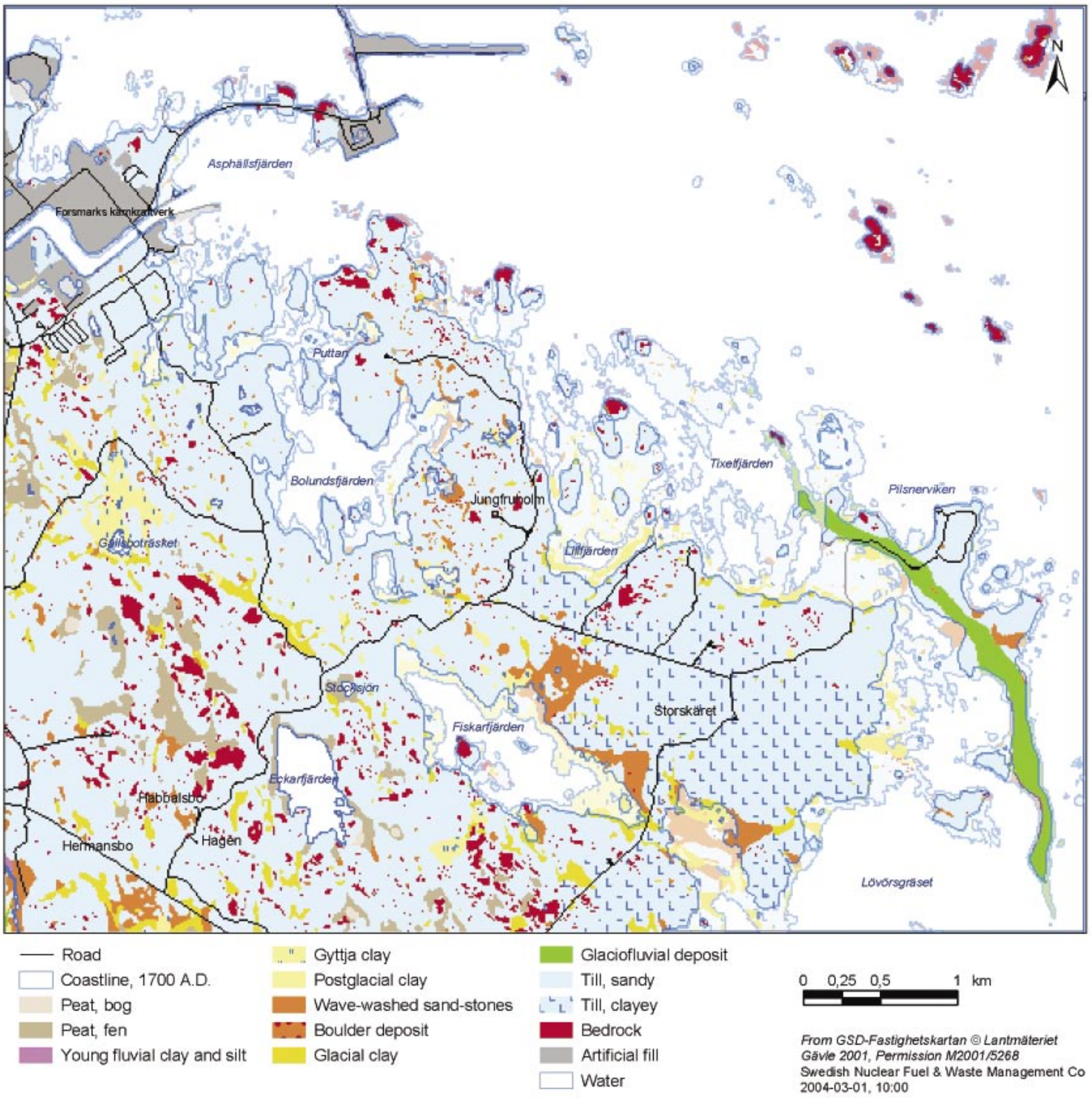

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Figure 3-10. *1,700 AD, the main part of the candidate area has emerged. The youngets lakes are still connected to the Baltic.*

3.1.2 Human geography

This section revolves around the historical land-use, the changes in settlement and how people have been working and using the landscape in Forsmark during the last centuries. The results and examples that is presented from the region is a summary and will give an insight to a project in progress, for further details /see Jansson et al. 2004/. The sources used include historical maps, cadastral material, interviews and fieldwork. The first phase ended in the summer of 2004 and the remaining work was reported in spring 2005. Some field-investigations and interviews are still in progress and the results have not yet been fully analysed.

Methods

One of the major challenges when analysing human geography is the data-capture of small-scale and large-scale historical and modern cadastral maps. The Forsmark area is examined at various levels of scale, and some investigations are overviews. The investigated areas consist of parishes, due to the fact that most of the sources for historical periods are organised in parishes. This is also a level that makes it possible to study the human activities, i.e. follow the use of forests in the context of a village. By studying a larger area we can also get o more comprehensive view of the society.

The method for the detailed analyses

The methods enabled us to digitise and georeference maps from the 17th, 18th and the 19th centuries so they could be treated and visualised together. The aim was to make the maps correspond, and enable a comparison between different periods in time, e.g. settlement, land under cultivation, pastures and roads.

The method follows a line of work that has been developed at the Department of Human geography at Stockholm University over the last 10 years. The method uses only existing software and is fairly straightforward and follows a general model of how to handle digital data in a GIS. The work consists of different stages. The first one is data capture; it is often scanning a map or the photograph of a map. In this case the maps were of varying ages and supplied in different formats and at different scales. The maps that were not in a digital format from the beginning were photographed with colour positive film that was subsequently scanned. The second phase is often referred to as pre-processing; this includes work with the scanned image. We often want to reduce the image size by adjusting the resolution and reducing the colour depth. The next stage is to geometrically adjust or rectify the image to fit to a modern co-ordinate system. This also includes adjusting for the errors the surveyor made during his mapping. Generally the older the maps are, the worse the geometrical quality is. These images were imported into a raster based GIS, in this case both ENVI and ArcMap were used. The process of rectifying consists of a selection of points, often known as ground control points when we deal with aerial photos. The work consists of trying to find points on a modern map that correspond with objects in an older map. This transformation can be made more or less "severe", from a simple a fine transformation to a polynomial warp of the image and makes the older map fit to a modern one as well as assigning it a co-ordinate system. When georeferencing old maps, it is important to find as many corresponding points as possible. It is difficult to find points of similar location if the landscape has changed dramatically between the time periods that are to be compared. The next phase, if we want to extract information from the image, is to do a vectorisation the image. That includes manually drawing the contours of features in the geometrically corrected map. This can be done at many different "levels", from extremely detailed information of each parcel of land and adding all kinds of attribute data to a more superficial selection of features. The level of detail is determined by what kind of analysis we want to conduct. The types of analyses that can be made with digital information are almost endless and must also be guided by the research question at hand. The last phase is presentation of the information. Most often a map is the best way of presenting the GIS information, but it could also be a graph or a table.

Method for processing large amounts of raster based information

The method used for the detailed maps is time-consuming and our goal to analyse a larger area required another technique. Firstly, all the maps had to be digitally re-sampled to fit to the co-ordinate system. This was relatively easy for the maps from the 20th century, but some of those were also of lesser quality. Some of the maps from the 19th century were, however, very hard to "conform" to the modern projection.

This method uses the colour information and extracts the land-use from the maps. Printed maps have however some problems. One is that the colours assigned to a certain feature are not as straightforward as one might think. Older maps have considerable variations in colour, both due to the manufacturing process and the ageing of paper and print. More modern maps as the Swedish economic maps have other problems. They use a backdrop of a photo that is overlaid with colours. This means that there is sometimes a blur of colours that has to be dealt with. A scanned map is a convenient way of obtaining digital geographic data. However, maps often contain information that might not always be of spatial relevance e.g. text and cartographic symbols. As these objects might range very much in size conventional filtering is not a very good approach when we want to get rid of these features. Instead we have found that using ordinary distance operators provides a very smooth and accurate way of solving the problem if two conditions are fulfilled: i) the objects to be removed do have a colour that is different from objects to be kept, and ii) the features to be kept are neither dithered nor patterned.

Sources for population and settlement data

The methods for obtaining information from historical records follow the source critical tradition of historians, human geographers and others that have been investigating agrarian history and rural landscapes. The methods are not technically challenging but require a careful selection of sources since the written material is vast in certain periods. The historical landscape study is based on medieval information, settlement information from cadastral books (*Sw. jordeböcker*) 1550–1880, information on population size from Tabellverket 1759–1855, registers on harvest (*Sw. tiondelängder*) and livestock (*Sw. boskaplängder*). In the detailed investigations registers on priest's interrogations (*Sw. husförhörslängder*) have been used.

The medieval sources are the most difficult historical material in Swedish history. In the local studies it has been possible to investigate the settlement and land owning structure during the Middle Ages. Sources from the medieval times are very scarce in Sweden, partly because of the fire in the Stockholm castle in the end of the 17th century when a lot of medieval documents were destroyed. In order to get a picture of the areas during the Middle Ages it is commonly used method to combine the land taxation register from the mid 16th century with the scarce medieval documents.

The regional studies of the settlement and land owning structure are based on cadastral books, (*Sw: kronans jordeböcker och årliga räntan*). Before the beginning of the 20th century the taxes in Sweden were based on land. The cadastral books were made by the Crown in order to control and manage the revenue in the country. Every farm in Sweden, except the demesnes of the aristocracy, was supposed to pay taxes. The amount of the taxes was decided by the size of the farm. The cadastral ledgers were made for each parish and show every single farm in the parish. If two or more farms are registered under the same name it is a village. It is therefor possible to study the settlement and its structure in these registers, and even pick out individual farms from farms in villages. The cadastral registers were systematically made in the middle of the 16th century during the reign of Gustav Vasa. In order to get control of the resources of the country he started to register the taxes paid by each farm in Sweden /Dovring 1951/. At that time the medieval land owning structure was still in function. That means that even the land owned by the church was registered, even if Gustav Vasa later confiscated that land. The records give a reliable picture of the settlement and land owning structure on farm and village level. Households and settlement that were paying land based taxes, for example cottagers, craftsmen and others, is not registered in the registers. For these categories of people is the Tabellverket and the husförhörslängder are more suitable.

Original cadastral ledgers from c 1630, 1680, 1730, 1780, 1825 and 1880 have been used (copied) in the National Archive (*Sw: Riksarkivet*) and the Kammarkollegie Archive (*Sw: Kammarkollegiets arkiv*). DMS-material has been used to get access to cadastral register c 1550. DMS, that stands for Det Medeltida Sverige was a project within the Bureau of national antiquities (*Sw: Riksantikvarieämbetet*).

The regional studies of the population are based on statistical material from Central board of statistics, founded in 1749, the so-called Tabellverket (later Statitiska centralbyrån). The material consists of pre-printed forms, which were filled in by the priests of the parishes every fifth year. On these forms there are columns for the numbers of different kind of people living in the parish during the period. The population is differentiated in several classes. These classes are changing over time, which are a problem when comparing the population structures of different times from 1749 and forward. In order to make such a comparison easier we have grouped classes of people. The statistical materials from the Tabellverket are often used as a source in historical studies and its value as a source for the population and the social differentiation of the population are good. The data from Tabellverket gives a good quantitative picture of the population and the growth of the population over time. It also gives a good picture of the social structure of the population and changes of the social structure over time /Palm, 2000/.

The geographer T. Lagerstedt's summaries on harvest and stock farming, gathered in the 1940s, have been used as source material /Lagerstedt, 1968/. The disadvantages about not using the original source material are that there could be mistakes made by Lagerstedt that is difficult to discover. There are however great benefits by using this material, as Lagerstedt's summaries are clear and easy to get access to. In all parishes, Lagerstedt's summaries of registers on harvest from the year 1640 have been used. There have been some difficulties in deciding what kind of units that were used at this time, as different units were used in different areas of Sweden.

Registers on priest's interrogations have been used in the detailed study. Based on priest's interrogation it is possible to illustrate household size and household structure. However, as going through these registers is a very time consuming activity, only selected parts of the parishes have been studied. These registers were made every fifth year when the parish priests visited every single household in the parish and made control of the religious knowledge of the people in the household. The registers therefor are a good source in order to catch all of the households, which are not farmers. The register covers craftsmen, sailors, salesmen and other people living in the parish. This material gives reliable and detailed information of different kind of households on a local level. In this material it is also possible to get information about the people and households which are not farmers.

Area of investigation

The physical landscape is the base for the cultural landscape. The physical setting to some degree always governs the land-use and sets the limits for human use in the present and through history. It is thus essential to understand for instance the topography, soils, vegetation and so on. Studies of this character is written and published within the framework of the SKB-investigations and will not be touched upon in the text in any detail, but the physical setting is often essential for an understanding of land-use, settlement, economy and so on throughout our history. In Forsmark one of the characteristics is the land upheaval and subsequent shore displacement that changed the landscape from sea, via an archipelago to the present day structure with hills covered with till and the lower fissure valleys filled with glacial and post-glacial sediments. The shore displacement in Northern Uppland and its effect on the settlements and the people living in the area has been treated in earlier research. One result from this research is that the shore displacement and the elevated land gave possibility to an increasing population and colonisation of former wetlands and colonisation in the woodlands /Dahlbäck, 1974/. Another result from this research is that the shore displacement caused dramatic effect on the economy /Broberg, 1990/. Farms which in the late Iron Age were situated at the coastline, and therefore had a large part of the incomes from the sea (fishing and hunting birds and seals), where just some hundred years later situated in the inland and had no longer contact with the coastline. This, in turn, forced the farm to change from an economy based on incomes from the sea to an economy based on agricultural. In the beginning the main part of the newly elevated land was wetlands not suitable for agriculture. This situation in combination with an increase in population and the establishment of new settlements on the new land caused a crisis in the area during the 13th and 14th centuries. This crisis is obvious in the archaeological material, where the health of people who died in the period was poor in comparison with earlier periods.

Medieval period

The tax register (*Sw. markgäld*) from 1312, which among others includes Hållnäs, Valö and Österlövsta, makes it possible to show the settlement changes between 1312 and c 1550. The prerequisites of this are particularly favourable in Hållnäs and Österlövsta, where the actual farmstead of each taxable person is registered. In Valö only a few farms are mentioned by name in the tax register (*Sw. markgäld*), which makes detailed analyses of settlement expansion more difficult here.

We do not know if the 1312 tax register (*Sw. markgäld*) really mentions all settlement units in the parishes at this time, (the church farms and the noblemen farms are probably not included /Dahlbäck, 1972/. However the majority of farmsteads in c1550 were tax farms, with only a few church and noblemen farms in the investigated area. A comparison between the tax register in 1312 and the cadastral book c1550, indicate a substantial decrease in settlement units. In Valö the reduction implies a diminution of settlement units from 122 in 1312 to 65 units in 1540. In Hållnäs the number of settlement units reduced from 135 in 1312 to 57 in 1546. However, the number of settlement names more than doubled in Hållnäs. In 1312 there were 11 registered names and in 1546 25 settlement units are mentioned, i.e. 13 new names can be registered. The same development pattern is found in Österlövsta, as the number of settlement units reduced from 166 in 1312 to 82 in 1554. It is interesting to notice that 24 cadastral units without settlement (*Sw. utjordar*) are registered in the 1554 cadastral book in Österlövsta, something that usually indicates deserted settlement units. As in Hållnäs, the number of settlement names in Österlövsta has increased between 1312 and 1554. In the tax register from 1312 only 14 settlement names are mentioned. In 1554 there are 53 settlement names registered, i.e. an increase of 39 units. It is particularly interesting to notice that the vast majority of the “new” settlements in both Hållnäs and Österlövsta consist of settlement names with the suffix –bo and –boda.

Since the 1312 tax register (*Sw. markgäld*) is based on persons liable to taxation, the register can also be usable to estimate the population size at this time, if the numbers of taxable persons are assumed to represent one household. All in all, there are 166 persons in Österlövsta, 135 persons in Hållnäs and 122 persons in Valö liable to taxation. If the average household is estimated to c 6–8 persons, i.e. 4–5 adults and some children, the population size in Österlövsta would be c 996–1,328 individuals (Broberg, 1990). The estimated population size in Hållnäs would be c 810–1,080 persons, and in Valö c 732–976 individuals, see Table 5. This can be compared to the estimated population size in 1571 (based on "Älvsborgs lösen"[1]), when Österlövsta had c 604 inhabitants, Hållnäs c 513 inhabitants and the population in Valö was c 264 persons /Palm, 2000/.

As we can see in Table 3-2, the figures indicate a rather strong reduction of population size between 1312 and 1571. In Österlövsta and Hållnäs the approximate population size in 1312 could have been about twice as large as the estimated population size in 1571. In Valö the estimated population size in 1312 was almost three times larger than in 1571. This could correspond to the population reduction after 1349 in the medieval crises.

The settlement situation in Forsmark in the early-modern period is heavily dependent on the establishment of Forsmarks bruk the ironworks. In the 17th century a lot of ironworks were created around Dannemora. Most of these are known as Vallonbruk due to the fact that people from southern and southeastern Belgium, i.e. Walloons, established them. These ironworks were often composed of a manor, houses for employees of various types and a church. They were in essence a community by themselves, separating them from the surrounding rural Society. Architecturally these areas also are different from the local Swedish farming settlement. They were thus more than a workplace or a production plant.

Table 3-2. Estimated population in three parishes.

Village	Estimated population 1312	Approximated population 1571	Population 1620
Österlövsta	996–1,328	604	953
Hållnäs	810–1,080	513	628
Valö	732–976	264	455

The Forsmark ironworks, land and settlement

Forsmark ironworks is situated close to the coastline, and at the border between Valö and Börstil parishes. The name Forsmark is first mentioned in the written sources in 1558. At that time Forsmark was a fishery in a lake at Simundö, south of the later Forsmark ironworks. At 1583 the name Forsmark was connected to ironwork. The ironwork was probably founded at about that time. The ironworks was built on he land of the former village Bolunda. At the beginning Forsmark was owned by the crown, but in 1624 it was leased out to a private company owned by i.a. Gerhard de Besche and Peter Rochet. Except the former village Bolunda the land that belonged to the ironworks consisted of the village Norrby and a couple of single farms, Gunnarsbo, Dannebo and Frebbenbo, in the northern part of Valö parish and the estate Kallriga, the single farm Länsö and the woodlands of Simundö in Börstil parish. The Forsmark parish was created in 1612 by the northern parts of Valö and Börstil parishes.

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[1] A specific tax that was collected for the payment of Älvsborgs castle that had been captured by the Danes in September 1563 and in May 1612.

The oldest map of the other part of the land that belonged to the ironworks, the northern part of Valö parish, is from 1699. This map shows the village Norrby and the single farms in the northern woodland. From this map it is also possible to conclude that a major part of the land that belonged to ironwork consists of the village Norrby and its woodlands. Norrby was a large village and consisted of 7 farms in the mid 16th century. All the farms were at that time owned by freeholders. The fact that the ironworks later owned the whole village means that the owners must have bought the freeholders farms sometimes before the end of the 17th century. At Norrby there are also ancient monuments from the late Iron Age, indicating that the village was established at that time. As the name Norrby means a settlement north of something else, it indicates that the village was a secondary settlement in the area. The primary settlements in the area, which Norrby is situated north of, are probably Vamsta or Lund in the central part of Valö parish. In Lund there are also ancient monuments from the Iron Age.

To judge from the map, the village Norrby was former very extensive. The three single farms in the Norrby forest, Gunnarsbo, Dannebo and Frebbenbo, all have place names ending with –bo. This –bo-names have, in earlier research about northern Uppland, been connected to a colonisation during the early Middle ages /Dahlbäck, 1974; Windelhed, 1995/. This colonisation took place in the woodlands of the existing villages. During the late medieval times and the 16th century these –bo-places become holdings with its own borders (*Sw. Avgärdning*) /Windelhed, 1995/. The fact that these –bo-holdings were surrounded by the woodlands of Norrby in 1699 shows that they were colonised on the land belonging to the village Norrby. To conclude, in late Iron Age Norrby was extended over the whole area north of the village. During the early Middle Ages, about 1,100 to 1,300, the area north of the village was colonised by settlers. In the beginning these new farms belonged to the village Norrby. In the late Middle Ages and the 16th century these farms were parcelled out from the mother village.

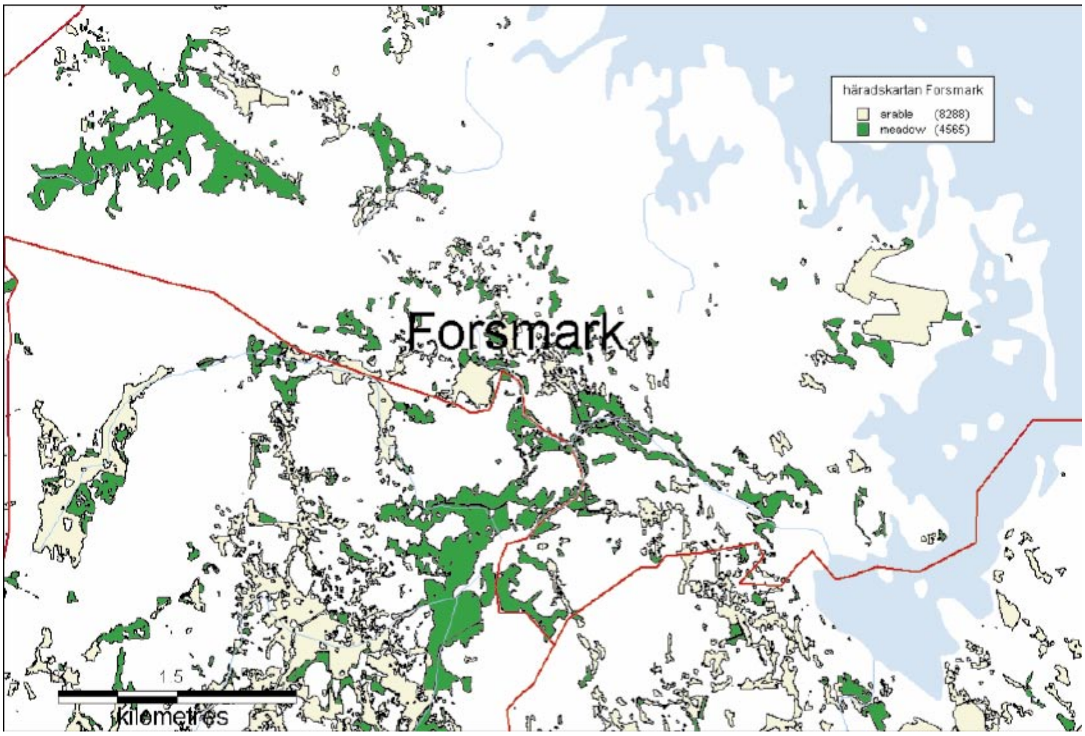

***Figure 3-11.** The arable and meadow from the map of hundreds (Sw: häradskartan), 1905. In the Forsmark area large areas of meadow covered the lower parts of the landscape.*

In the early 18th century there were also a lot of crofters in the forest of Norrby (at this time the forest belonged to Forsmark ironwork). On a map from 1734 there were 19 crofters spread over the area. The crofters had small areas of arable land and meadows near their houses. Probably this crofter's places were established during the 17th century as a consequence of the need of labour to the ironwork. The crofter's places were localised in small valleys with fruitful soil in the woodlands. In the beginning of 20th century the number of crofters had increased to 120. The crofter's places represent a new wave of colonisation in the area, which took place from the 17th century and onwards. The crofter's places also represent the physical mark of the need of labour at the Forsmark ironwork. In the beginning of the 20th century, then, the area was quite densely settled. During the 19th century agricultural land was established at the island Storskäret, west of Forsmark. To judge from the map of Storskäret from 1840 the land were used by the workers at the ironwork

If we look at the changes over the last 100 years it is clear that there is an increase in arable land in Forsmark from the late 19th century to the mid 20th century. The total amount of arable land in the Forsmark region in 1950, 148 million square metres. One of the dramatic changes was the reduction of numbers and areas of the meadows. More than one hundred years ago the landscape was to some extent dominated by the often wet meadows.

Table 3-3. Number of settlement units in Forsmark area. 1550, 1630, 1680, 1730 and 1871 are based on cadastral records whereas 1750, 1800, 1850 and 1895 are based on the priests records (*Sw. husförhörslängder*), that means that the information from the later mentioned records more represent households than cadastral units.

	1550	1630	1680	1730	1750	1800	1850	1871	1895
Lund	4	4	4	4	8	22	11	4	11
Vreta				1	1	2	1	1	1
Lundsvedja	4	4	4	4	7	12	10	4	20
Tomta	1	1	1	1	3	3	3	1	1
Kämbo							1 (croft)		2 (croft)
Dannebo	1	1	1	1	5	7	2	1 (croft)	4

The population in Forsmark

An estimation of the population size in the investigated parishes in Uppland implicate that 2,856 people lived here in 1571. However, it must be remembered that this figure is an approximation, since there are no comprehensive source material on Swedish population size before c 1750. The population increase was not linear, but was characterised of periods of growth and periods of temporary regression. In 1900 15,882 people lived in the investigated area. The smallest population size during the investigated period is found in Forsmark. Österlövsta had the largest population size, except for a period around 1571 and between 1880 and 1900, when the population in Börstil was larger. In the 20th century (1952–1990) there has been a negative population trend in all parishes except for Börstil. In 1990 all in all 10,252 persons lived in the investigated area.

In Forsmark, the social population structure is different from other investigated parishes in the region, as the share of works- and mine workers were very dominating in 1750 (Figure 3-13). In addition there were no farmers, but quite a large share of others without property. In 1850 this structure had changed rather drastically. The share of works- and mine workers had decreased significantly and the share of craftsmen had increased extensively. At the same time the share of crofters increased and a small share of farmers can be noticed in 1850. Furthermore, the share of noblemen decreased a little between 1750 and 1850.

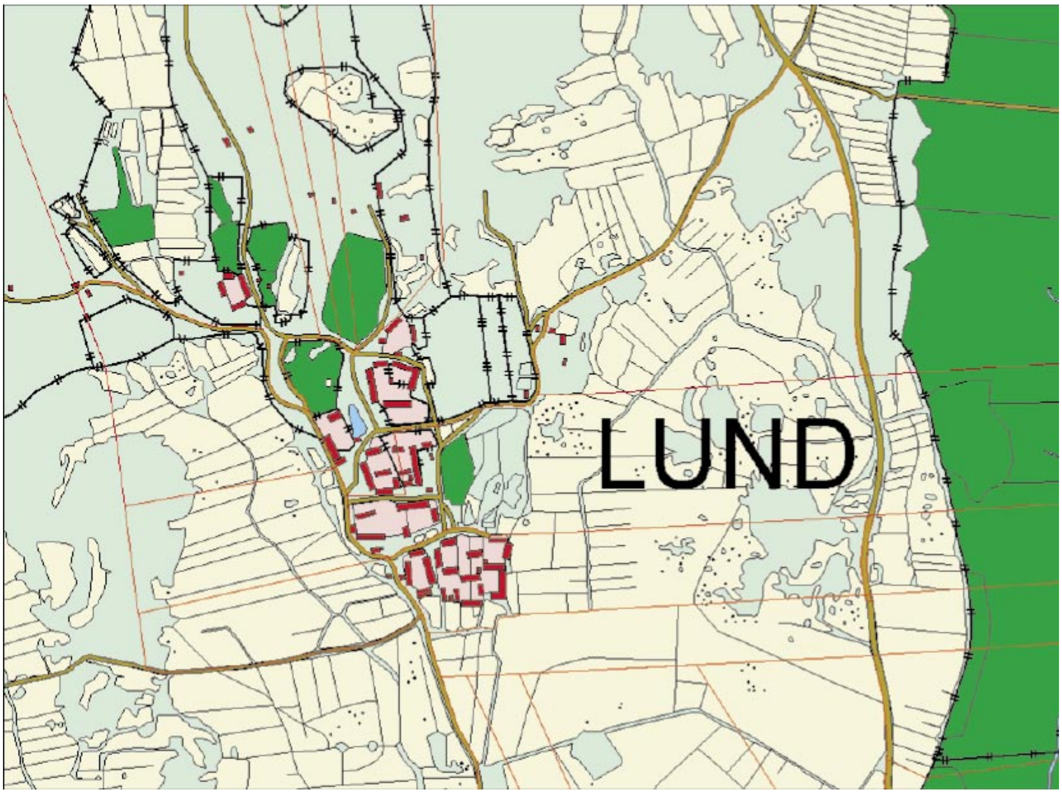

Figure 3-12. *In the maps it is possible to study details and the more modern maps from the 19th century the actual layout of the buildings. Note the amount of clearance cairns to the east of the village.*

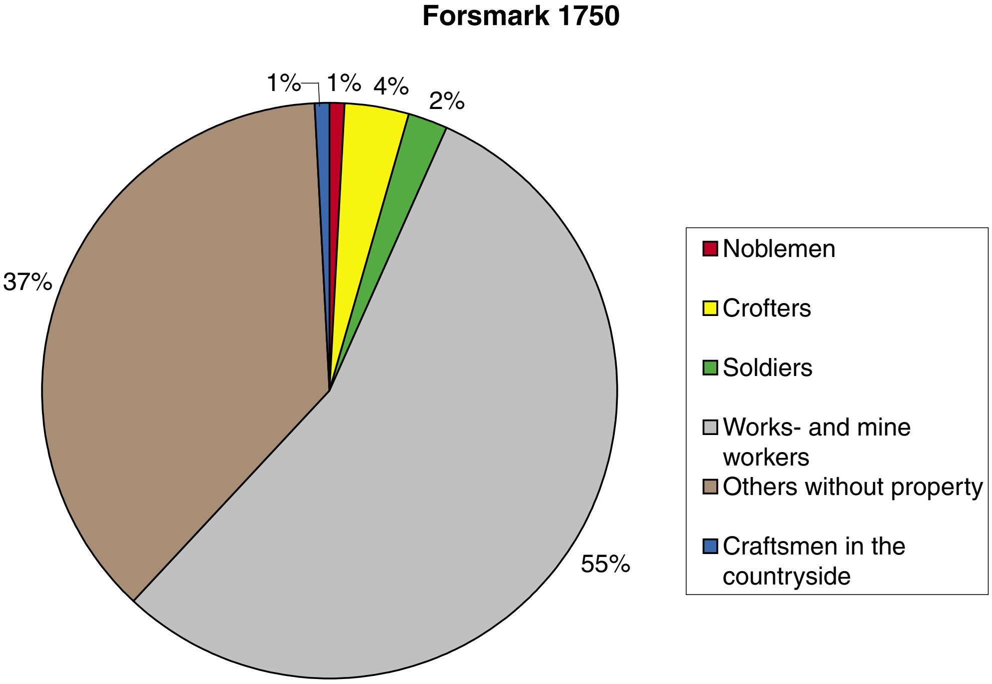

Figure 3-13. *Social population structure in the Forsmark region. (Data source Tabellverket).*

3.2 Geometry model DEM

3.2.1 Introduction

A digital elevation model (DEM) is a digital representation of a continuous variable over a two-dimensional surface by a regular array of z-values referenced to a common datum. Digital elevation models are typically used to represent terrain relief.

A DEM is required as input data for many types of surface models such as hydrological models, geomorphometrical models etc. The DEM resolution is the size of the cells in a DEM. The DEM is constructed by interpolation from irregular spaced elevation data. In both these models the Kriging interpolation method were used. Kriging is a geostatistical interpolation method based on statistical models that include autocorrelation (the statistical relationship among the measured points). Kriging weights the surrounding measured values to derive a prediction for an unmeasured location. Weights are based on the distance between the measured points, the prediction locations, and the overall spatial arrangement among the measured points.

Referenced to a common datum, a regular array of z-values allows a digital elevation model (DEM) to represent a continuous variable over a two-dimensional surface. Typically, digital elevation models describe terrain relief. Normally, a DEM has a constant value for sea surface (0 m a s l) and constant values for lake surfaces. The DEMs for the Forsmark area exists in two versions; (i) negative values in the sea to represent water depth, but constant positive values for lake surfaces represent the lake elevations or (ii) negative values in the sea to represent water depth, varying values represent lake bottom elevations.

Input data for the interpolation have many different sources, such as existing DEMs, elevation lines from digital topographical maps, paper nautical charts, digital nautical charts, and depth soundings in both lakes and the sea. All data are converted to point values using different techniques. The Kriging interpolation was performed in ArcGis 8 Geostatistical Analysis extension.

3.2.2 Methods

Data catch from land areas

Two sources were used to collect elevation point data for land: the existing DEM from the Swedish national land survey (LMV) with a resolution of 50 m (Light green areas in Figure 3-14) and the SKB DEM with a resolution of 10 m (Dark green areas in Figure 3-14) /Wiklund, 2002/.

The existing DEMs were converted to point layers in shape-format using ArcToolbox in ArcGis 8. There are errors in the 10-metre grid values for lake surfaces. In Lake Fiskarfjärden, for points situated at least 25 m from the shoreline, the Z-value has 16 unique values ranging from 0.589 to 0.755 m a s l. Two values dominate these points, 0.6726 in the western part of the lake and 0.5889 in the eastern part. These areas are separated by a distinct straight north – south line that acts like a threshold in the lake surface at 0.0837 m. This threshold seems to intersect with the border between two adjacent flying transects.

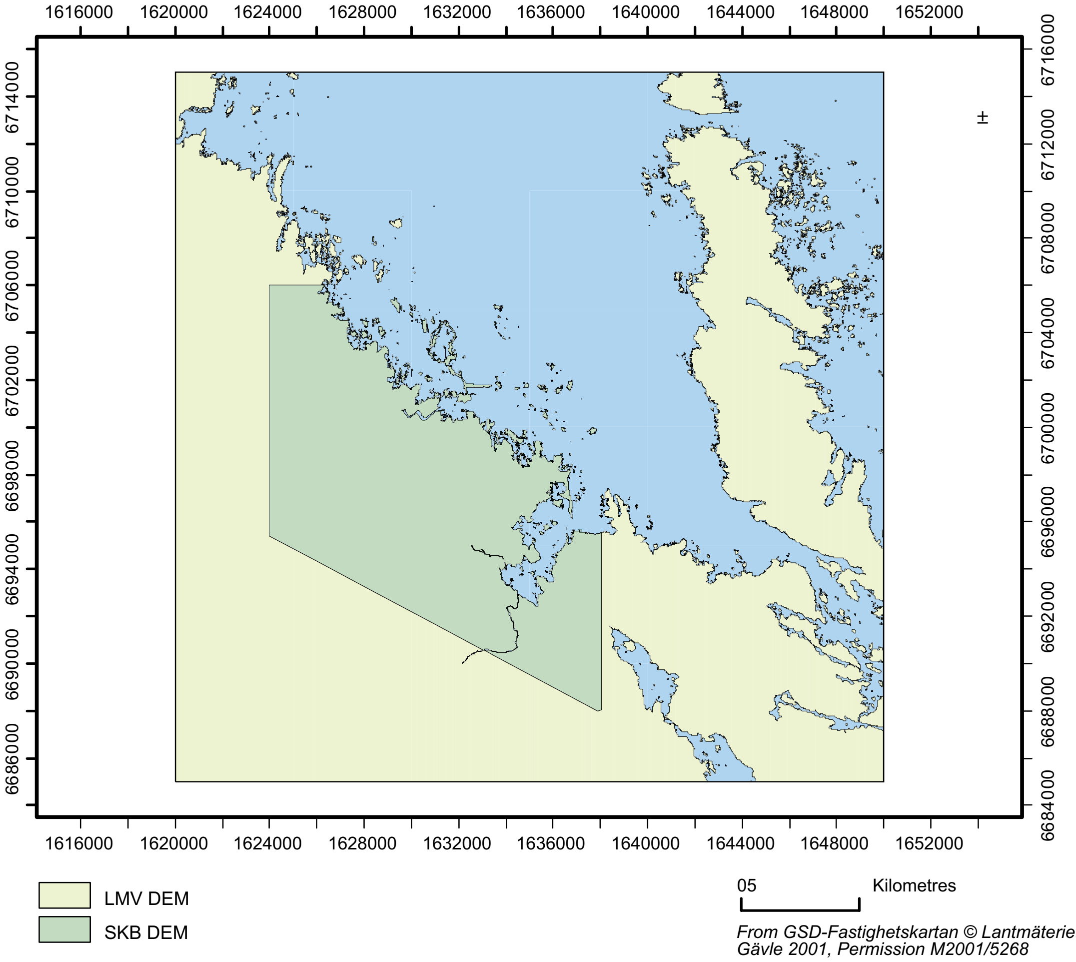

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Figure 3-14. *Extensions of the data sets from land, the LMV DEM and the SKB DEM, respectively.*

The same phenomenon exists in most of the lakes within the 10-metre grid extension. All points placed within lakes with levelling instruments (see Figure 3-15) were replaced by the measured values. It should be noted that these levels are not the mean lake levels but the levels at each measuring occasion.

These two point-layers (LMV DEM points and SKB DEM points) were merged into one single point layer, and all points placed on the sea surface polygon from the digital localities maps were deleted from the datasets. The final layer is in the Swedish national grid projection (RT 90 2.5 gon W) and in the Swedish national height system 1970 (RH 70).

Data catch from sea areas

Figure 3-16 shows the extensions for elevation data for the sea area. The elevations have been obtained from the following sources:

(i) The digital nautical chart (the Swedish National Administration of Shipping and Navigation), area B in Figure 3-16.

(ii) The base map to the nautical chart, area E in Figure 3-16.

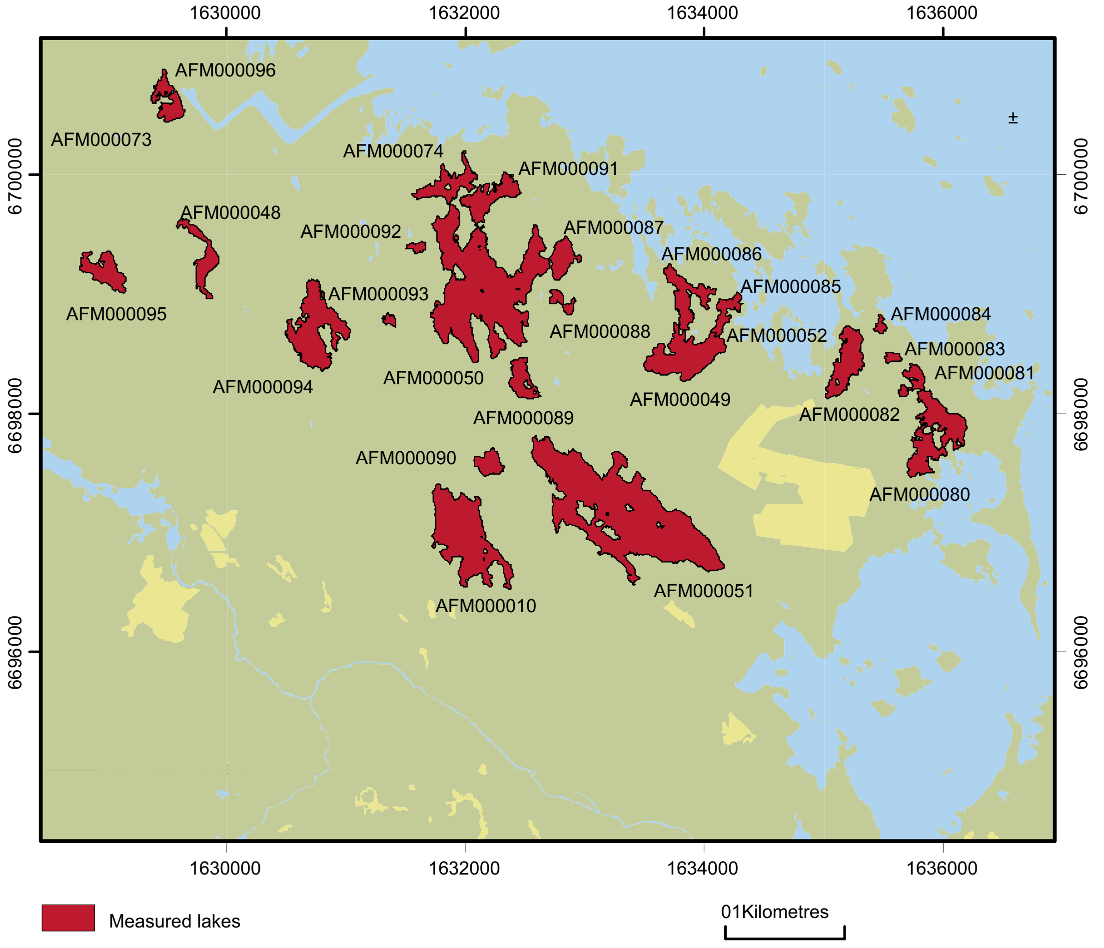

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Figure 3-15. *Lakes were the SKB DEM points are replaced by measured values. For all other lakes the elevation were set to the mean value from the SKB DEM.*

(iii) The paper nautical chart (number 535 Öregrund – Grundkallen – Björn), area B in Figure 3-16.

(iv) Depth soundings performed by the Geological Survey of Sweden, SGU /Elhammer and Sandkvist, 2004/, area D in Figure 3-16.

(v) Depth soundings of shallow bays /Brydsten et al. 2004a/, area F in Figure 3-16.

(vi) With DGPS measured shoreline points.

(vii) Digitized shoreline points from IR orthophotos.

(viii) The sea shoreline from the digital localities maps from Lantmäteriet.

(ix) Constructional drawings for the inlet channel to the nuclear power plant /Vattenfall, 1977/, area H in Figure 3-16.

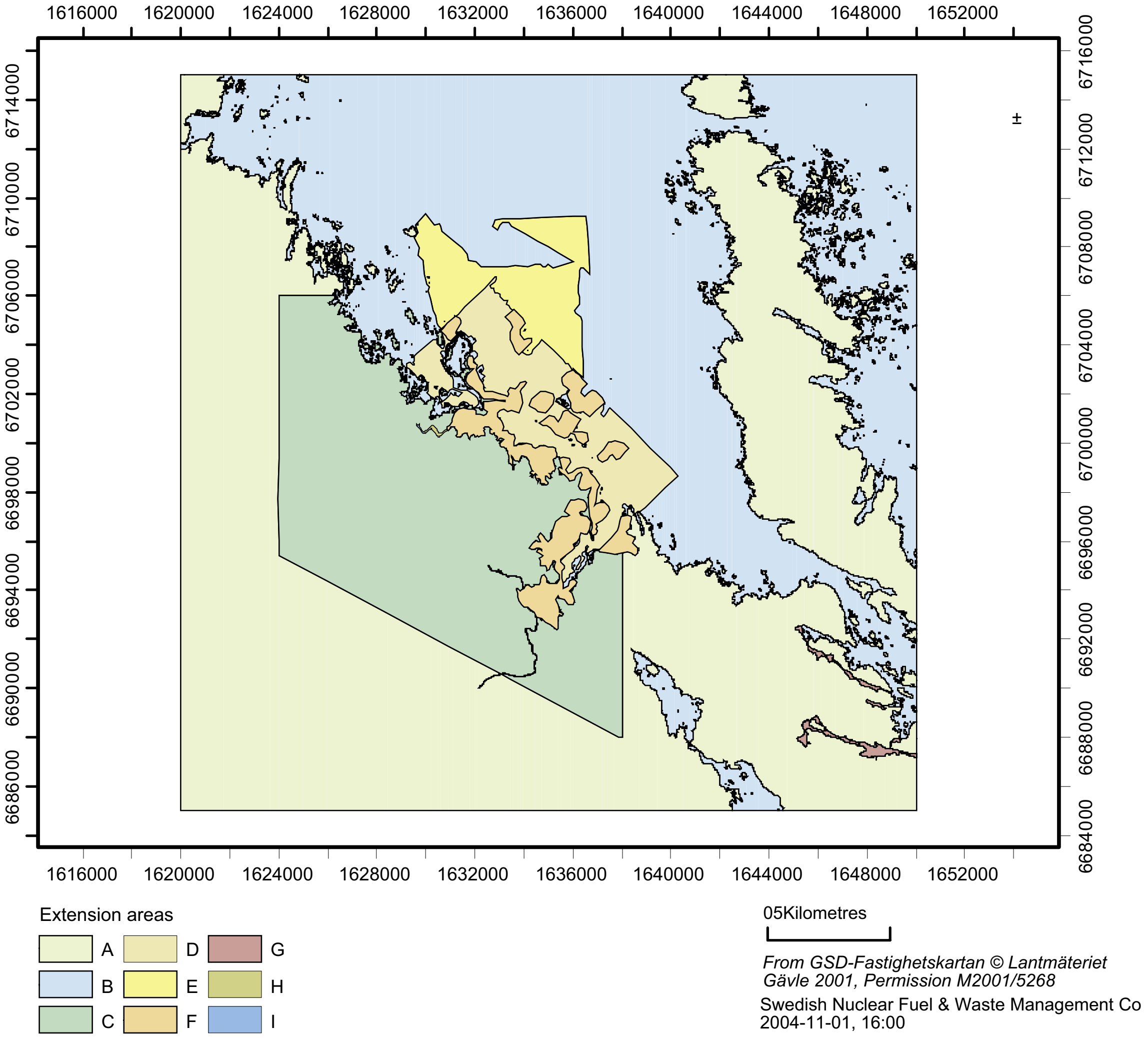

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Figure 3-16. *Extensions for different data sources for the sea areas; the digital nautical chart, the base map to the nautical chart, the paper nautical chart, depth soundings performed by the Geological Survey of Sweden, depth soundings of shallow bays, with DGPS measured shoreline points, digitized shoreline points from IR orthophotos, the sea shoreline from the digital localities maps from Lantmäteriet and constructional drawings for the inlet channel to the nuclear power plant.*

The digital nautical chart has depth lines for 3, 6, 10, 15, 25, and 50 m. These line objects have been transformed into point objects in ArcView using the Avenue script LineToPoints.avx. The maximum distances between adjacent points were set to 10 m. Because the digital nautical chart lacks the point depths that are present in the paper nautical chart, these points were manually digitized from the paper nautical chart. The paper nautical chart was scanned and rectified to WGS-84 with ArcGis 8, and the point depths were manually digitized on screen. The point depths (single water depth values) and symbols for "Stone in water surface" (a plus sign with dots in each corner) and "Stone beneath water surface" (a plus sign) were digitized as points. The water depth for "Stone in water surface" was set to –0.1 m and for "Stone beneath water surface" to –0.3 m.

For the area E in Figure 3-16, the base map for the nautical chart was used to digitize point depths. Because these depth soundings were performed as early as 1898, it was necessary to convert these values from foot to metre and at the same time adjust the values for shore displacement since 1898. The adjustment for shore displacement (1898–1970) was calculated to +0.45 m using equations presented in /Påsse, 1997/ with the following parameters:

As = 300, Bs = 7,250, Af = 95 and Bf = 1,000.

The base map was scanned and rectified to WGS-84 using the point depths from the paper nautical chart. The point depths on the base map were then manually digitized on screen. The depth values in both the digital nautical chart and the paper nautical chart refer to mean sea level 1970, so no adjustment is needed for mixing soundings and land elevation data in RH 70. The total number of depth soundings in the base map is 4,300.

The SGU depth soundings were delivered to SKB as 201 files in ascii-format, generally one file for each transect in the survey /Elhammer and Sandkvist, 2004/. The columns in the files consist of X-coordinates and Y-coordinates with a resolution of 4 digits (1/10 of a mm) and a Z-value with a resolution of two digits. The coordinate system is RT 90 and the Z-values are corrected to RH 70. The ascii-files were imported to Excel and exported in dBase4-format to make it possible to import these files to ArcGis 8. All 201 files were merged into one single point layer in ArcGis 8. The total number of measurements are approximately 180,000.

The SGU depth soundings were not performed in the shallow bays due to size of the vessel. Therefore, a completing depth sounding using a small boat was performed /Brydsten et al. 2004a/. To map water depths, a digital echo sounder was used (Simrad EQ32 Mk 11) and a DGPS (Trimble Pro XR) connected to a field computer (Itronix GoBook) using ESRI ArcPad real time GIS software. For each update of the GPS position (every second), the X and Y co-ordinates were recorded from the GPS; The Z values (water depth) were recorded from the digital echo sounder. Approximately 2000 depth values per hour were recorded. The co-ordinates were measured in RT 90 coordinate system with an accuracy of one centimetre.

An orthophoto (1 m resolution) was used as background imaging in the field computer. Each recorded depth point was displayed on top of the orthophoto. It was possible to observe which parts of the area had already been mapped, and this was used as a navigational aid. The depth values were adjusted because of different water levels in the sea over time. Using sea level records from Forsmark with hourly accuracy, the water depth values were adjusted to zero sea levels in the RH 70 height system. The total number of depth soundings in shallow bays are approximately 84,000 points.

Although a small boat was used in the shallow bay depth soundings, depth values are absent between the shoreline and approximately 0.7 water depth. When using the final DEM in modelling of the modern hydro-geological properties, the DEM of the sea shoreline must be very accurate. A measurement of elevation points close to the present shoreline was therefore performed.

There are four opportunities to catch elevation points close to the sea shoreline:

(i) using the sea shoreline from the digital cadastral maps,

(ii) using the 0-line from the digital nautical chart,

(iii) manually digitizing the shoreline with the IR orthophoto as background, and

(iv) measuring the sea shoreline by walking the line with a DGPS.

The accuracy of the sea shoreline from the digital localities maps and the 0-line from the digital chart was tested using GIS and the IR orthophoto. The test shows that both the shorelines in the localities map and the nautical chart have low accuracies, but some areas have higher accuracy for the cadastral map. The test also showed that it is difficult to digitize the shoreline from IR orthophotos if the shoreline has a low gradient, because low gradient shorelines are often covered with reeds (*Phragmites*).

The most appropriate method for catching elevation data close to the zero level is therefore measuring the sea shoreline by walking the line with a DGPS. This approach is too expensive to use for the whole area, so this was only performed for vegetated shores within the local model area that are difficult to observe using the IR orthophoto. The rest of the shorelines within the local model area were manually digitized with the IR orthophoto as background, and the sea shoreline from the digital localities maps was used for the rest of the grid.

During a post-processing procedure, each x/y-record was given a z-value using sea level data from a water level gauge situated close to Forsmark nuclear power plant. The time resolution of the gauge was one hour. The DGPS measurements were carried out during the third week of August 2004, during this period the sea water level varied between –0.046 and 0.091 m in the RH 70 height system. The water level gauge in Kallrigafjärden, managed by SKB, was not working during this period, so only the gauge close to SFR was used.

During depth soundings of shallow bays, the depths of the inlet channel of the nuclear power plant were also measured. However, we were only permitted to survey from the bay up to the bridge, approximately 500 m. The depths of the rest of the channel were digitized from a scanned and rectified construction drawing. For the innermost 400 m part of the channel, no depth data is available. At some small areas within the grid extension, no elevation data are available; e.g. part of the inlet channel mention above and two shallow bays in the Southeast part of the model area (area I in Figure 3-16 and area G in Figure 3-16) are missing. For these areas, we have manually placed "false depth values", –5 ms in the channel and –1 m in the bays. This keeps these areas from being classified as land in the final grid. Elevation data from different sources were in different coordinate systems; therefore, the data that was not in the Swedish national Cartesian system (RT90 2.5 gon W) was transformed to RT 90. This transformation was performed using the GIS software ArcGis 8.

Handling data from different data sources that are overlapping

Because some of the extensions of different point elevation data overlap, different tests were performed to determine whether both data sets in the overlapping area should be used or only one of the sets. For land areas the test is based on the 10-metere grid and for sea areas the tests are based on SGU depth soundings. These data sets are estimated to be the most accurate. The second most accurate depth measurements for sea areas are estimated to be depth soundings of shallow bays. The five tests are as follows:

(i) the 10 m grid against the 50 m grid,

(ii) the digital nautical chart against SGU depth soundings,

(iii) the base map to the nautical chart against SGU depth soundings,

(iv) the depth soundings of shallow bays against SGU depth soundings,

(v) the digital nautical chart against the base map.

The point elevation data sets were joined against the SGU or SKB 10 m DEM data sets. This GIS function (point to point join) gives a new attribute with the distance to the closest point in the join to data set. Points in actual data set with a distance shorter than 1 m were selected and the difference in z-value was calculated. Only in an exceptional case, the differences in Z-values larger than one metre are allowed for the data set to be classified as accurate as the join to data set (one metre difference in XY-plane and one metre in Z-value means at least a 45 degree slope).

Based on the test results /Brydsten and Strömgren, 2004b/ the following data sets were used in the final interpolation procedure:

(i) When the 50-metres grid overlapped the 10-metres grid, only values from the 10-metres grid were used.

(ii) When the digital nautical chart overlapped the SGU depth soundings, only the SGU data set were used.

(iii) When the base map overlapped the SGU depth soundings, only the SGU data set were used.

(iv) When the depth soundings of shallow bays overlapped the SGU depth soundings, both data sets are used

(v) When the digital nautical chart overlapped the base map, only data from the base map were used.

The total number of points in the merged point data set after deletion of some of the overlapping data sets is approximately 1,890,000.

3.2.3 Results

Construction of the digital elevation models

All elevation point values were collected in two databases, and with these databases new digital elevation models were created, one representing land surface, lake water surface, and sea bottom and one representing land surface, lake bottoms, and sea bottoms.

The DEMs were created with a resolution of 10 m. The interpolation from irregularly spaced point values to a regularly spaced DEM was done using the software ArcGis 8 Geostatistical Analysis extension. Kriging was chosen as the interpolation method /Davis, 1986; Isaaks and Srivastava, 1989/. The choice of theoretical semivariogram model and the parameters scale, length, and nugget effect were done with the extension.

Because of the large size of the merged point file, it was impossible to construct the grids by one single interpolation process. Therefore, the grid was divided into 36 sub-grids (see Figure 3-17) that were processed one by one and finally merged together into one single grid. Each sub-grid was treated with regard to its conditions; i.e. different Kriging parameters were set to different sub-grids.

Common to all sub-grids are an Ordinary Kriging Geostatistical Method, a spherical theoretical model, and an elliptical search shape. The parameters that differ between different sub-grids are the search size (the length of the major and minor semi-axis of the ellipses), the angle of the major semi-axis, the nugget value, the number of lags, and the lag size. Before the interpolations start, the models are validated both with cross-validation (one data point is removed and the rest of the data is used to predict the removed data point) and ordinary validation (part of the data is removed and the rest of the data is used to predict the removed data). Both the cross-validation and ordinary validation goals produce a standardised mean prediction error near 0, small root-mean-square prediction errors, average standard error near root-mean-square prediction errors, and standardised root-mean-square prediction errors near 1.

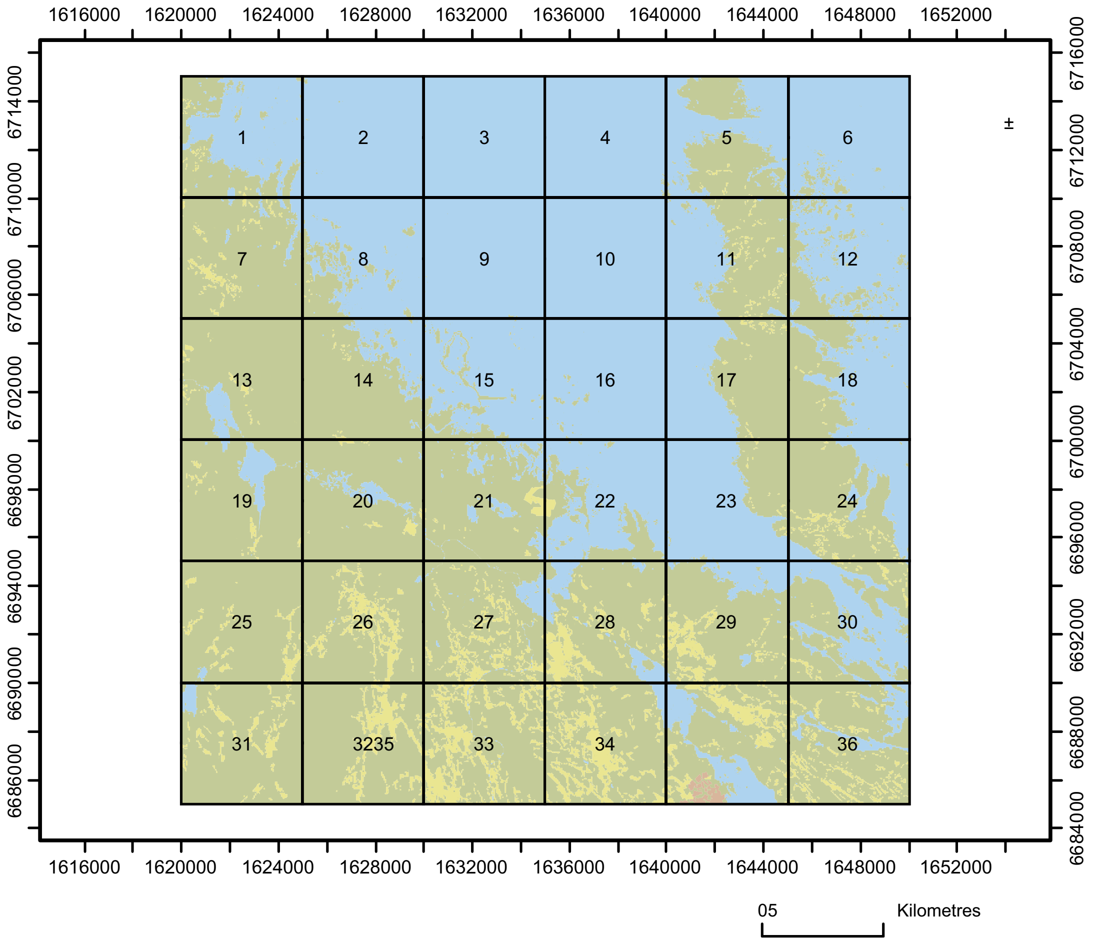

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Figure 3-17. *The grid was divided into 36 sub-grids due to the large size of the point data set. The figure shows the extensions of the 36 sub-grids.*

Cross validations with different combinations of Kriging parameters were performed until the standardised mean prediction errors were close to zero, but not necessarily the lowest values were always chosen. Because the aim was to determine the most valid model for both measured and unmeasured locations, care was taken to produce low values for the root-mean-square prediction errors and minimise the difference between the root-mean-square prediction errors and the average standard errors. Different models were compared and the ones with the most reasonable statistics were chosen.

Finally, validations were performed with the most appropriate Kriging parameters in order to verify that the models fit unmeasured locations. Unfortunately, the standardised mean prediction errors and the standardised root-mean-square prediction errors were not calculated for all of the models.

The quality of the digital elevation models

The validation procedure changed the Kriging parameters to minimise the prediction errors. The best combination of Kriging parameters is impossible to find, but the validation procedure was performed until only a minor change was noted by the prediction errors. The final choice of parameters is presented in /Brydsten and Strömgren, 2004b/.

Figure 3-18 shows the quality of the sub-grids as the values of root-mean-square prediction errors that should be low for a high quality grid. Sub-grids with low quality are those with data only from the digital nautical chart and those are also the sub-grids with lowest point density.

The coordinates of the starting point (upper left corner) was chosen so that the values from the SKB 10-metres DEM was not changed by the Kriging interpolation process; i.e. the central points in the cells in the new DEM coincide with the central points in the SKB 10-metre DEM. The digital elevation model with lake surface values is illustrated in Figure 3-19.

The final grid had a size of approximately 30×30 km, a cell size of 10-metres, 3,001 rows, and 3,001 columns: a total number of grid cells of 9,006,001 and a file size of approximately 35.3 MB (ESRI Grid format). The extension is 1619995 west, 1650005 east, 6715005 north, and 6684995 south in the RT 90 coordinate system. As mentioned earlier, the height system is RH 70.

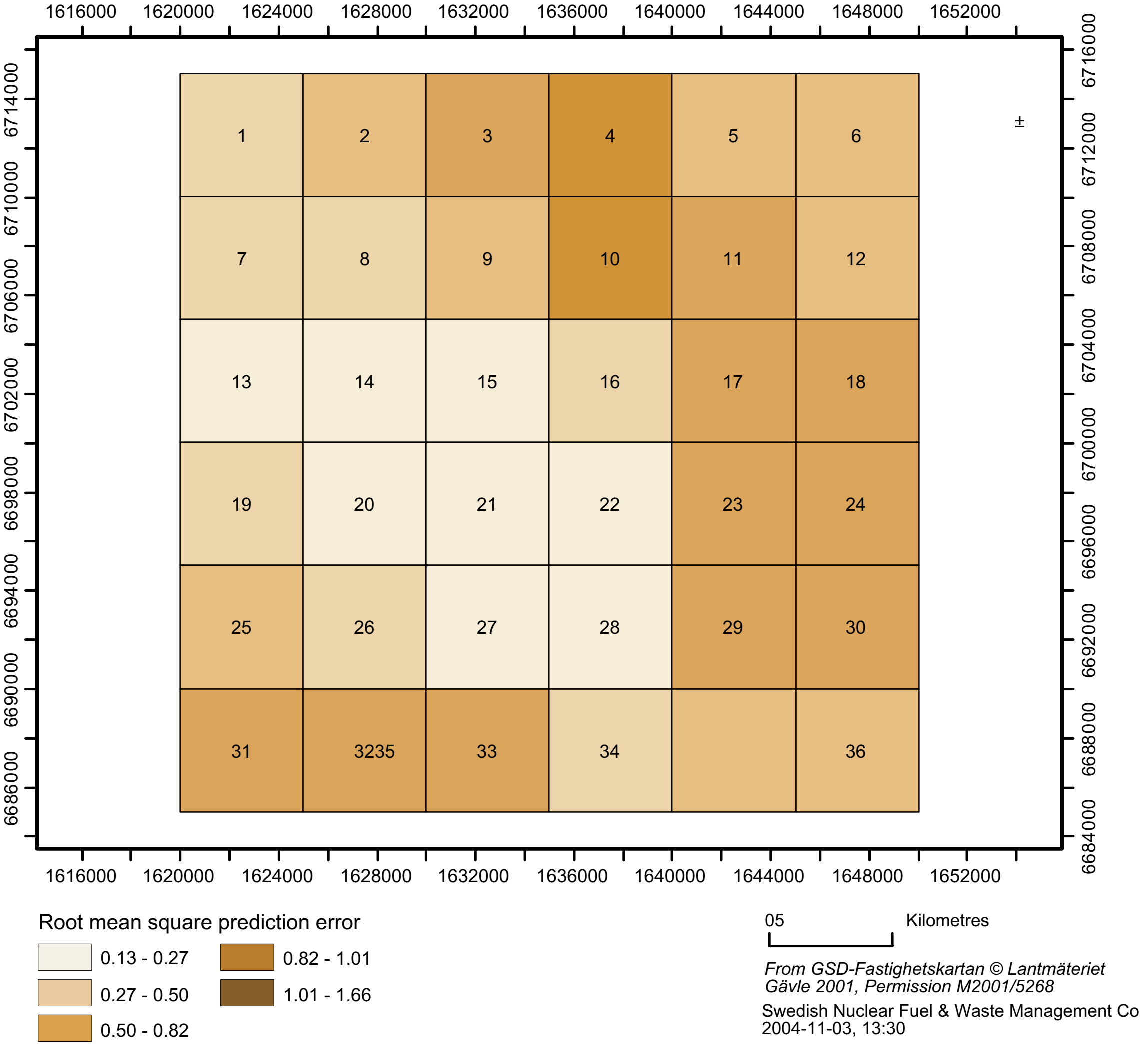

Figure 3-18. *Quality of the sub grids as the values of root-mean-square prediction errors from the cross-validation in ArcGis Geostatistical program.*

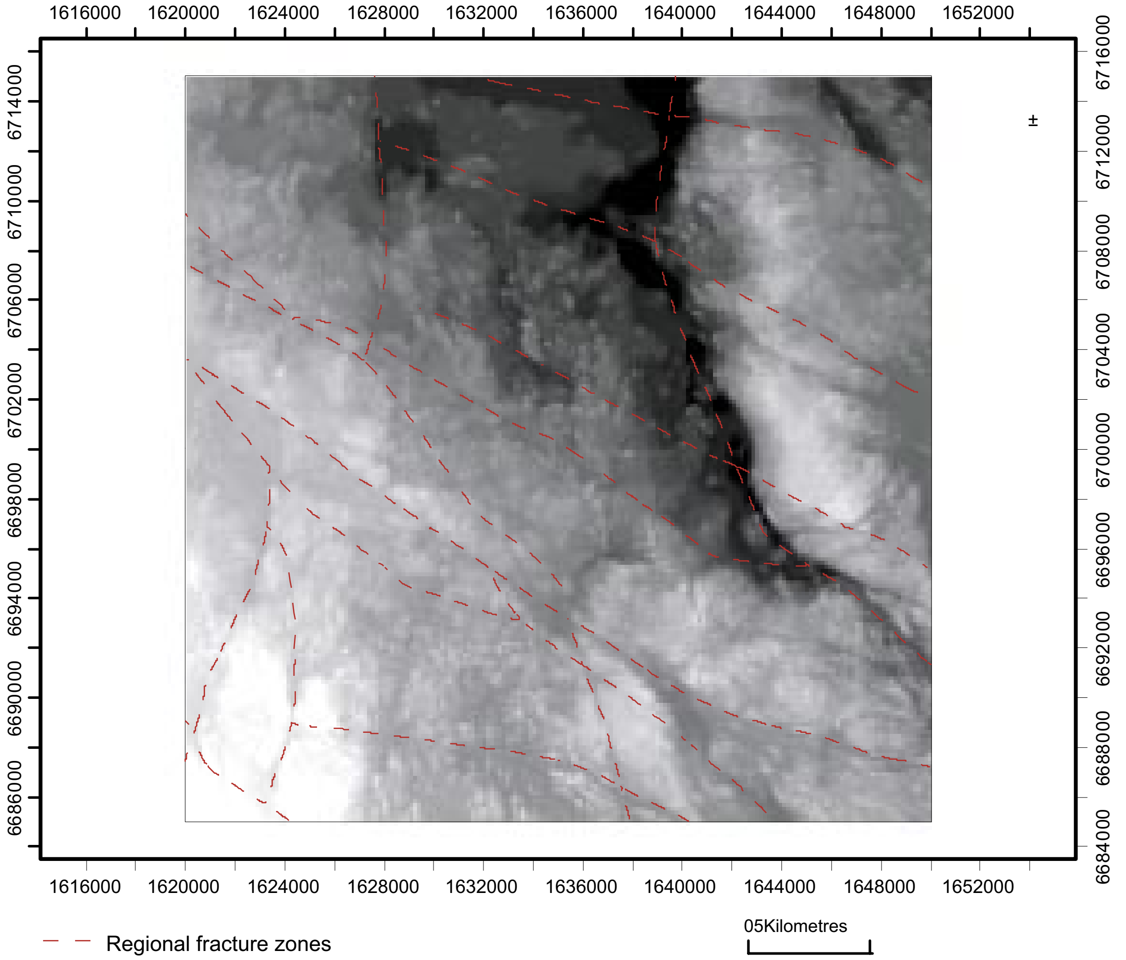

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Figure 3-19. *The digital elevation model with lake surfaces.*

The area is extremely flat; the range in elevation is only approximately 109 m with the highest point at 51 m above sea level at the south-west part of the grid and the deepest sea point at –58 m in the northern part of the so called Gräsörännan. The mean elevation in the grid is 2 m and 58% is land and 42% is sea. The flat landscape is also shown in the statistics of the slope grid where the mean slope is 1.50 degrees, and 97.2% of the cells have slopes lower than 5 degrees and 2.7% have slopes between 5 and 10 degrees. Almost all of the cells with slope steeper than 10 degrees (0.15%) are man-made, e.g. the inlet channel, piers and wharfs close to Forsmark nuclear power plant.

3.3 Overburden (Quaternary deposits)

3.3.1 Introduction

This section describes the data available and the modelling of the overburden in the Forsmark regional model area. The overburden is often called Quaternary deposits (QD) and includes glacial deposits such as till, glaciofluvial deposits and clay, as well as postglacial deposits such as marine and lacustrine sediment and peat. The upper part of the overburden, affected by soil forming processes, is referred to as the soil.

The information of the distribution and composition of QD in the Forsmark regional model area comprises initial data, compiled in connection with the Östhammar feasibility study /Bergman et al. 1996/ together with the results from the initial site investigations, IPLU, in Forsmark. Most information derives from the central part of the regional model area, where a detailed geological map has been produced and a majority of the stratigraphical investigations has been undertaken.

The models of the overburden are both descriptive/conceptual and quantitative. The 3-dimensional distribution of QD is used as input data for modelling of near-surface hydrogeology, see Section 3.4. The 2D distributions of QD and soiltypes are used in quantitative modelling of e.g. carbon budget for the Forsmark regional model area. The descriptive models are used for the understanding of the Late Quaternary history of the Forsmark site.

3.3.2 Input data and data evaluation

This model is based on the data available at the Forsmark data-freeze 1.2, July 2004. Below follows a summary of the maps (2D models), stratigraphical information and analytical data included.

Maps

The regional model are has earlier been mapped by the Geological Survey of Sweden /Persson, 1985, 1986/. These maps give a good view of the relative distribution of QD and bedrock outcrops in a 1:50,000 scale. The maps are relatively modern and available digitally as GIS files. From the central part of the regional model area, a map that can be presented in scale 1:10,000 has been produced within IPLU /Sohlenius et al. 2004/. The detailed map includes bedrock exposures and QD with an area larger than 10×10 m located within the blue box in Figure 3-20. The maps show the Quaternary deposit at a depth of 0.5 m below ground surface. The superficial boulder frequency of the till is also shown on the map as well as the direction of glacial striae on bedrock outcrops, which gives information of the direction of the ice movements during the latest ice age.

Data from the detailed marine geological survey of the sea bottom outside Forsmark gives information regarding the horizontal and vertical distribution of QD on sea bottoms situated at water depths greater than 3 m /Elhammer and Sandqvist, 2004/. This information is presented in a map of the QD on the sea bottom (scale 1:100,000). The data was collected from boat (Ocean Surveyer in the deeper area and a smaller boat from SGU in the areas with less than 6 m waterdepth) in lines with a spacing of 100 m in a detailed area and with a spacing of 1 km further out in the Baltic (Figure 3-21). Sediment samples were taken with 1 and 6 m cores. The information gained during the marine geological survey contains details regarding geology and bathymetry, which can at present not be printed due to safety reasons. The marine geological maps in this report are therefore presented in the scale 1:100,000.

A map showing the distribution of the soil types in the Forsmark area was derived from secondary spatial data on vegetation types, distribution of QD and a topography-based hydrological index. The properties of the QD have a large effect on the soil forming processes. This model version has used the regional geological map by /Persson, 1985, 1986/ scale 1:50,000. A comparison with the detailed geological map /Sohlenius et al. 2004/ shows that the occurrence of peat was overestimated in the regional map. This has probably resulted in an overestimation of the areas covered with of Histosoils in the soil map.

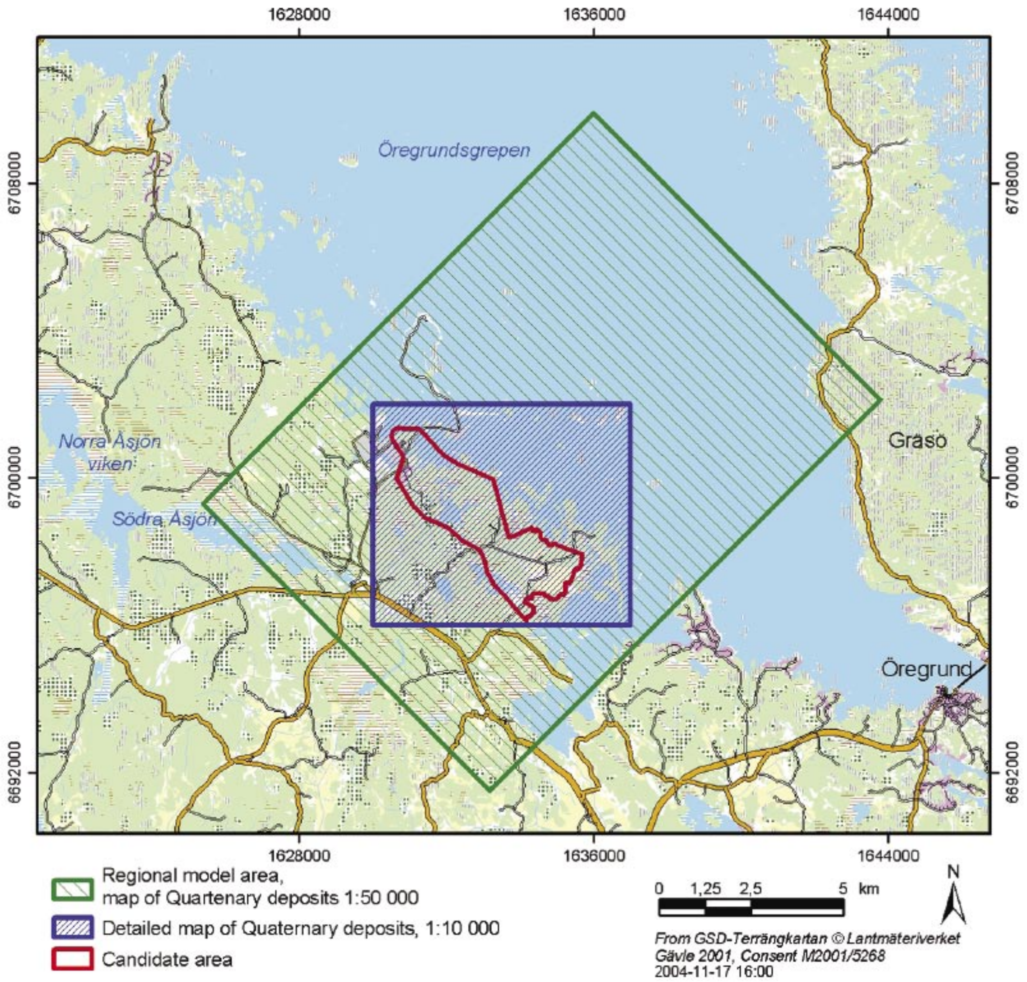

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Figure 3-20. *Map showing the areas where Quaternary deposits have been mapped, and the scale in which the information is presented.*

Stratigraphical data

Stratigraphical data comprises information of the spatial distribution of the different layers of QD. The information has been gained from the large number of overburden/rock drillings, machine cut trenches, corings in sediment and peat, stratigraphical observations from the geological mapping and geophysical data. The stratigraphical data was compiled into a depth model for QD within the area including the catchment area of Lake Bolundsfjärden (Figure 3-22).

A large data set was obtained from the installation of groundwater monitoring wells. Graphs showing the stratigraphical profiles based on geotechnical classifications and the location for samples collected are presented by /Johansson, 2003; Werner et al. 2004; Werner and Lundholm, 2004a/. Stratigraphical descriptions based on geological observations and grain size distribution are described by /Hedenström et al. 2004/. Stratigraphical data from lake sediment and peat comprises profiles, descriptions and physical and chemical analyses from 19 lakes and two mires (Figure 3-22) /Hedenström, 2003, 2004b; Fredriksson, 2004/. Detailed stratigraphical descriptions of the glacial till was obtained from machine cut trenches /Sundh et al. 2004/. The trenches are distributed within the area where detailed mapping of QD has been performed and represents two of the three identified different till types present in the area.

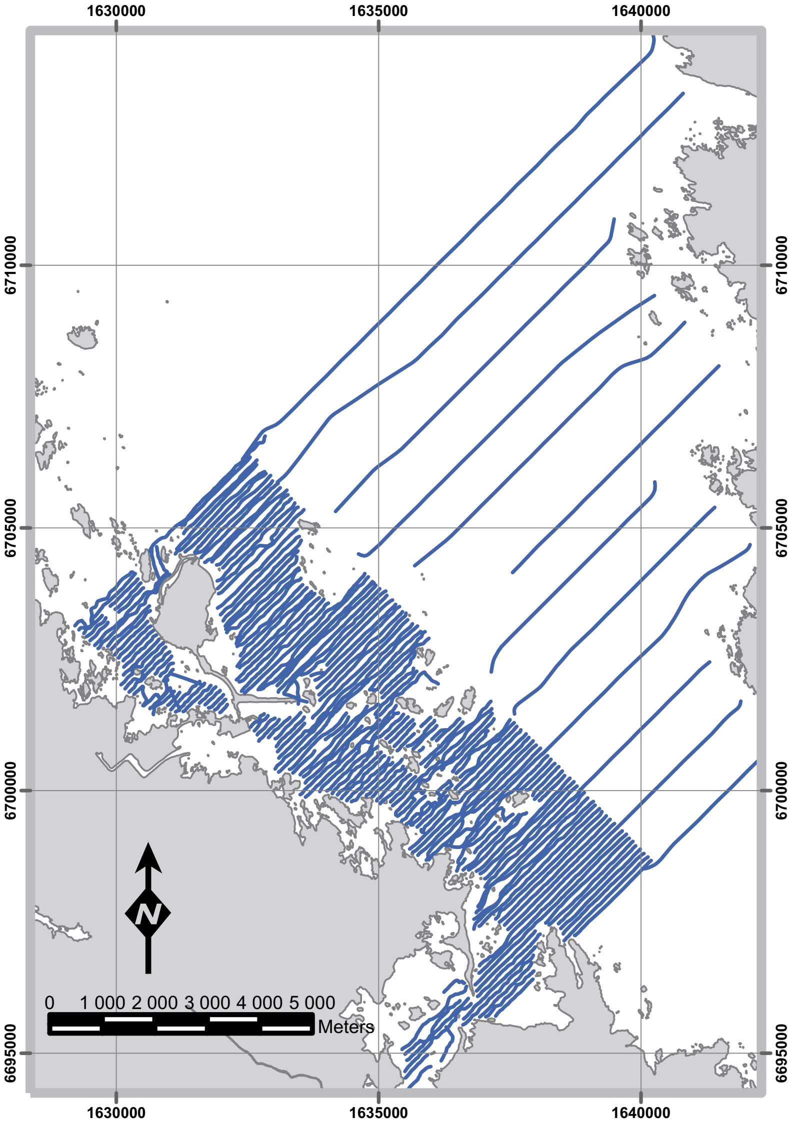

***Figure 3-21.** Map showing the lines where the marine geological mapping was performed.*

Thickness of overburden, without description of the stratigraphy, has been calculated from the interpretations of seismic profiles /Bergman et al. 2004a/. Approximately 16 km of high-resolution seismic data, distributed along five profiles within the regional model area, has been analysed. A ground penetrating radar (GPR) survey was conducted in Forsmark during the winter 2003 /Marek, 2004a/. Data from 64 km of surveying was collected and later reinterpreted in order to obtain assignments of the depth to bedrock /Marek, 2004b/. The data from the GPR was correlated with drillings and surface geology to produce geological sections. The informations of the depth to bedrock obtained from the seismic profiles and the GPR survey was used as input data to a model of the depth of the QD.

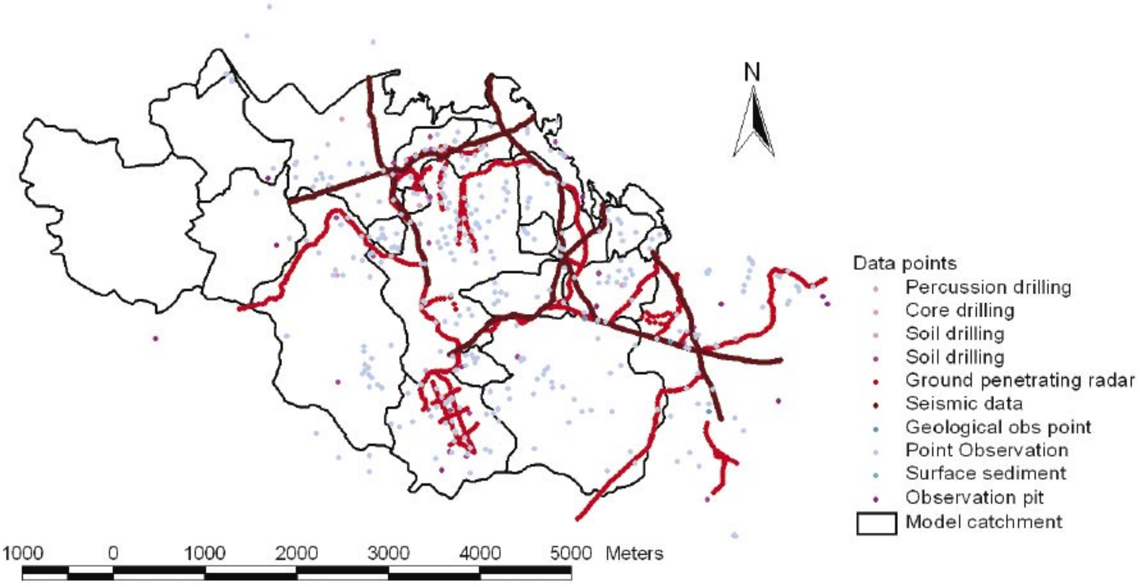

***Figure 3-22.** The data used for constructing a depth model of the Quaternary deposits /Vikström, 2005/. The data density varies in the modelled area. The western and southern parts of the area have low data density. This version of the QD-depth model includes the area within the Bolundsfjärden catchment area, showed by the black solid line. Blue dots are observations where the bedrock surface was not reached, thus giving a minimum depth to bedrock whereas the red and purple dots are observations that include the bedrock. The geophysical data represents a majority of the input data in the model.*

Analytical data

The analyses performed on the overburden comprises: grain size composition, $CaCO_3$, geochemical analyses of till and sediment, elemental composition in peat and till, clay mineral analyses of till and clay and microfossil analyses of till. In the soil type inventory, texture, pH, carbon and nitrogen was analysed at the different horizons in each soil class. A summary of the analyses performed is presented in (Table 3-4).

Table 3-4. Analyses performed on Quaternary deposits during the initial site investigations in Forsmark.

Parameter analysed	Number of samples	References
Grain size composition and $CaCO_3$	c 200	/Sohlenius and Rudmark, 2003; Lundin et al. 2004; Hedenström, 2004a,b; Hedenström et al. 2004; Sundh et al. 2004/
Geochemical alanyses of till	36	/Sohlenius and Rudmark, 2003; Nilsson, 2003/
C, N, S analyses of lake sediments	47	/Hedenström, 2004a/
Clay mineralogy in till and sediment	12	/Sohlenius and Rudmark, 2003; Hedenström, 2004a/
Chemical analyses of peat	3	/Fredriksson, 2004/
Microfossil analyses of till	13	/Robertsson, 2004/
Soil profile chemistry	c 60	/Lundin et al. 2003/

3.3.3 Metodology

Mapping of Quaternary deposits

A detailed mapping of the surface distribution of QD and bedrock outcrops was performed within the site investigations. The distribution of exposed bedrock was first interpreted from infrared aerial photos taken from a height of 2,300 m and later checked in the field. The field inventory took place during the summer months 2002 and 2003 /Sohlenius et al. 2004/.

The uppermost deposits were investigated using a spade and a hand driven probe (Figure 3-23). Orientation was made using GPS and detailed aerial infrared photographs, plotted in scale 1:5,000. A mirror compass was used to measure the directions of the glacial striae. The different QD were marked directly on the aerial photographs during the field mapping. All QD that could be distinguished from other deposits, and has an area larger than 10×10 m, were marked on the map as separate surfaces. The map shows the distribution of QD at a depth of 50 cm. Some surface layers thinner than 50 cm are also shown on the map (e.g. peat overlaying other deposits). The surface frequency of boulders are estimated in the field and shown on the map.

Descriptions of geological observations, glacial striae and stratigraphical information were noted in the field and later entered into a database of geological observations, Jorddagboken version 5.4.3, or later, and exported to SKB database SICADA.

Figure 3-23. *The equipment used during mapping of Quaternary deposits. Orientation was made using a hand held GPS and high-resolution IR photos. The geological observations were made in spade dug holes or, more frequently, using a hand held probe.*

Marine geological investigations

The geological mapping of the sea floor was performed by detailed hydro acoustic mapping that was controlled by sediment sampling /Elhammer and Sandkvist, 2004/. The investigations comprised approximately 410 km survey lines. Forty seven bottom inspections with video camera were carried out and, where possible, sediment sampling was done at these locations.

Surveying in areas with greater water depths than 6 m was made from S/V Oceans Survey, whereas at smaller boat was used at water depths between 3 and 6 m. The survey include echo sounding, sediment echo sounding, reflection seismic and side scan sonar. Samples were taken to verify the interpretation from the acoustic measurements. Soft bottoms (clay) were sampled with a core and coarser deposits with a grab sampler. The results were used to produce a map showing the distribution of QD at a depth from approximately 0.5 m below the overburden-water interface (same as on land). Thin surface layers of sand and gravel were also mapped.

Soil type investigation

Soils from eight different land types were studied within the Forsmark regional model area /Lundin et al. 2004/. The land types were defined based on vegetation, land use, and wetness. Classifications of soil type and the parent material in the QD were carried out in spade dug profiles at two sites from each land type. Soil studies at the land type "rock outcrops" reefers to sites, which have a thin cover of overburden and are situated close to rock exposures. Glacial till is the most common Quaternary deposit at these sites. The investigation did not have a total spatial coverage, such as the mapping of QD. Instead the spatial distribution of the soil types in the area was determined from a GIS based inventory including information on vegetation types, distribution of QD and a hydrological index.

The aim of the soil classification is to define soils with special properties, which then can be compared with soils from other areas. Samples were taken from the 2–3 uppermost soil horizons and analysed for pH, calcium carbonate, organic carbon and nitrogen.

Stratigraphical investigation

When stratigrapical descriptions and observations were made in connection with drillings, a Quaternary geologist was present and classified the lithology directly in the field. Samples were collected for analyses of e.g. grain size composition and $CaCO_3$ content. Some samples were used for geochemical analyses /Sohlenius and Rudmark, 2003; Nilsson, 2003/ while others were subject to microfossil analysis /Robertsson, 2004/. The samples derived from percussion bore holes (HFM) are disturbed, flushed, samples, sometimes holding crushed fragments of bedrock or boulders, thus the stratigraphical descriptions from these sites may some times be of poor quality. At the installation of ground water monitoring wells (SFM-sites), the samples were usually obtained using a geotechnical auger drill, resulting in a better quality both for description and sampling (Figure 3-24).

Figure 3-24. *At the installation of groundwater monitoring wells, corings were performed using an auger drill. The coring sites are distributed within the investigation area and resulted in samples of higher quality than the percussion corer. The picture shows clayey till obtained from 4 m depth at Storskäret. Note the detail in the bottom right hand corner.*

A special study to investigate the stratigraphical distribution of glacial till was conducted in august 2003, as a sub-activity within the mapping of QD /Sundh et al. 2004/. Machine-cut trenches were dug out at 22 sites to investigate the composition and stratigraphical distribution of the till and, where possible, the stratigraphic relation between different till-beds. The trenches were dug to bedrock, if possible, or to a depth of c 5 m as a maximum (Figure 3-25). Clast fabric analyses were performed in the different till beds and glacial striae were measured at the bottom of the trenches, thus getting information of ice flow direction at different phases of glaciation /Sundh et al. 2004/.

Stratigraphical investigations of sediment in lakes and mires were performed using a hand driven corer, a Russian peat corer /Hedenström, 2003/. The corer derives undisturbed 1 or 0.5 m long samples (Figure 3-26) which were classified directly in the field.

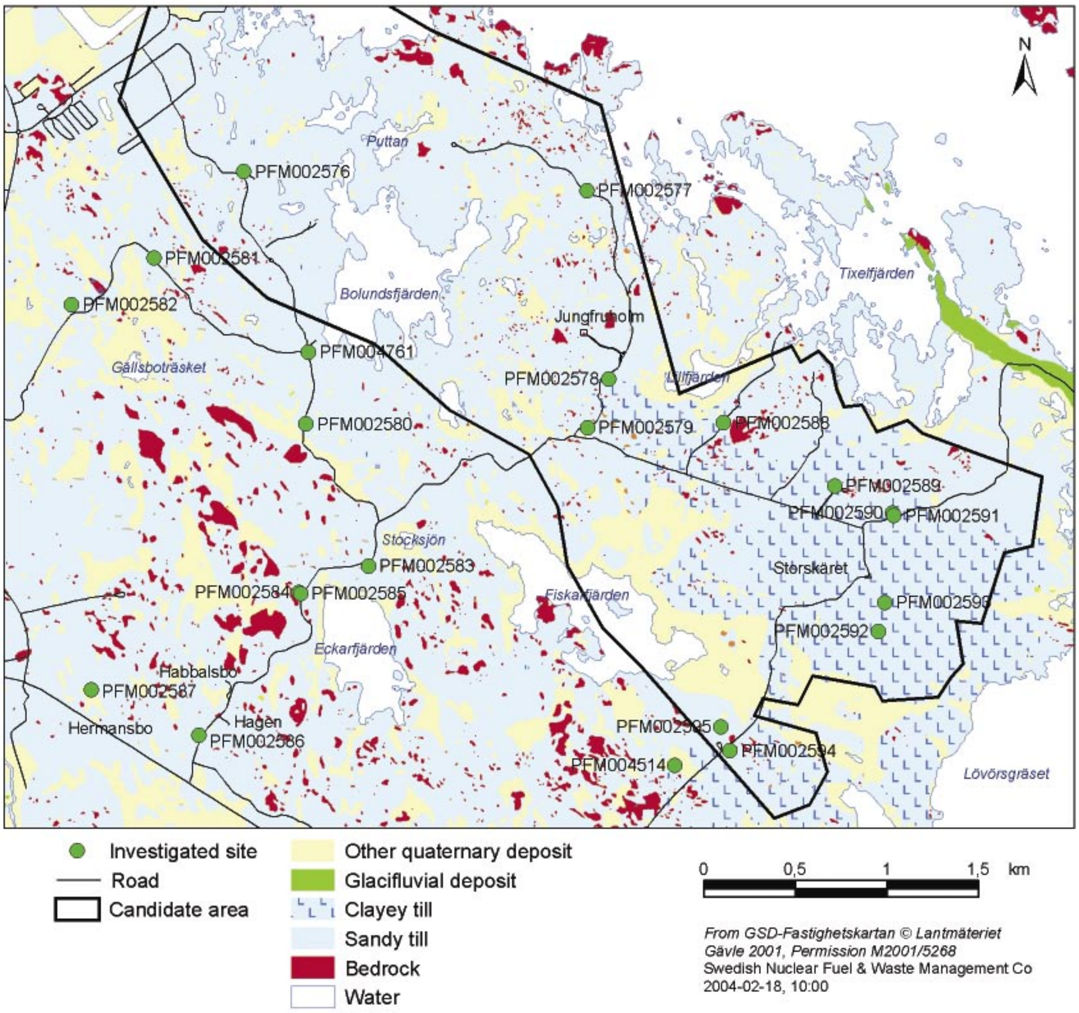

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Figure 3-25. *The location of the sites where the stratigraphical relations of the till beds in Forsmark was studied in machine cut trenches. Fabric analyses and orientation of glacial striae were measured and used in the development of a glacio-geological model for the area.*

Figure 3-26. *Example of a sediment sample collected from the bottom of Lake Eckarfjärden. The corer collects 1 m long sediment sequence that is inspected and described in the field. The corer is hand driven and is used in soft deposits such as gyttja, clay and peat. The investigated sediments do not include coarse-grained deposits such as till.*

Geophysical methods

The geophysical investigations used to calculate the dept of the overburden in this model version is Ground Penetrating Radar and seismic tomography along reflection seismic profiles /Marek, 2004 a,b; Bergman et al. 2004a/.

The GPR method is an electro-magnetic geophysical method, which is frequently used for detecting subsurface objects and geological structures at depths of approximately 0–10 m. The method uses the dielectrical properties of the overburden and bedrock. The depth penetration and resolution of the method depend on the frequency and strength of the signal, and the dielectrical properties of the ground. A low frequency can "see" deeper down than a higher frequency, while a high frequency gives a higher resolution. A dry and well-sorted material transmits the signal better than a water saturated fine-grained or poorly sorted material. For a detailed description of the methods used, see /Marek, 2004a,b/.

In seismic tomography the travel times of the first arriving seismic waves that reach the receivers from the source are used. The first arriving wave travels directly from the source to the receivers and does not need to be reflected in the bedrock. The travel times depend on the distance between source and receiver, and the seismic wave velocities in the bedrock and the thickness of the overburden. For a detailed description of the methods used, /see Bergman et al. 2004b/.

Depth model of Quatrnary deposits

The data from the stratigraphical investigations listed above were compiled into a depth model of the QD /Vikström, 2005/. The program used in the modelling is GeoEditor, which is an ArcView3.3-extension developed by DHI in cooperation with the Geological Survey of Denmark and Greenland (GEUS). Seismic data was delivered in excel-format and included five profiles across the area /Bergman et al. 2004/. Each observed point had coordinates, a surface elevation and an estimated smoothed bedrock elevation that was used in the model. The total number of observation points was 1,532.

Interpreted ground penetrating radar data was delivered for 31 profiles, with a total number of observations of 1,158. For each point the co-ordinates, surface elevation and bedrock elevation was represented /Marek, 2004/. One hundred and nineteen boreholes with an estimated bedrock elevation were delivered as well as 472 observation points with detailed lithology /Johansson, 2003; Sohlenius and Rudmark, 2003; Hedenström, 2004 a,b; Hedenström et al. 2004/.

Figure 3-22 shows the distribution of observation points within the model area. The western and south-eastern parts of the area have low data density. In the southern parts the data density with respect to estimated bedrock elevation is low. Observation points in this area do not describe the actual bedrock elevation. They do, however, describe the minimum depth of the QD at each location. Observation points with measured and estimated bedrock elevation have a pink to red tone colour in Figure 3-22 and shallow observations giving a minimum depth to bedrock are marked with a blue to purple tone.

Analytical methods

At data-freeze 1.2, approximately 200 samples of QD have been analysed regarding grain size distribution and $CaCO_3$. These are the standard analyses performed on samples in order to characterise the physical properties. From grainsize distribution curves, the hyudraulic conductivity (K-values) has been calculated for some representative samples, see Section 3.4. The analytical methods used are national standard methods such as sieving and sedimentation for determining the grainsize composition /SIS 1992a,b/. Passons apparatus was used for analysis of $CaCO_3$ /Thalme and Almén, 1975/.

Geochemical analyses

Analyses of chemistry and mineralogy to characterize the Quaternary deposits

The content of $CaCO_3$ in till was determined (grain sizes < 63µ) using Passon apparatus /Thalme and Almén, 1975/. Chemical analyses were carried out on parallel till samples from eight locations (Till chemistry 1 in Figure 3-27) /Sohlenius and Rudmark, 2003/. Grain sizes < 63µ and < 2 mm were analysed with ICP-MS after leaching with 7M HNO_3. The leaching dissolve a smaller fraction of the samples compared to the method used by /Nilsson, 2003/. Qualitative analyses of clay mineralogy composition of "oriented" samples of till (material < 2 µm) were determined on four samples according to /Drever, 1973/. Quantitative X-ray diffraction was carried out at SGU in Uppsala according to /Środoń et al. 2001/. The mineralogy of eight till samples were analysed with X-ray diffraction on randomly oriented material < 2 mm.

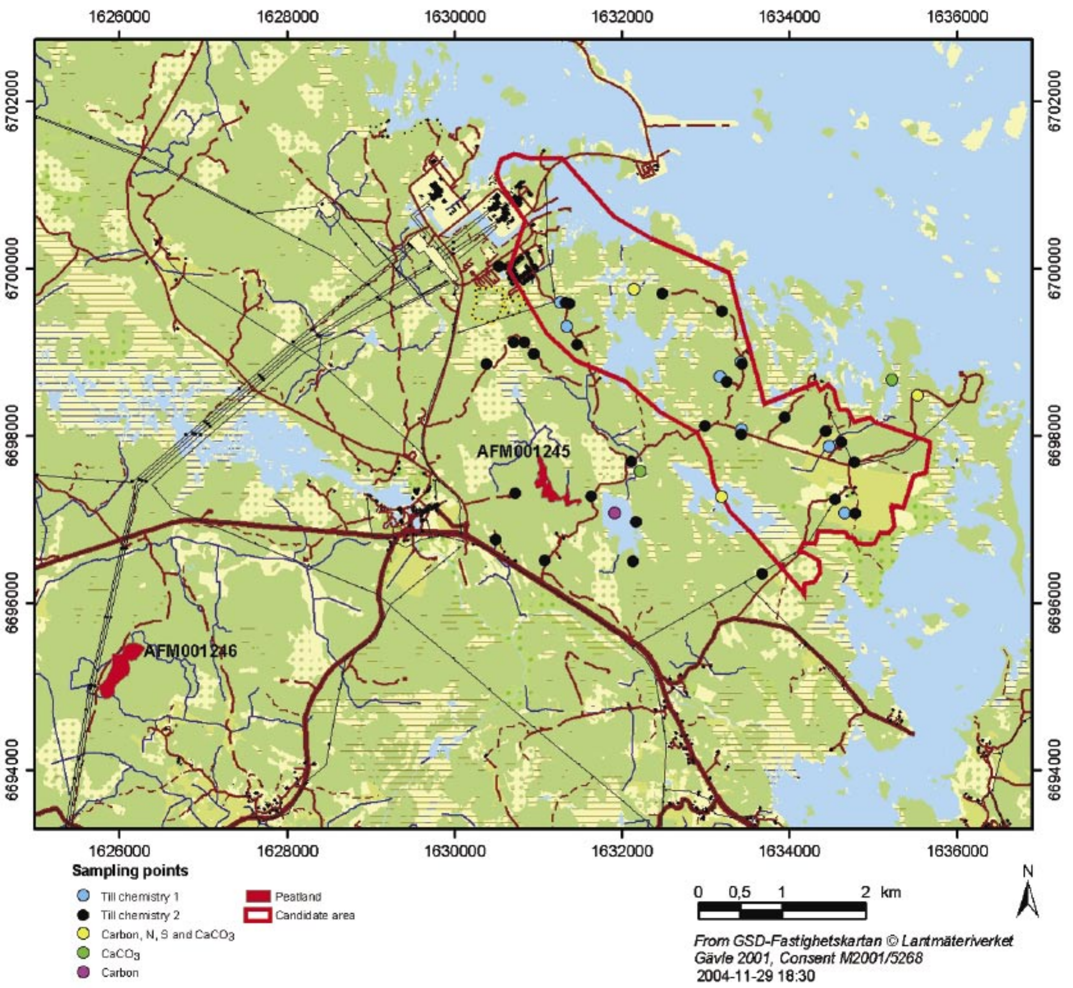

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Figure 3-27. *Sites where chemical composition of the till has been analysed are marked with black /Nilsson, 2003/ and blue /Sohlenius and Rudmark, 2003/. Sites were the chemical composition of lake sediments and were analysed are marked with yellow, green or red dots /Hedenström and Risberg, 2003; Hedenström, 2004/. The two peatlands investigated by /Fredriksson, 2004/ are marked with red.*

Chemical analyses of till to evaluate ore potential

Till material < 0.063 mm from 43 samples of till taken at altogether 28 sites (Till chemistry 2 in Figure 3-27), was digested in Aqua Regia and then analysed with ICP-MS (35 elements including Au) /Nilsson, 2003/. The precision of the gold analyses is low, since the content of that element is low in the area. The results from the ICP-MS analyses were presented in colour shaded maps. These maps were produced from gridding with the Kriging Method of Spherical Variogram model. The result from each site is also presented as a circle, proportional to the content of the element.

Chemical analyses of lake sediment

The total contents of carbon (C) have been analysed in marine and lacustrine sediments from four lakes /Hedenström, 2004a; Hedenström and Risberg, 2003/. In addition, the total content of nitrogen (N) and sulphur (S) was analysed in sediments from three of these lakes (Figure 3-27). The analyses of elemental C, N and S was carried out on a LECO elemental analyser according to /SIS, 1996/.

The total carbon content includes carbon from both organic material and carbonates. Earlier studies have shown that both the glacial and postglacial fine-grained sediments contains calcium carbonate ($CaCO_3$) /e.g. Sohlenius and Rudmark, 2003/. The calcium carbonate content was therefore analysed /Talme and Almén, 1975/ in sediment from altogether five lakes. The organic carbon content was then calculated as the difference between organic and total carbon. Qualitative analyses of clay mineralogy composition of "oriented" samples from clay (material < 2 µm) were determined on four clay samples from two lakes according to /Drever, 1973/.

In order to determine the age of the isolation of Lake Eckarfjärden, four ^{14}C (AMS) dates were carried out on macrofossils and sediments /Hedenström and Risberg, 2003/. The results were also used to determine the rate of sediment accumulation. The ^{14}C ages have been calibrated to calendar years BP (before present, i.e. 1950).

Chemical analyses of peat

Stenrösmossen (AFM001245, Figure 3-27) was selected since it is situated close to the candidate area. One additional peatland (AFM001246) was chosen to represent an older and more developed peatland. Peat samples from the two mires were dried and thereafter mixed to altogether three general samples. Stenrösmossen is represented with one such sample representing the uppermost metre of peat. AFM001246 is represented by two samples one from the uppermost metre of peat and the other from 1–2 m. The three samples were burned and the ash was analysed for major and trace elements with ICP-MS according to /Svensk Standard, 1998/. The results have been compared with the mean and median values for Swedish peatlands /Fredriksson, 1984/.

Analyses of microfossils in glacial sediment

In order to test if re-deposited microfossils in till and glacial sediment could contribute to the relative dating of glacial sediment, 13 samples were collected (Figure 3-28). The microfossils were concentrated from the sediments and analysed under microscope /Robertsson, 2004/.

3.3.4 Conceptual model

The overburden includes all unconsolidated QD such as till, sand, gravel, clay and peat. The upper part of the overburden, affected by soil forming processes, is referred to as the soil. The description of the QD is focused on the spatial distribution of the different units, together with a description of physical and chemical properties. The physical properties are used as input data for the hydrogeological modelling where as the chemical properties will be used in the biological models of the upper geosphere. The surface distribution of the QD is presented as geological maps for the land area and the sea floor. This model version will present an outline of a 3D model of the depth of the QD on land.

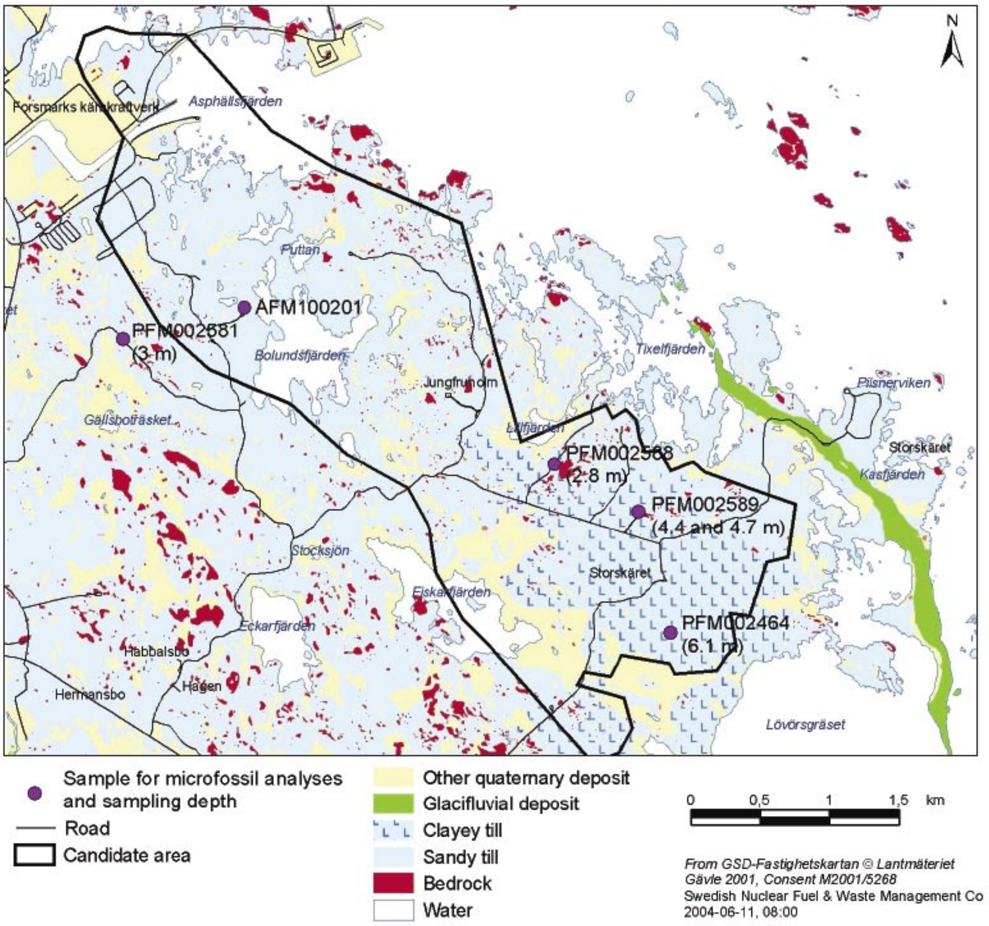

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Figure 3-28. *Map showing the location of the samples collected for microfossil analyses, from /Robertsson, 2004/.*

The QD are divided according to grain size and environment in which they were formed into two main categories: glacial and post-glacial deposits. This classification is used in the geological maps presented in this chapter. Below follows a general summary of the QD observed in the Forsmark area. In (Figure 3-29), a generalised stratigraphic profile of the different units present below the highest coastline is presented. The QD in Forsmark are probably distributed in the same order, however not necessarily with all units present at all sites.

Glacial deposits were deposited either directly from the inland ice or from the water, derived from the melting of this ice. Glacial till consist of bedrock fragments and older unconsolidated sediments, deposited directly by the ice. Till is characterised by poor sorting, resulting in grain size composition including all grain sizes from clay particles to large boulders. Till is the most common type of Quaternary deposit in Sweden. Melt water from the ice transported and deposited the glaciofluvial sediments. These deposits comprise coarse material, often forming eskers of sand and gravel, but also finer particles such as clay and silt, which often form flat areas. The glacial clay and silt were deposited at the deepest bottoms below the highest coastline. The glaciofluvial deposits often overlie the till. Compared to the glacial till the glaciofluvial sediments are well sorted with respect to grain size composition.

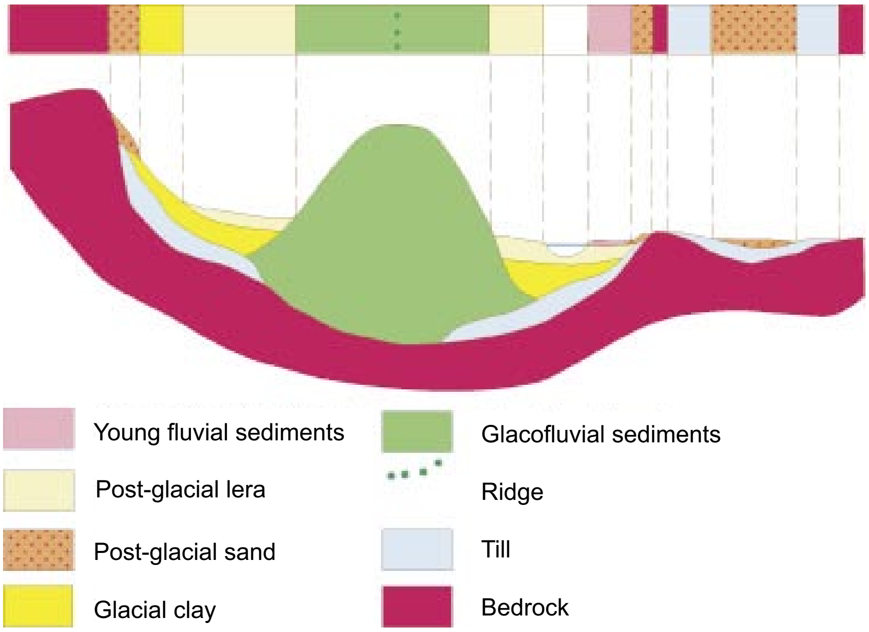

Figure 3-29. Schematic stratigraphical distribution of Quaternary deposits in areas below the highest coastline.

Post-glacial deposits were formed after the inland ice had melted and retreated from the area. Post-glacial sediment and peat forms the youngest group of overburden. In general, they overlie till and, locally, glacial clay or crystalline bedrock. The post-glacial deposits are dominated by organic sediment and re-deposited, wave washed clay, sand and gravel. Processes forming post-glacial deposits have continuously been active since the latest deglaciation. The re-deposition of sediment often has a levelling effect on the topography as the fine-grained sediments are deposited in local depressions.

Post-glacial clay was deposited after erosion and re-deposition of some of the previously deposited sediments, such as glacial clay. The post-glacial clay can often be found in the deeper parts of valleys below the highest coastline. The post-glacial clay may contain organic material and is then often referred to as gyttja clay.

Post-glacial sand and gravel has been deposited by streams and waves, which have altered and reworked glaciofluvial deposits and till as the water depth in the sea successively decreased. The sand and gravel, is subsequently deposited at more sheltered localities.

Gyttja sediments consist of high proportion of organic material formed in lakes and consist mainly of remnants from plants that had grown in the lake. In areas with calcareous soils, such as the Forsmark area, calcareous gyttja forms when the lime saturated ground water enters the lake.

Peat consists of remnants of dead plants, which are preserved in areas (often mires) where the prevailing wet conditions prevent the breakdown of the organic material.

3.3.5 Descriptive and quantitative model

Surface distribution of Quaternary deposits and bedrock outcrops

The description of the surface distribution of QD focuses on to the central part of the regional model area. Within this area, detailed mapping and stratigraphical investigations has been performed /e.g. Sohlenius et al. 2004; Sundh et al. 2004; Hedenström et al. 2004/. The data in model version 1.2 confirm the general information from the north eastern Uppland region /Persson, 1985, 1986/.

The detailed investigation, however, gives additional information, summarised below:

- The distribution of bedrock outcrops follows a small scale pattern. Numerous localities with small exposures of bedrock have been found and are included in the map over bedrock exposures. Despite the large number of outcrops, the total area represented by bare bedrock is less (c 5%) than known from the initial geological maps (c 11%).
- The striae show a somewhat different pattern from what was observed during the former mapping. Several localities with preserved older striae were observed. The oldest striae are formed from the north, median age from North West and the youngest striae are formed from the north.
- The occurrence of peat was overestimated in the initial maps. The detailed investigations showed that gyttja clay forms the surface in many of the wetlands in the north eastern part of Forsmark.

To get an overview of the QD and deglaciation history in the entire Östhammar region, the readers are referred to the earlier SGU investigations in the area (SGU Ser. Ae, scale 1:50,000) /Persson, 1985, 1986, 1992/. Several publications provide an overview of the processes forming the QD /e.g. Fredén, 2002/. The general overview below includes information from the Forsmark regional model area (Figure 3-30).

The bedrock morphology is characterised by a peneplain, which is dipping gently towards the north-east. The upper surface of the Forsmark area is typically flat, dominated by a cover of glacial till. Unconsolidated QD cover c 84% of the land area in the regional model area and artificial fill, principally around the Forsmark nuclear power station and an area close to Johannisfors, c 3% (Table 3-5). Exposed bedrock or bedrock with only a thin Quaternary cover (< 0.5 m) occupies c 13% of the land area in the regional model area.

The frequency of outcrops varies within the mapped area. Areas with low frequency of outcrops are e.g. the eastern part at Storskäret and west of Lake Bolundsfjärden (Figure 3-31). Areas with high frequency of bedrock outcrops are e.g. the western and the eastern part of the regional model, e.g. the island of Gräsö. Many of the outcrops are Roches mountonnées with a smooth abraded northern side and a rough, steep plucking side towards the south. An ice moving from the north (350–360°) has formed a majority of the glacial striae (Figure 3-31). An older system from north-west is preserved on lee side positions.

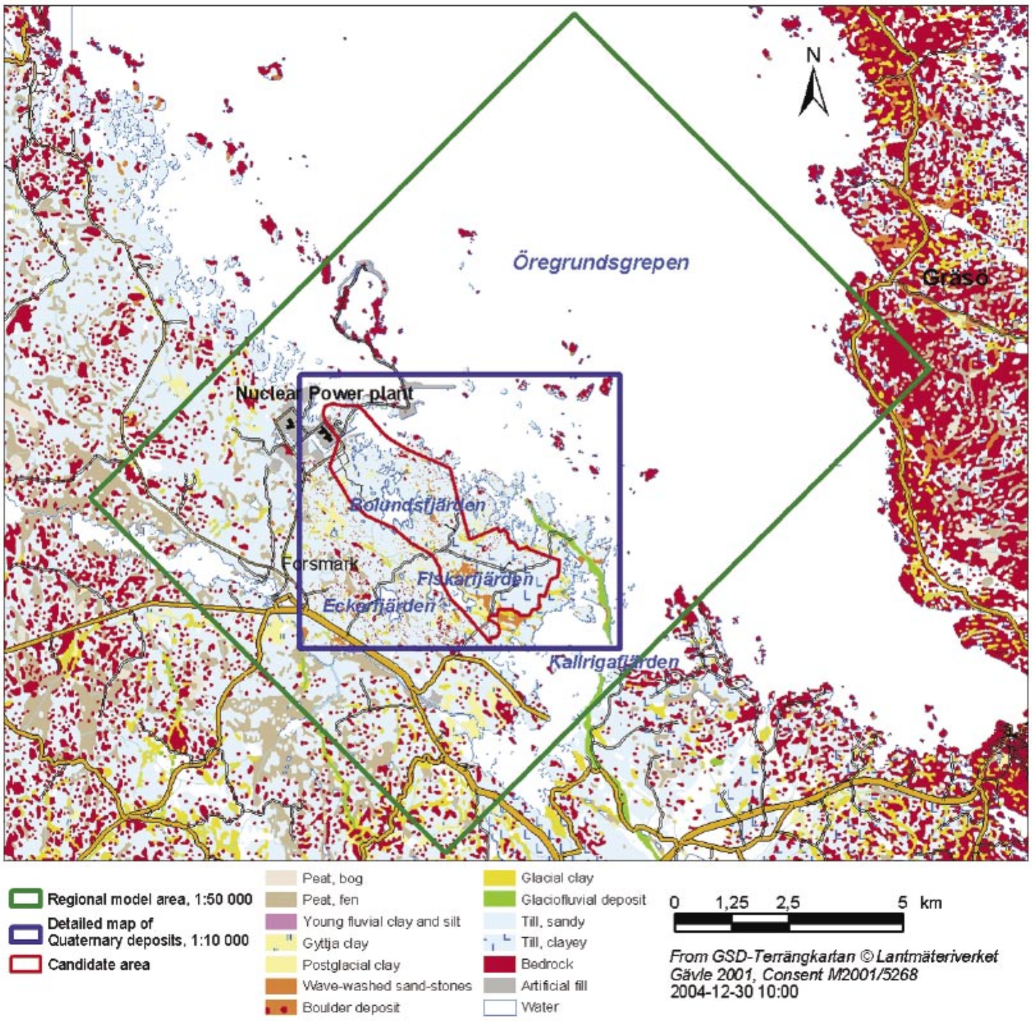

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***Figure 3-30.** Map showing the distribution of the Quaternary deposits in the regional model area. Note the different scale in the picture. The major part of the description refers to the area included in the blue frame, presented in higher resolution in Figure 3-33.*

Table 3-5. The areal coverage of the different types of Quaternary deposits and bare bedrock from the different subareas. The first column gives the proportion within the land areas in the regional model area, the second column gives the distribution from the land areas in the central part where detailed mapping has been performed, see Figure 3-20. The three right-hand columns gives the proportion of the Quaternary deposits at sea, see Figure 3-21.

	Forsmark land total	Forsmark land detailed	Forsmark Sea total	Forsmark Sea detailed	Forsmark Sea regional
Bedrock exposures	13	5	6	2	8
Glacial clay	4	4	41	41	41
Post-glacial clay (including gyttja clay and gyttja)	4	4	17	3	23
Post-glacial sand and gravel	2	4	2	2	2
Post-glacial fine sand	–	–	4	15	0
Till (sandy/clayey)	65 (58/7)	74 (63/11)	30	37	26
Glaciofluvial sediment	1	2	0		0
Peat	8	3	–	–	–
Artificial fill	3	4	–	–	–

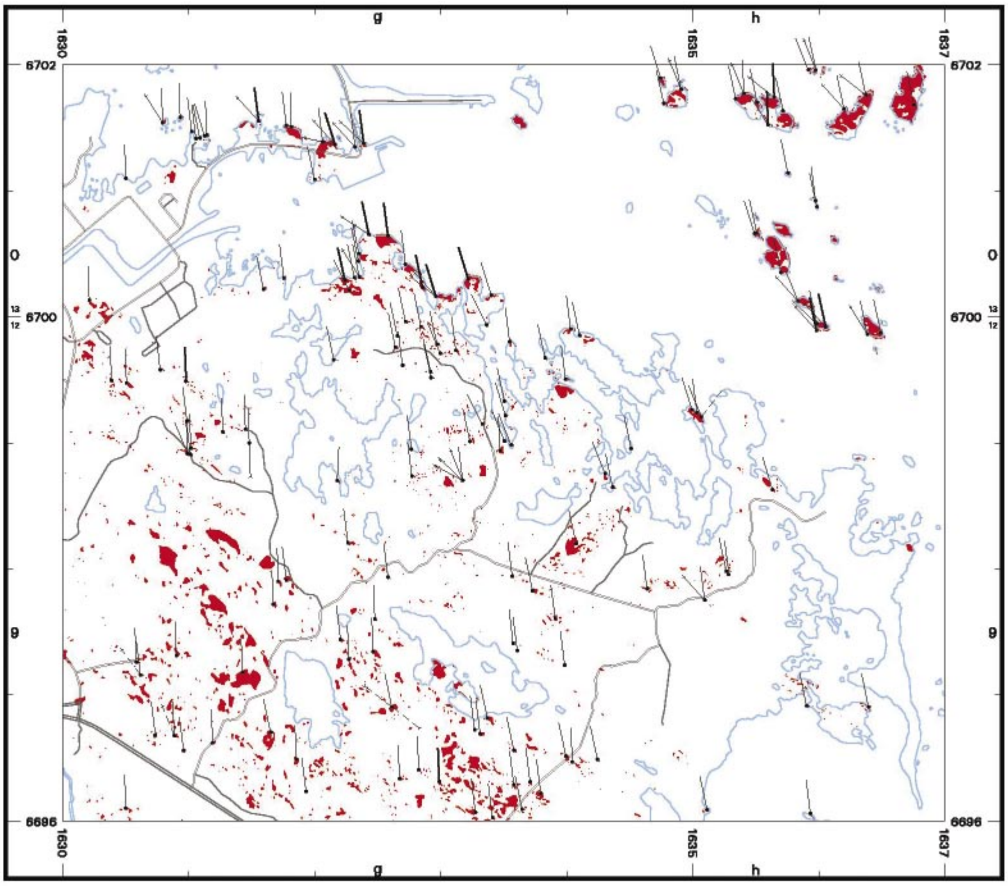

Figure 3-31. Map showing bedrock outcrops (red) and the direction of glacial striae. On several sites, more than one direction of striae has been identified, representing different directions of ice movements. The youngest striae are marked with black line and the older striae with coloured lines. Red represents the youngest ice movement, green the second youngest and blue is the oldest direction /Sohlenius et al. 2004/.

Till

Glacial till is the oldest known, and dominating Quaternary deposit in the Forsmark area. The till distribution in Forsmark is characterised by heterogeneity, in textural composition as well as spatial distribution. The most typical for the area is the occurrence of a clayey till in the eastern part and a general high content of calcium carbonate in a majority of the QD. The clayey till has been identified along the northern coast of Uppland, described by /Persson, 1992/. The calcium carbonate has its origin from Paleozoic limestone on the bottom of the sea north of Forsmark, incorporated and deposited by the glaciers.

A till type more typical for areas with crystalline bedrock, sandy and silty till, dominates in the western part of the area. The complex composition of the till types makes it necessary with some generalisations. Based on the composition of the surface layer, three till areas has been distinguished (Figure 3-32). The stratigraphic distribution between the different units is complex and has not been fully understood.

Till area I. The major part, especially in the west and south, of the model area is dominated by sandy till with medium bolder frequency.

Till area II. At Storskäret and on Gräsö island, a clayey till with low boulder frequency dominates. At Storskäret, the clayey till is used as arable land. The frequency of bedrock outcrops is low in areas with clayey till.

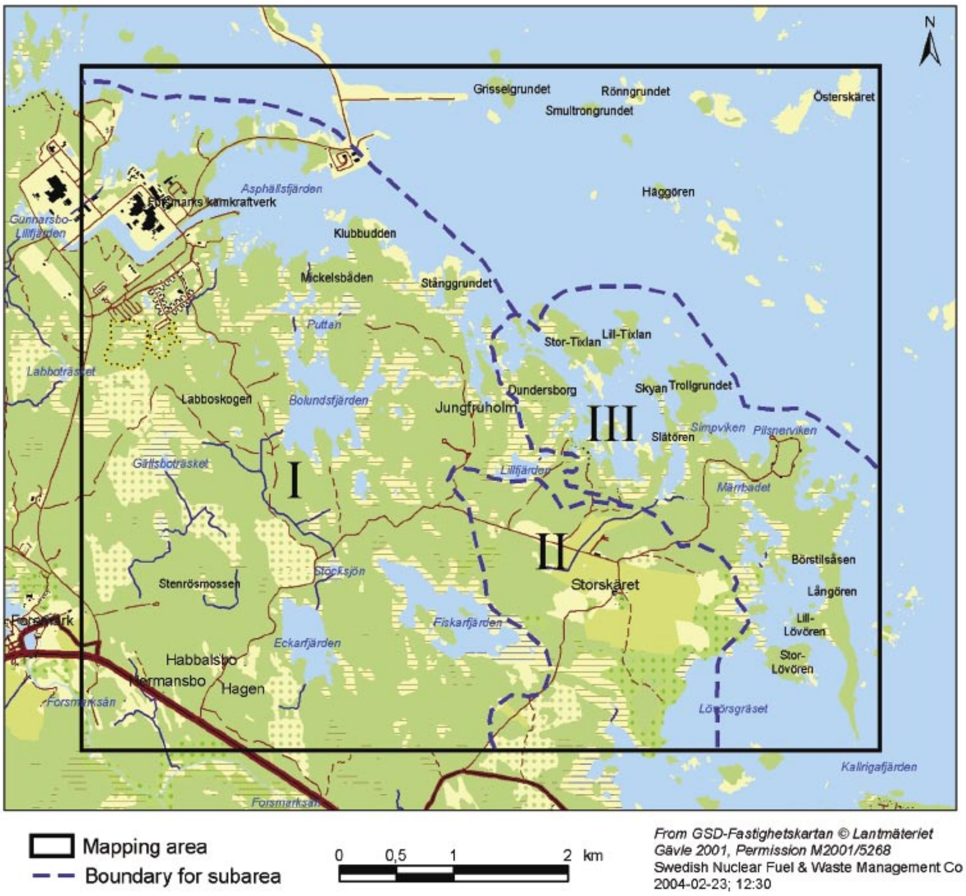

Figure 3-32. The superficial distribution of the three till types identified in Forsmark.

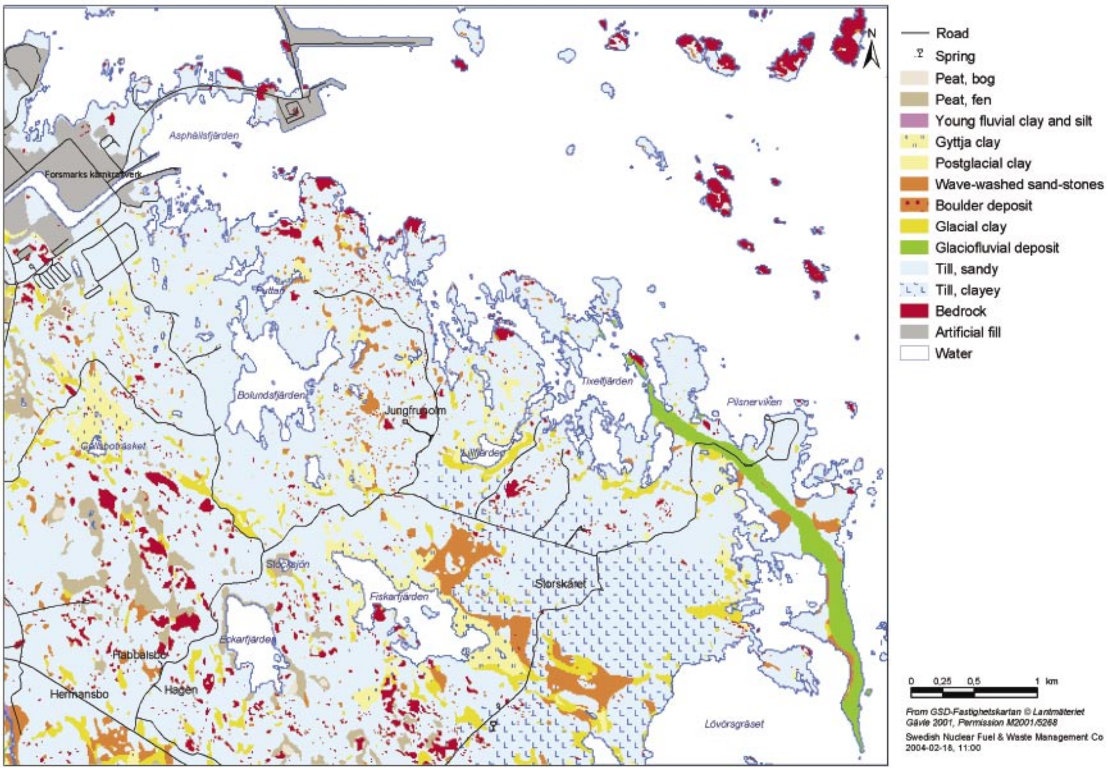

Figure 3-33. Map showing the spatial distribution of Quaternary deposits in the central part of the Forsmark regional model area, from /Sohlenius et al. 2004/.

Till area III. In the area close to the Börstilåsen esker, the till is characterised by a high frequency of large boulders. The major part of this till area is situated within the Kallriga nature reserve.

The contact between till area I and II gives the impression of being undulating with small patches of clayey till situated within the sandy till. The stratigraphical investigations gave the same impression where the clayey till was observed to be incorporated in the sandy till /Sundh et al. 2004/.

Glaciofluvial sediment

Glaciofluvial sediments are deposited in a small esker, the Börstilåsen esker, with a flat crest reaching c 5 m above the present sea level. The Börstilåsen esker has a N-S direction and is the largest glaciofluvial deposit in the Östhammar region and can be followed from Harg situated c 30 km south Forsmark /Persson, 1985/. The esker is, however, small compared to several of the large eskers found further west around Lake Mälaren. The section of the esker within the Forsmark area is completely situated within the Kallrigafjärden nature reserve. Therefore, the stratigraphical information from the esker is very sparse. Drilling at the crest of Börstilåsen (SFM0060) showed c 7 m of glaciofluvial sediments (gravel) resting directly on top of the bedrock /Werner et al. 2004/. Open sections, from abandoned gravelpits, confirm a coarse material consisting of gravels and stones. Wave washing has affected the esker, where a raised shingle shoreline is developed (Figure 3-34).

The distal glaciofluvial sediments (glacial clay), deposited in stagnant water at some distance from the retreating inland ice, are concentrated to local depressions such as the bottom of lakes and small ponds. Areas with glacial clay are also frequently found in small pockets in the surface. These deposits are often only a few dm thick and are probably remnants after erosion between boulder and stones. Glacial clay is also found in association to lakes or wetland, e.g. south east of Lake Fiskarfjärden and south of Lillfjärden. At these localities, the uppermost surface is often covered by organic sediment, gyttja clay and clay gyttja.

Figure 3-34. *A raised shingle shoreline at the crest of the Börstilåsen esker.*

Postglacial sediment and peat

Postglacial clay, gyttja clay, sand and peat occur frequently as the superficial QD and cover many small (less than 50×50 m) areas. These small deposits are frequent, but cover only a small part of the total area under investigation (Table 3-5). Larger areas of post glacial sediment are e.g. gyttja clay along the shore of Lake Fiskarfjärden and Lake Gällsboträsket.

Many of the wetlands situated in the north-eastern part of the investigated area consist of gyttja clay and clay gyttja, often covered by *Phragmites* (growing) and a thin (a few dm) layer of *Phragmites* peat. Actual peat accumulations > 0.5 m deep, are restricted to the south-western part of the investigated area. This is the most elevated area that been situated above the sea level for long enough time for peat to form. The wetlands situated to the north east may have peat cover < 0.5 m and has therefor not been marked as peat on the geological map.

Artificial filling

There are two areas with artificial filling within the Forsmark regional model area. The largest one is the area around the nuclear power plant where the filling material consisting mainly of blast bedrock and glacial till excavated from the sea bottom. At an excavation south of reactor Forsmark 3, the artificial fill was exposed. The sediment had an appearance very similar to silty till.

The other area with artificial filling material is located at Johannisfors, in the south-eastern part of the regional model area. The deposit at Johannisfors consists of calcareous waste material (*Sw. mesa*) from an old pulp mill. The site is presently object for an inventory by The County Administrative Board of Uppsala (*Sw: Länsstyrelsen Uppland*) since this type of deposits are known to contain pollutants, mainly heavy metals.

Wave washing and shore displacement

The entire model area is situated > 120 m below the highest shoreline. The highest altitudes (c 20 m a. s. l.) are found in the south-western corner of the area. Until about 500 BC the Forsmark area was situated under the Baltic and the first small islands reached above sea level. A majority of the land area has been raised above the sea during the last 1,500 years, see the section on shore line displacement in the Historical description, 3.1.1. A small-scale topography is reflected in a large number of shallow lakes, small ponds and wetlands. The flat upper surface, in combination with the relatively fast land upheaval results in a continuous formation of new lakes and ponds. At present, the land upheaval is 6 mm/year.

Stratigraphy

Glacial till

The stratigraphical relations between the different till beds in Forsmark were studied in a campaign where 22 machine cut trenches were distributed evenly within till area I and II (Figure 3-25). The results from the stratigraphical investigations are summarised in (Table 3-6).

Table 3-6. Summary of the results from the till stratigraphical investigations /Sundh et al. 2004/.

Id-number	Description of till-unit	Depth (m)	Fabric (°)	Striae (°)/bedrock
PFM004761	Sandy	0–1.6	353	/ not reached
PFM002576	Sandy-silty, boulder rich surface	0.4–5.2		/ not reached
PFM002577	Sandy-silty, wave-washed surface, resting on bedrock	0.3–0.9		younger 350 older 310
PFM002578	**1** Sandy-silty, stone-enriched surface	0–0.5		
	2 Clayey sandy-silty, the layer ceases in a vertical contact towards sandy-silty till	0.5–1.9		
	3 Sandy-silty, resting on bedrock	1.9–4.2	313	300
PFM002579	**1** Sandy-silty, gravel on clay in surface	0.4–0.7		
	2 Sandy, resting on bedrock	0.7–1.4		younger 350 older 320
PFM002580	Sandy, gravel on clay in surface	0.6–5.0		/ not reached
PFM002581	**1** Sandy with erosive contact against unit 2, gravel on clay in surface	0.4–1.9		
	2 Clayey sandy-silty– boulder clay	1.9–5.0	2	/ not reached
PFM002582	**1** Sandy -slided mtrl? Gravel in surface, glacial clay beneath.	0.4–0.7		
	2 Clayey - stonerich, sandy layer beneath	1.0–1.3		
	3 Sandy, resting on bedrock	1.6–2.6		no striaes /
PFM002583	Sandy, stonerich with stone-enriched surface	0.2–2.1	random	345
PFM002584	Sandy, resting on bedrock	0.2–0.9		355
PFM002585	Sandy, resting on bedrock	0.4–1.2		355
PFM002586	Sandy, stonerich with stone-enriched surface	0.2–1.8	329	320
PFM002587	**1** Sandy, local or ablation till	0.2–2.8		
	2 Sandy, resting on bedrock	2.8–3.3		no striaes /
PFM002588	**1** Sandy-silty, stonerich	0.4–1.2		
	2 Clayey sandy-silty	1.2–1.9		
	3 Boulder clay	1.9–2.9	337	
	4 Sandy-silty, resting on bedrock	2.9–3.1		younger 350 older 320
PFM002589	**1** Clayey sandy-silty	0–2.0	331	
	2 Boulder clay	2.0–4.3	339	
	3 Sandy	4.3–5.0		/ not reached
PFM002590	**1** Sandy-silty	0.2–1.2		
	2 Clayey sandy-silty, resting on fragmented rock	1.2–4.6	322	no striaes /
PFM002591	**1** Clayey gravelly, not consistent layer	0–1.3		
	2 Clayey sandy silty	1.3–3.5		/ not reached
PFM002592	**1** Clayey sandy silty	0.2–1.6	318	
	2 Boulder clay	1.6–4.1	327	/ not reached
PFM002593	**1** Clayey sandy silty	0.4–1.4		
	2 Boulder clay	1.4–3.6		/ not reached
PFM002594	**1** Clayey sandy-silty	0–1.2	3	
	2 Clayey and sandy-silty layers builds up the till	1.2–4.0	332	/ not reached
PFM002595	Clayey sandy-silty, resting on an uneven bedrock-surface	0–1.2		younger 360–20 older 285
PFM004514	**1** Clayey sandy-silty	0–1.2		
	2 Sandy, steep contact against unit 1, underlain by glacial clay	1.2–1.4		
	3 Boulder clay	1.4–2.4		
	4 clayey sandy-silty	2.4–3.0		/ not reached

In summary, the stratigraphic investigations confirmed the distribution on the surface with sandy till dominating the western area and clayey till dominating the eastern parts, at Storskäret. The area with high frequency of large boulders, till area III in Figure 3-32, is situated within the Kallrigafjärden nature reserve, thus no excavations has been performed.

When the stratigraphical distribution of till was studied, the same impression that form the mapping in the surface was obtained: the till stratigraphy in the area is complex.

One example of a complex till stratigraphy is site PFM002581, located within till area I, north of Lake Gällsboträsket (Figure 3-25). The surface was covered by c 2 m thick unit consisting sandy till underlain by a dark clayey till. The most striking feature about the dark clayey till is the extreme degree of consolidation. The clast fabric analyses of the dark clayey till showed deposition from the north /Sundh et al. 2004/. The contact with

Figure 3-35. *The erosive contact between the two till beds at PFM002581. The upper unit consist of a sandy silty till while the lower unit is a very hard, dark clayey till.*

the upper till unit showed that the dark clayey till has been affected by erosion by a younger ice flow (Figure 3-35). Pollen analysis was performed in order to give information of the age of the dark clayey till /Robertsson, 2004/. Re-deposited pollen grains observed in the dark clayey till showed an interglacial composition known from deposits originating from the last interglacial, the Eemian. This composition gives information of the assumed maximum age of the deposition of the unit to bee post Eemian, i.e. some time during the Weichselian glaciation. High calcite and clay content, together with a high amount of redeposited pre-Quaternary microfossils /Robertsson, 2004/, indicates that the parent material originates from the areas north east of Forsmark with Palaeozoic limestone present at the sea bottom /Persson, 1992/. In central and northern Sweden, a very hard clayey till, probably of the same age as the unit observed at PFM002581, has been observed at several localities beneath a coarser till /Björnbom, 1979/.

The depth of the 13 trenches cut in till area I vary between 0.9 and > 5 m. At nine sites, bedrock was reached but at four sites the depth of the QD was > 5 m. The average depth in the trenches that reached bedrock in till area I was c 2 m. In till area II, bedrock was reached at three of 9 trenches, thus the reminding six trenches had a depth of > 5 m. This is consistent with the results from corings where the deepest QD are recorded in the eastern part of the investigated area /cf Johansson, 2003/.

In the contact zone between till area I and II, clayey till was incorporated in the sandy till (PFM002578). At PFM004514, glacial clay, with preserved primary varves, was incorporated in the upper till unit /Sundh et al. 2004/. These observations confirm the impression of a complex distribution of the different till units in Forsmark, especially in the contact zone between the two till types. The results from the clast fabric analyses show a dominating direction for deposition from the north-west, in both the sandy and clayey till /Sundh et al. 2004/. Analyses performed close to the ground surface indicate a youngest deposition from the north. This, together with analyses of glacial striae, indicates that there are at least three generations of ice flow directions preserved: the probably oldest from the north, median age direction from the north-west and finally the youngest ice flow direction from the north. The two youngest ice flow directions probably origins from the last glaciation and de-glaciation.

Thickness and representative sequences

Additional information derives from the large number of corings performed during the initial site investigations, e.g. at the installation of groundwater monitoring wells /Johansson, 2003/. The thickness of the QD as observed in corings varies between 0 and 17 m within the investigated area. It should be noted, however, that the locations of the groundwater monitoring wells are clustered at topographical low points. In the north-western part of the investigated area, in till area I, the depth to bedrock is generally between 4 m and 8 m in the corings performed /Johansson, 2003/.

Close to drill site 1, the thickness of the QD varies between c 4 m and 12 m in eight corings, located within c 200 m from the drill site. The altitude of the upper surface of the regolith, on the contrary, is flat and varies between c 2 m and 4 m a s l. The variation in depth to bedrock support the impression of a small scale undulating upper surface of the bedrock surface and a till cover that fills out the depressions. This means that the depth from the upper regolith to the upper bedrock surface varies over short distances, although the impression from the surface is flat and homogenous.

In the central part of the candidate area, close to Lake Bolundsfjärden, the thickness of the glacial till as recorded in drillings is < 4 m. One typical sequence from till area I is at SFM0030, c 3.5 m sandy silty till covers the bedrock (Table 3-7). In the eastern part of the investigated area, in Till area II at Storskäret, the thickness range from < 4 to c 17 m. One typical example for a sequence in till area II is PFM002464, where c 9 m glacial till covers the bedrock. Clayey till and boulder clay (> 15% clay content) covers a coarser (clayey silty) till (Table 3-7). A consistent feature in the area close to Storskäret is low frequency of bedrock outcrops and relatively thick till cover.

This model version contains information regarding the till situated beneath the sediments in some of the lakes. Analytical data from Lake Fiskarfjärden reviled sandy till (SFM0022), at Lake Bolundsfjärden (SFM0062) sandy till and under Lake Gällsboträsket (SFM0064) boulder clay /Hedenström, 2004b/. The glaciofluvial sediments in the Börstilåsen esker consist of 5–7 m well sorted, mainly sand and gravel. At SFM0060, 7 m gravel rested directly on bedrock.

The minerogenic sediment under wetlands consists of clay, sand and gravel and till. At some sites, all units are present while at others, the organic sediment rest directly on the till. Two examples of the later are the Stenrösmossen mire (AFM001245) and the mire situated south west of Lake Eckarfjärden, at SFM0017 (Table 3-7).

Table 3-7. Compilation of some analytical data from the minerogenic soils at sites representative for five different types of Quaternary deposits.

QD type	ID code	Sample depth (m)	Quaternary deposit	Clay content	$CaCO_3$
Till area I	SFM0030	0.6–1.05	Sandy till	4.8	21
		1.4–1.7	Sandy till	4.8	18
		2.8–3.4	Clayey sandy till	5.2	17
Till area II	PFM002464	3.5–3.9	Boulder clay	15.4	24
		5.0–5.3	Boulder clay	15.2	21
		5.6–5.9	Clayey sandy silty till	9.4	31
		7.2–7.6	Clayey sandy silty till	7.7	28
		7.8–8.2	Clayey sandy silty till	14.8	29
		9.0–9.4	Clayey sandy silty till	14.9	33
Glaciofluvial esker	SFM0060	0–7	Gravel	Not analysed	Not analysed
Beneath lake	SFM0062	2.75–3.15	Sandy till	3.0	11
Beneath wetland	SFM0017	1.2–1.8	Gravelly till	3.9	11
		1.8–2.5	Gravelly till	2.3	19
		3.0–3.7	Clayey sandy silty till	10.8	17

Physical properties

In Table 3-8, a summary of the results the analyses of grain sizes and $CaCO_3$ is presented. In the right hand columns, the diameter of 10, 60 and 90% of the sample weight are given. The grain size composition in 132 till samples (top), 8 samples of wave washed sand and gravel (middle) and 20 samples of clay (bottom). In this summary, all till samples are treated together. Since till is the overall dominating Quaternary deposit, the mean grain size composition can be regarded as mean values for the overburden in Forsmark. Sand and fine material dominates where as gravel constitutes c 20% of the till. Notable is the high clay content, c 11%, and CaCO3, c 19%, as mean values for both till types. Separate calculations are made for wave washed sediment and clay.

Table 3-8. A summary of the results the analyses of grain sizes and $CaCO_3$. In the right hand columns, the diameter of 10, 60 and 90% of the sample weight are given. The grain size composition in 132 till samples (top), 8 samples of wave washed sand and gravel (middle) and 20 samples of clay (bottom). All till samples are treated together.

132 Till samples	Fine material (%)	Sand (%)	Gravel (%)	Clay content (0.002 mm) (%)	d10 (mm)	d60 (mm)	d90 (mm)	d60/d10	CaCO3
Mean	36.84	43.20	19.97	11.53	0.01	0.62	5.86	81.89	19.21
Standard dev	13.06	8.26	11.76	7.54	0.02	1.03	3.90	121.68	6.544966
Max	78.10	67.67	53.91	42.12	0.13	5.80	15.25	1,026.34	38
Min	4.41	20.50	0.90	1.70	0.00	0.03	0.12	2.70	0.00

8 samples wave washed	Fine material (%)	Sand (%)	Gravel (%)	Clay content (0.002 mm) (%)	d10 (mm)	d60 (mm)	d90 (mm)	d60/d10
Mean	7.86	67.08	25.05	16.78	0.16	1.54	6.73	12.32
Standard dev	6.08	13.75	16.44	17.21	0.08	1.59	5.10	8.89
Max	15.51	85.00	51.52	34.15	0.25	4.33	14.00	26.54
Min	1.80	45.64	3.89	1.10	0.02	0.41	1.45	3.32

20 samles clay	Fine material (%)	Sand (%)	Gravel (%)	Clay content (0.002 mm) (%)	d10 (mm)	d60 (mm)	d90 (mm)	d60/d10	CaCO3
Mean	97.81	1.88	0.30	55.48			0.06		19.70
Standard dev	8.39	7.10	1.30	11.34		0.01	0.17		12.48132
Max	100.00	33.40	6.10	74.00		0.06	0.81		38.00
Min	8.39	0.00	0.00	11.34		0.00	0.01		0.00

The bulk density of the upper 60 cm of the regolith was investigated at different profiles in the soil type inventory. In the upper horizon, low bulk density values are recorded: 0.4–1.5 g/cm^3. The density increases downward to 1.4–2.3 g/cm^3 /Lundin et al. 2004/.

Lake sediment and peat

Contradictory to the complex composition of the glacial till described above, the distribution of marine and lacustrine sediments in the Forsmark region is fairly uniform. In a majority of the lakes investigated, the total thickness of the sediments (not including glacial till) were less than 2 m and only three lakes contained sediments thicker than 4 m. Generally, thicker sequences of varved glacial clay were obtained in small basins close to the Börstilåsen esker. The maximum coring depth in the area was 8.8 m (including 0.5 m water), recorded at Lake Fiskarfjärden. A generalised outline of stratigraphical units in the investigated sediments at Forsmark is presented in Table 3-9. It should be noted, however, that not all strata were present at every basin.

Table 3-9. Generalised stratigraphical distribution of marine and lacustrine sediments in lakes. The average contents of C, N and S in glacial clay and algal gyttja have been calculated (algal gyttja n = 27, gyttja clay n = 14).

Environment	Lithology		C	N	S
Freshwater lake	Calcareous gyttja	Youngest			
Freshwater lake and coastal lagoons	Algal gyttja		14	1.3	1.9
Postglacial Baltic Basin	Clay gyttja	↑	4.7	0.6	1.6
Shallow coast	Sand and gravel				
Postglacial Baltic Basin	Postglacial clay	↑			
Late glacial Baltic Basin	Glacial clay	Oldest			

The stratigraphical information from the inventory of sediments in the lake basins were used in the 3D model of the QD /Vikström, 2005/. One of the profiles from this model is presented in Figure 3-36. The sedimentary sequence in Lake Eckarfjärden follows a consistent pattern. The depth of the till is based on GPR /Marek, 2004b/ while the depth of the sedimentary strata is based on corings /Hedenström, 2004a/. The blue areas represents the till, however the three layers displayed in the profile are not represented by different till units but are instead fabricated layers, assigned different hydraulic properties (see Section on near surface hydrology, 3.4). The depth to bedrock, including the lake sediments, is approximately 10 m through out the profile. The sedimentary layers, represented with the yellow and brown areas, forms continuous units on the bottom of the lake. Glacial clay was deposited in the deep water, shortly after the deglaciation from c 10,800 years ago onwards.

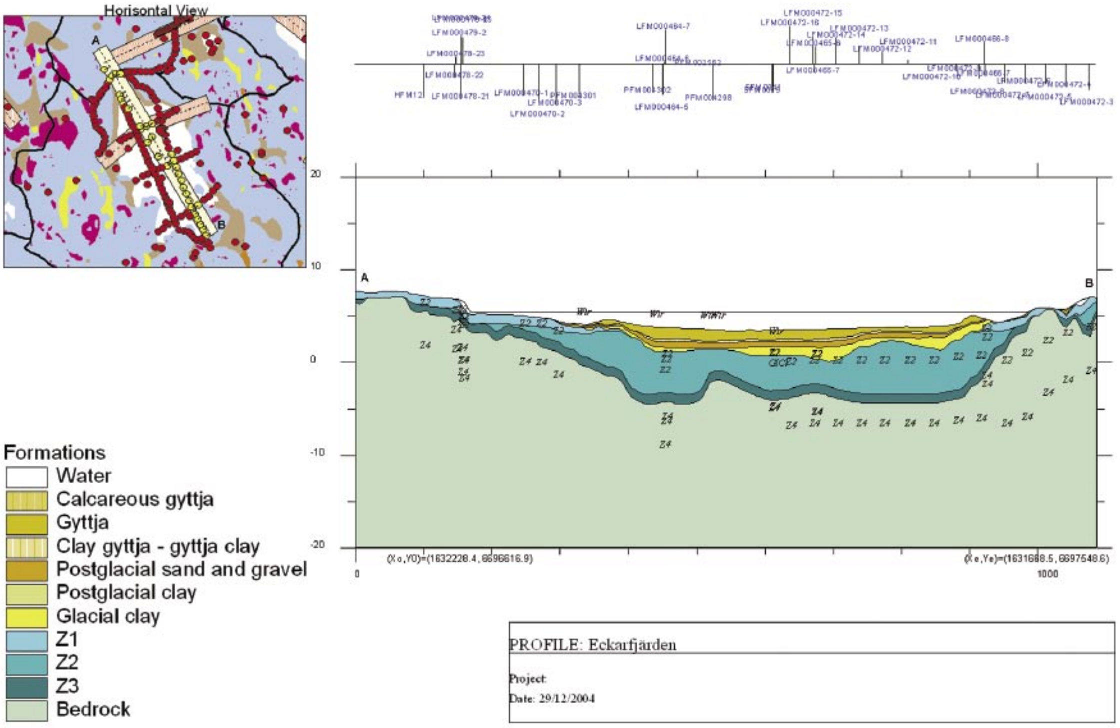

Figure 3-36. Stratigraphic profile showing a transect through Lake Eckarfjärden. The profile is part of the soil depth model, constructed in Geo Editor /from Vikström, 2005/. The depth of the sedimentry layers are based on stratigraphical corings /Hedenström, 2003/. The depth of the till is based on investigations using GPR /Marek, 2004b/.

This unit has a clay content of approximately 55% and calcite content of c 25% /Hedenström, 2004a/. Post-glacial clay does only contribute with minor patches, thus not represented in the stratigraphical profile. The next stratigraphical unit consists of sand and gravel which forms a permeable layer throughout almost the entire lake basin. The sediment is re-deposited sand and gravel, formed when the area was subjet to erosion by currents on the bottom of the sea and/or in connection to the emergence from the Baltic c 1,500 years ago /Hedenström and Risberg, 2003/. Thus, the boundary between the clay and the sand marks a hiatus representing the major part of the Holocene. Erosion in the same stratigraphical position has frequently been identified on land areas, e.g. at several sites investigated for traces of post-glacial faulting /Lagerbäck et al. 2004/. The ongoing isostatic uplift results in new land areas which transfers the lake basin to a sheltered position, favouring the formation and accumulation of gyttja clay and clay gyttja. Many of the ponds and lakes in Forsmark are very shallow, often less than 1 m at the deepest and will have only a short duration as a lake before the basins are filled in replaced by a wetland.

The sediment in Lake Eckarfjärden has been subject to detailed stratigraphical investigations in order to reconstruct the shore displacement in northern Uppland /Hedenström and Risberg, 2003/. The isolation of Lake Eckarfjärden has been dated c 850 cal years BP, recorded approximately at the transition to the gyttja layer. After the isolation, algal gyttja and calcareous gyttja has been deposited in the freshwater lake. Analysis of diatoms in the sediment, in combination with radiocarbon determinations shows that the present Lake Eckarfjärden experienced a lagoon stage between 1,100 and 850 calendar years BP. The lake was thereafter finally isolated from the Baltic Sea. Based on an interpolation between radicarbon dates of macrofossils extracted from the sedimentary column and the present sediment surface, the average rate of sediment accumulation during the last 850 years has been 1 mm/year (Table 3-8). This is consistent to the calculated sedimentation rate for Lake Eckarfjärden, 1.36 mm/year /Brydsten, 2004a/. The carbon and water contents varies throughout the lake sediments and it has therefore not been possible determine the present rate of material accumulation (e.g. organic carbon) in the lake. Lake Eckarfjärden is a typical oligotrophic hardwater lake, described in several reports /e.g. Blomqvist et al. 2002 and references therein/.

The groundwater in Forsmark has high carbonate content due to chemical weathering of calcite from the soils. When calcite precipitates and accumulates in the sediments, calcareous gyttja and lake marl forms, for example in Lake Eckarfjärden and Lake Stocksjön.

Table 3-10. Results from radiocarbon dating of plant macrofossils and sediments from Lake Eckarfjärden, from /Hedenström and Risberg, 2003/.

Depth below lake ice (cm)	Lab no	Material dated	^{14}C yrs BP ± 1σ	δ^{13}C %o PDB	Cal yrs BP (± 1σ)
310	Ua-18073	Betula, Pinus, Alnus	850 ± 65	–27.1	800 (830–680)
340	Ua-18072	Pinus	1,245 ± 95	–25.6	1,175 (1,270–1,060)
344	Ua-18071	Betula	1,060 ± 85	–28.2	975 (1,070–900)
387	Ua-18070	Bulk sediment	8,805 ±105	–29.3	9,900 (10,150–9,600)

Another typical example of sedimentary sequence is represented in Lake Bolundsfjärden. The continuous clay layer at the bottom of Lake Eckarfjärden and Lake Fiskarfjärden is absent in Lake Bolundsfjärden. The sediment is generally less than two m thick with sediment focusing in the central part of the lake (Figure 3-37). The sequence starts with a thin layer of sand covered by gyttja clay and gyttja. Probably, the erosion has been more effective in this basin compared to e.g. Eckarfjärden since there is almost no protection from wave activity from the north. Lake Bolundsfjärden is still occasionally in contact with the Baltic.

Additionally example of organic sequence is the peat formation in the Stenrösmossen mire (AFM001245), for the location see Figure 3-27. The description is based on the investigation by /Fredriksson, 2004/. Stenrösmossen is shallow minerotrophic mire of fen type, formed after isolation from the Baltic at approximately 1,500 years ago and a short lake stage. Stratigraphical investigations showed a thin gyttja layer, resting directly on till. The gyttja is overlain by a thin layer of *Phragmites* peat with *Equisetum* remnants. Further up, *Carex* peat and at the top *Carex-Sphagnum* peat represents a typical succession of an infilling of a shallow pond and the succession into a mire. The peat is 1.2 m thick at the deepest coring point, indicating an average accumulation rate of c 0.8 mm/year. The central part of the mire contains an area characterised as a well-drained pine bog, less influenced by nutrient rich groundwater. The pH in the surface water is between 5 and 6 in the nutrient poor, central part. In the south western part, the mire vegetation is more nutrient demanding and the pH in the surface water is between 6 and 7, indicating contact with the nutrient rich groundwater from the surrounding mineral soil. The chemical analyses from the lake sediments and peat are presented below.

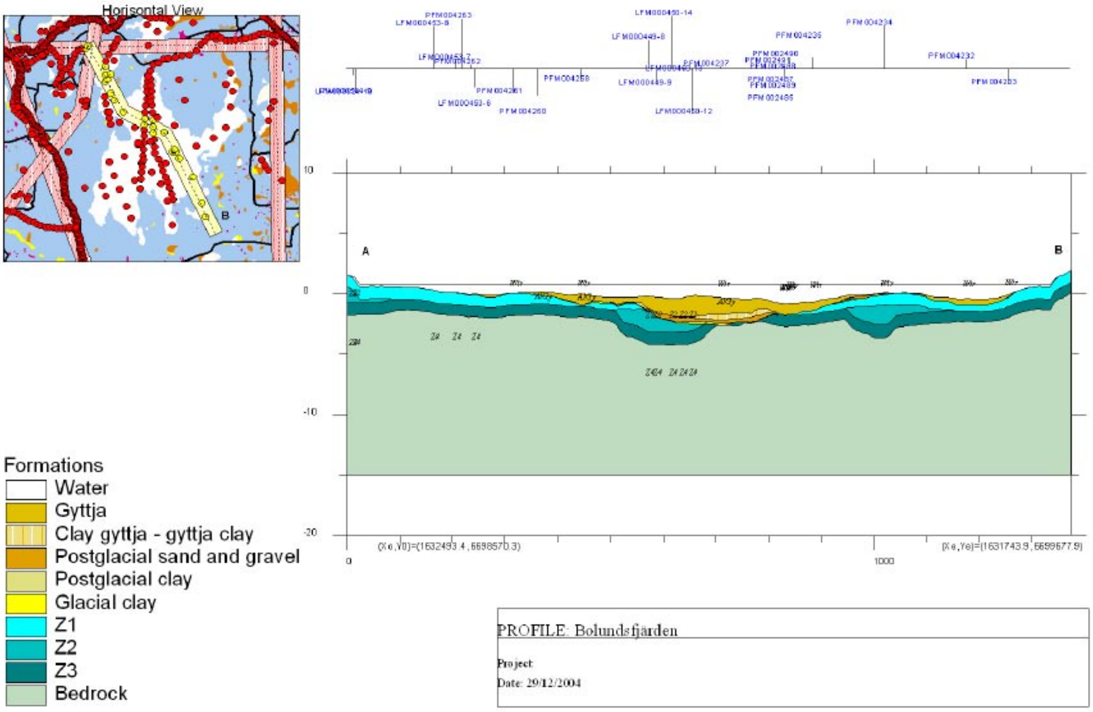

Figure 3-37. Stratigraphic profile through Lake Bolundsfjärden. The profile is part of the 3D model of Quaternary deposits, constructed in Geo Editor /from Vikström, 2005/.

Offshore Quaternary deposits

Compared to the map of QD on land areas, the sea floor is to a larger extent covered by waterlaid sediments (Figure 3-38). Offshore QD are dominated by glacial and post-glacial clay, together covering c 55% of the sea floor (Table 3-5). The clay in this area occurs most conspicuously in a narrow belt, which trends in a NNW and N-S directions. The occurrence of clay may be linked, in some cases, to fracture zones in the bedrock. The thickness of the offshore QD varies considerably from < 2.5 m to > 10 m. In the area above SFR, till varies in thickness between 4 and 14 m and clay between 0 and 4 m. In the next model version, analyses of the detailed marine geological investigations outside Forsmark will provide depth of the QD on the sea floor be included. The clay deposits are overlain by a thin layer of silt, sand or gravel, i.e. similar to the on shore distribution. The area covered by glacial till on land is c 75% but only c 30% on the bottom of the Sea. The difference is partly the result of erosion and re-deposition of fine-grained material, e.g. postglacial clay, in the deeper areas still situated below the sea level. The discrepancy may also, to some extent, be caused by the different methods used in the mapping.

The soiltypes

The upper part of the overburden is referred to as the soil. The soil is characterised by horizons with certain physical and chemical properties. The soiltype developed is a result of the interaction between several parameters such as the parent material (Quaternary deposit), climate, hydrology, soil organisms and time. In Sweden, the soil forming processes has been active since the last deglaciation. In areas below the highest coastline, these processes have been active from the time the area emerged from the sea. In Forsmark, the soils in general are young and immature since the area has been uplifted for a relatively short period of time /Lundin et al. 2004/. At several sites calcite occur from the ground surface and downwards /Sohlenius and Rudmark, 2003/. A study from northern Uppland showed that the depth of the carbonate-free zone increases at higher altitudes /Ingmar and Moreborg, 1976/. The high calcite content is reflected e.g. in the pH in the surface water /Lundin et al. 2004/ and in the rich flora (see Section on Terrestrial ecosystems, 4.1). The results from the soil type classification and description of the distribution and character of the soiltypes in the Forsmark area are described and analysed in a report by /Lundin et al. 2004/.

The predominant soil classes of the Forsmark area (names according to the soil classification, /WRB, 1998/) are shortly summarised below:

Histosol (HI) – peatland and open mires as well as forested peatland with at least 40 cm depth. In the Forsmark area the Histosol soil are typically covered with a sparse tree layer of birch, pine and alder. Hisotsols also include the reed areas surrounding many of the lakes.

Leptosol (LP) – shallow soils with less than 25 cm overburden overlaying the bedrock. Leptosols are predominant in local high altitudes in the landscape. This soil type also includes bedrock outcrops.

Gleysol (GL) – moist soils that are periodically saturated with water. This soil type can be found in wetlands which are not covered by peat but instead by different types of clay sediments such as gyttja clay.

Gleysol/Cambisol (GL/CM) – fertile forest soils on fine texture parent material, often located in local depressions in the landscape. The Cambisol is a young soil that develops on fine textured material. The tree layer is dominated by deciduous trees.

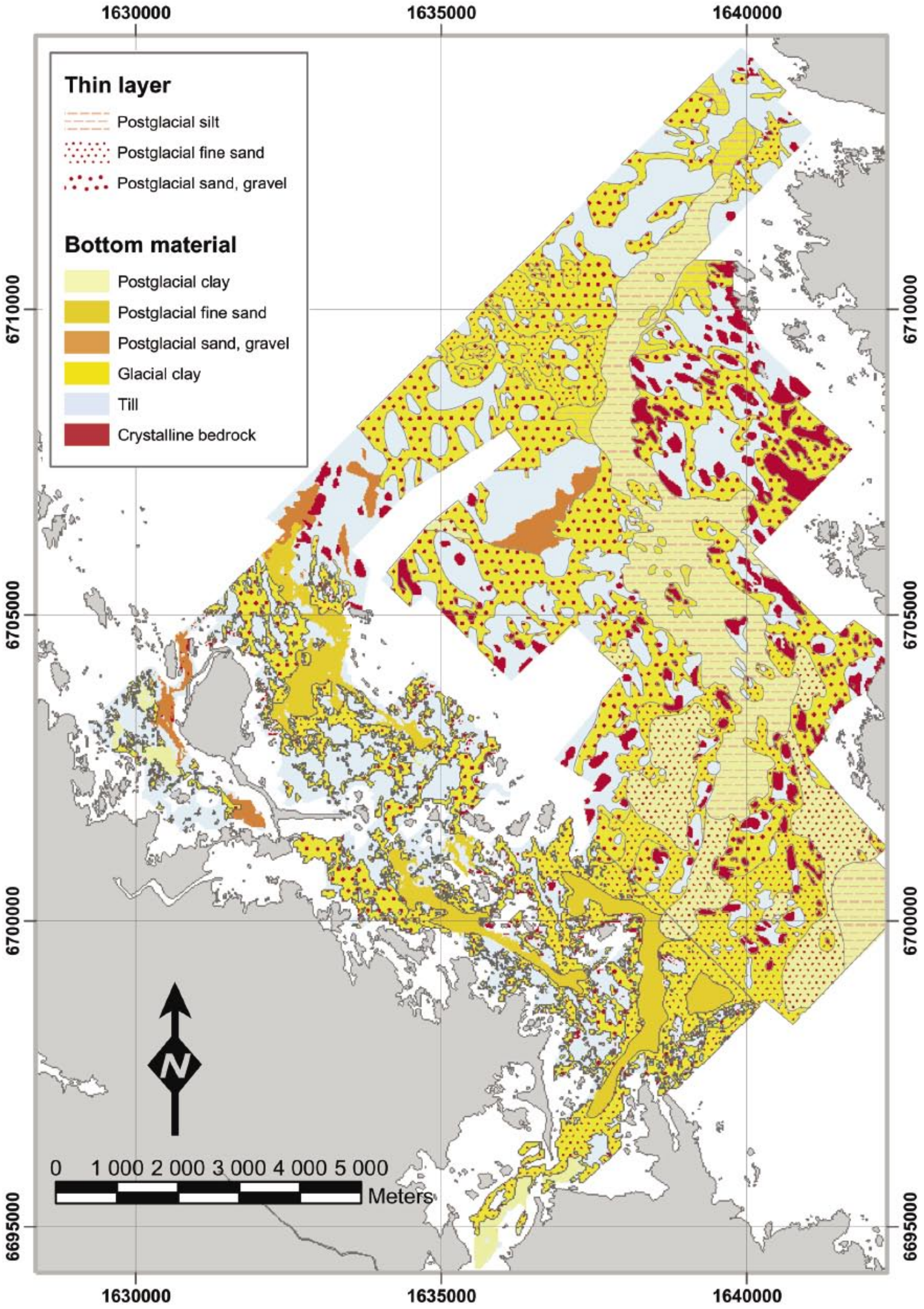

Figure 3-38. *Map showing the spatial distribution of bedrock exposures and Quaternary deposits on the sea floor outside Forsmark, from /Elhammer and Sandkvist, 2004/.*

Arenosol/Gleysol (AR/GL) – soils along the sea shoreline on sandy material of sediment origin.

Regosol/Gleysol (RG/GL) – less developed soils on coarse grained parent material and characterised by a minimal soil profile development as a consequence of young age. The tree layer is dominated by mixed coniferous forests.

Regosol/Gleysol on arable land (RG/GL-a) – less developed sediment soils and clayey till soils of Cambisol type. The soiltype covers arable land, pasture and abandoned arable land.

Regosol (RG) – less developed soil on course glacifluvial material found on the Börstilåsen esker in the eastern part of the area.

The soils in the Forsmark area are typically poorly developed soil types on till or sedimentary parent material, which is influenced by calcareous material /Lundin et al. 2004/. The poor soil development is a result of young age; since most of the candidate area emerged from the sea during the last 1,500 years. As the sea withdrew it influenced the soil by wave action, which washed out the tills and redistributed the fine-grained material into sedimentary deposits. In exposed position all soil was washed away and in many places across the area there is bare rock or very thin soil cover. Furthermore, former bays of the Baltic which were uplifted and isolated now form inland lakes and ponds which are being developed into swamps and peatland. This has resulted in a heterogeneous area with a large variety of soil parent material, from bare bedrock to washed out tills, and sorted sediments. The calcareous soil material has yielded nutrient-rich conditions, which can be observed in the rich and diverse flora of the area. This can also be seen in the predominant humus forms of mull type and of the intermediate moder type, which indicate a rich soil fauna. Because of the young age of the soils, the Forsmark area exhibits less soil of Podsol type than most similar areas in Sweden. Instead, the typical soil types are the less developed Regosols soils, together with Gleysols and Histosols, which are formed under moist conditions (Figure 3-39).

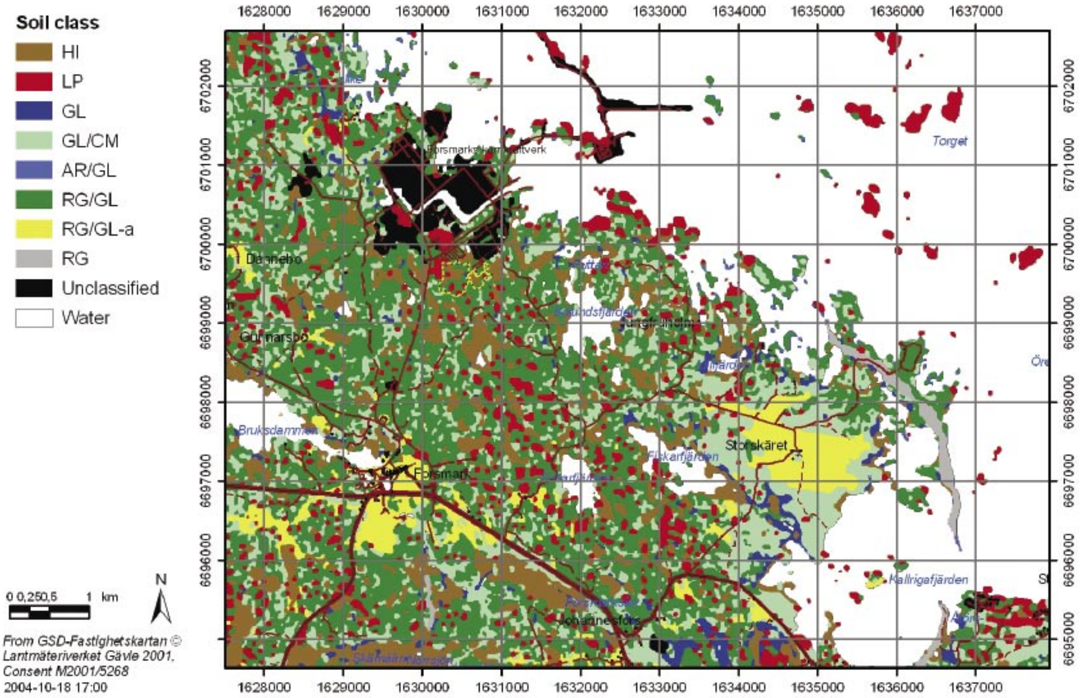

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Figure 3-39. *Map showing the spatial distribution of the soiltypes in the Forsmark regional model area /from Lundin et al. 2004/.*

The pH map (Figure 3-40) is produced by extrapolations of results from soil studies at 16 sites, which represent eight land types /Lundin et al. 2004/. The soil pH is generally above or close to seven in mineral soil sampled 55–65 cm below the ground surface. The relatively high pH in the soils is an effect of calcite, which is present in most of the Quaternary deposits. The lowest pH values were recorded on the glaciofluvial eskers, which may indicate the absence of calcite in these deposits (AFM001074), at least in the fine fraction analysed. Stones and gravel of limestone, however, is present in the esker.

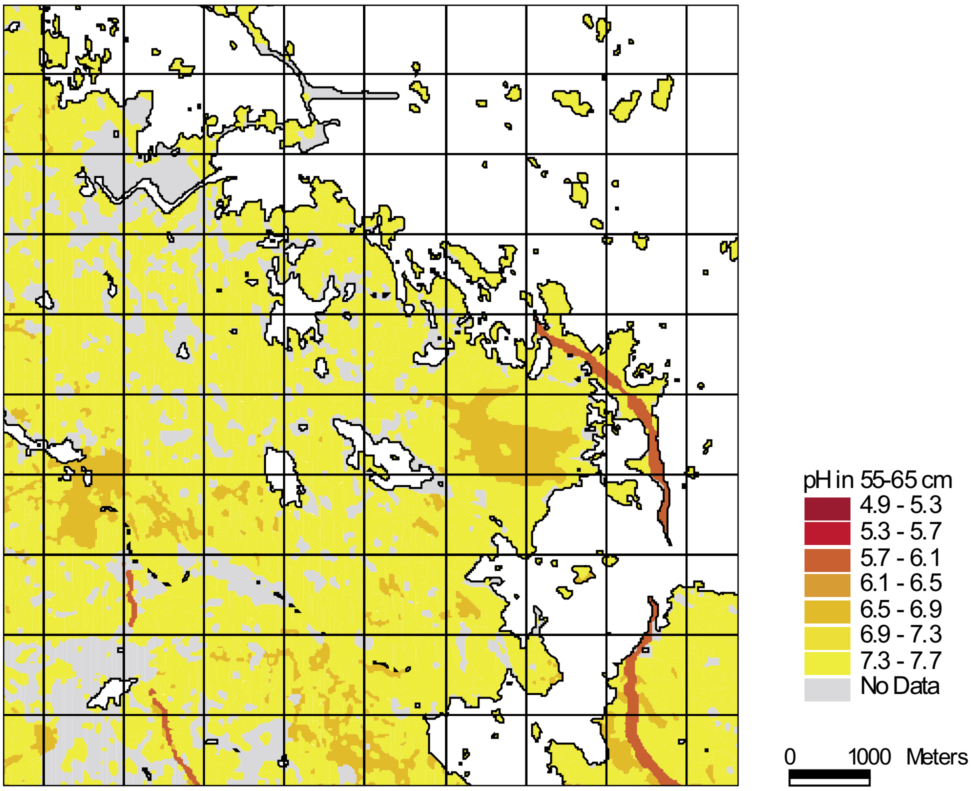

Figure 3-40. *Mineral soil pH 55–65 cm below the ground surface.*

Table 3-11. Distribution of soil classes for Bolundsfjärden drainage area and the whole Forsmark area.

Code	Soil class	Bolundsfjärden (%)	Forsmark area (%)
	Unclassified	0.03	3.15
HI	Histosol	17.0	12.9
GL	Gleysol	0.83	2.70
GL/CM	Gleysol/Cambisol	22.2	20.9
RG/GL	Regosol/Gleysol	46.9	36.4
RG/GL-a	Regosol/Gleysol on arable land	1.30	8.85
AR/GL	Arenosol/Gleysol	0.0	1.40
RG	Regosol	0.0	1.42
LP	Leptosol	11.8	12.3

The distribution of soiltypes within the north western part of the regional model area, corresponding to the Bolundsfjärden drainage area, consist s of more Histosols, which are often more developed than the common young organic soils found along the border of lakes in other parts of the Forsmark area. Also the coniferous forest soils of Regosol/Gleysol type are more common. Further, Bolundsfjärden has much less Regosol/Gleysol on arable land than Forsmark in general since no areas with clayey till parent material occur within this catchment. The catchment also has less Gleysol soils. Two soil classes do not occur in Bolundsfjärden at all, i.e. Arenosol/Gleysol, which is associated with the Baltic shoreline area, and Regosol, which is found by the esker south-east of the catchment.

The soils in the Bolundsfjärden catchment are more nutrient poor than the Forsmark area in general, especially due to the small amount of fertile arable land. The high proportion of Histosols might also indicate large discharge areas in low positions in the landscape that might be associated with the outflow of water-soluble substances. The soil type Histosol is however, overestimated within the entire area since the classification is based on the initial geological map with to large areas mapped as peat. The drainage water from the area should also be of a more humic character than the whole Forsmark area.

3.3.6 Chemical properties

Chemical properties in the overburden have been analysed in several activities. Calcium carbonate, clay mineralogy and geochemical composition of till samples was analysed in order to characterise the properties of the till units in the area /Sohlenius and Rudmark, 2003/. Elemental analyses on till samples collected from corings and machine cut trenches was performed. The focus of the activity was to invent the occurrence of ore potential compounds /Nilsson, 2003/. Total content of carbon, nitrogen and sulphur was analysed in sediment from the bottom of lakes /Hedenström, 2004a/. Peat chemistry includes ash content and elemental analyses /Fredriksson, 2004/. In the investigation of soil types, soil pH, carbon content and nitrogen was analysed at each horizon of the soil classes /Lundin et al. 2004/.

Chemistry in Glacial till

The geochemical distribution pattern of trace elements in till has been presented in two reports /Sohlenius and Rudmark, 2003; Nilsson, 2003/. The aim of the study by /Nilsson, 2003/ was to evaluate if there is any ore potential bedrock material incorporated in the till in the Forsmark area. The investigation by /Sohlenius and Rudmark, 2003/ was made for geochemical characterisation of the overburden. The samples analysed by /Nilsson, 2003; Sohlenius and Rudmark, 2003/ were retrieved from activities were the surface and stratigraphical distribution of QD were studied /e.g. Sohlenius and Rudmark, 2003; Sohlenius et al. 2004; Sundh et al. 2004/.

The glacial till in the Forsmark area is characterised by its high content of calcium carbonate, which is present in all the analysed samples. The calcite emanates from Ordovician limestone present at the sea bottom north of the Forsmark area. The till with a clay content higher than 5% (clayey till and boulder clay) have a slightly higher content of calcite (average content 24%, $n = 84$) in the fine fraction (grain sizes $< 63\mu$) compared to the sandy till (average content 18% $n = 52$). The calcite content has not been determined in the sand and gravel fraction.

The colour shaded maps presented in /Nilsson, 2003/ show that the contents of copper (Cu), lead (Pb) and zinc (Zn) in the till coincide with that of the local bedrock. There is one area west of Lake Bolundsfjärden with relatively low contents of Cu (Figure 3-41), Pb and Zn.

This area coincides with the area with granitic bedrock, which occupies the central part of the Forsmark candidate area. The highest contents of Cu, Pb and Zn coincide with areas constituting of felsic to intermediate meta-volcanic rocks and amphibolites, situated in the north-eastern and south-western parts of the investigated area (Figure 3-41). The contents of Cu, Zn, and Pb are close to the median values for till in central Sweden. The Ca content is high, 7.5%, compared to the median, 0.18%, in central Sweden. This is an effect of the high contents of calcite in the till. Also the arsenic (As) content is high probably due to the precipitation of Ca-arsenates, which is favoured by the occurrence of calcite /cf Nilsson, 2003/. The study by /Nilsson, 2003/ suggests that there is no potential for ore explorations of Cu, Pb, Zn or gold (Au) in the Forsmark area.

The results presented by /Sohlenius and Rudmark, 2003/ show a positive correlation between the clay content and the contents of most elements in the eight samples analysed. The elements are probably leached out more effectively with HNO_3 from fine-grained material compared to coarser material. The results from this investigation indicate to what degree different elements can be leached and taken up by biota in the natural soil environment. That is not evident from the total metal contents presented by /Nilsson, 2003/.

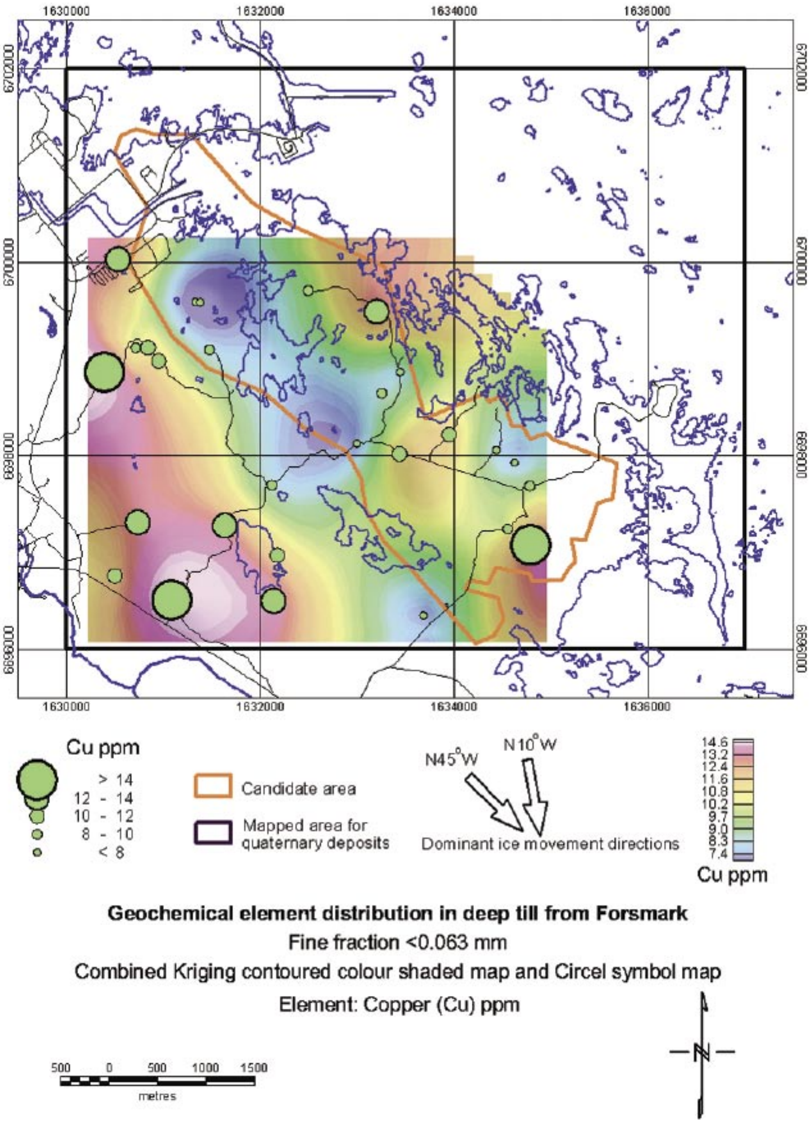

Figure 3-41. *The content of copper in till, from /Nilsson, 2003/. The highest values are recorded in the area north east and south west of the candidate area while the lowest concentration was recorded in the till samples collected west of Lake Bolundsfjärden.*

Results from the quantitative XRD analyses show small variations in the contents of most silicate minerals in the till. The samples contain almost 40% of quartz, which is similar to most of the bedrock in the investigated area. There is a relatively high content of hornblende in the two samples from HFM02, situated west of Lake Bolundsfjärden. The hornblende may emanate from an occurrence of gabbro c 1 km west of that site.

Results from the qualitative XRD analyses of clay mineralogy show that illite is the most common clay mineral in all four samples. The result shows that the illite/chlorite ratio is higher in the clayey till compared to the silty-sandy till. It has been shown in an earlier study that the illite/chlorite ratio is higher in eastern Uppland, probably due to different bedrock mineralogy /Snäll, 1986/.

The results show that the chemical and mineralogical compositions of the till mainly reflect that of the local bedrock. The high $CaCO_3$ content of the till shows, however, that one fraction of the till has been transported several tens of kilometres. The exact occurrence of limestone at the sea floor is so far unknown and it is therefore not possible to determine the how far the $CaCO_3$ have been transported.

It has been shown that most of the tills in the area has been deposited by ice moving from north-west /Sundh et al. 2004/. At certain localities the uppermost till has been deposited from north /Sundh et al. 2004/. It can consequently be concluded that most of the till material emanates from bedrock situated north to north-west of each site. It must, however, be kept in mind that the till material may have been re-deposited during several glaciations and some of the bedrock, material constituting the till may therefore originate from another direction than north to north-west, which is supported e.g. by the high calcite content and Palaeozoic microfossils in till samples from the Forsmark area /cf Robertsson, 2004/.

Most bedrock types in the Forsmark area has a north-west to south-east strike, which correspond to the dominating direction of ice movements. That may have strengthened the pattern of element anomalies (Figure 3-41).

Chemistry in Lake sediments

A general stratigraphy has earlier been established for the marine and lacustrine lake sediments, see above. Not all these sediment types are present in all the investigated lakes. The general stratigraphy represents the development from late glacial sea bottom to a shallow lagoon stage and finally the isolation from the Baltic and a lake stage. One of the most complete stratigraphies was recorded in Lake Fiskarfjärden, one of the sites where the sediment was analysed (Figure 3-42).

In all investigated lakes, the content of carbon (C), sulphur (S) and nitrogen (N) shows an increasing trend from the oldest to the youngest sediments (Figure 3-42). The total contents of C, S, and N are relatively low in the glacial clay. The average contents of C, N and S in glacial clay and algal gyttja have been calculated (algal gyttja n = 27, gyttja clay n = 14).

The carbon and nitrogen contents increase stepwise at the transitions to gyttja clay and algal gyttja (Figure 3-42). The sulphur contents are close to or higher than 1% in all sediments overlying the glacial clay and the highest values, up to 3%, were recorded in the organic rich gyttja sediments.

Nitrogen and carbon contents are well correlated in sediments from the three lakes, where both elements were analysed (Figure 3-42) and the C/N ratio ranges between 8 and 12.

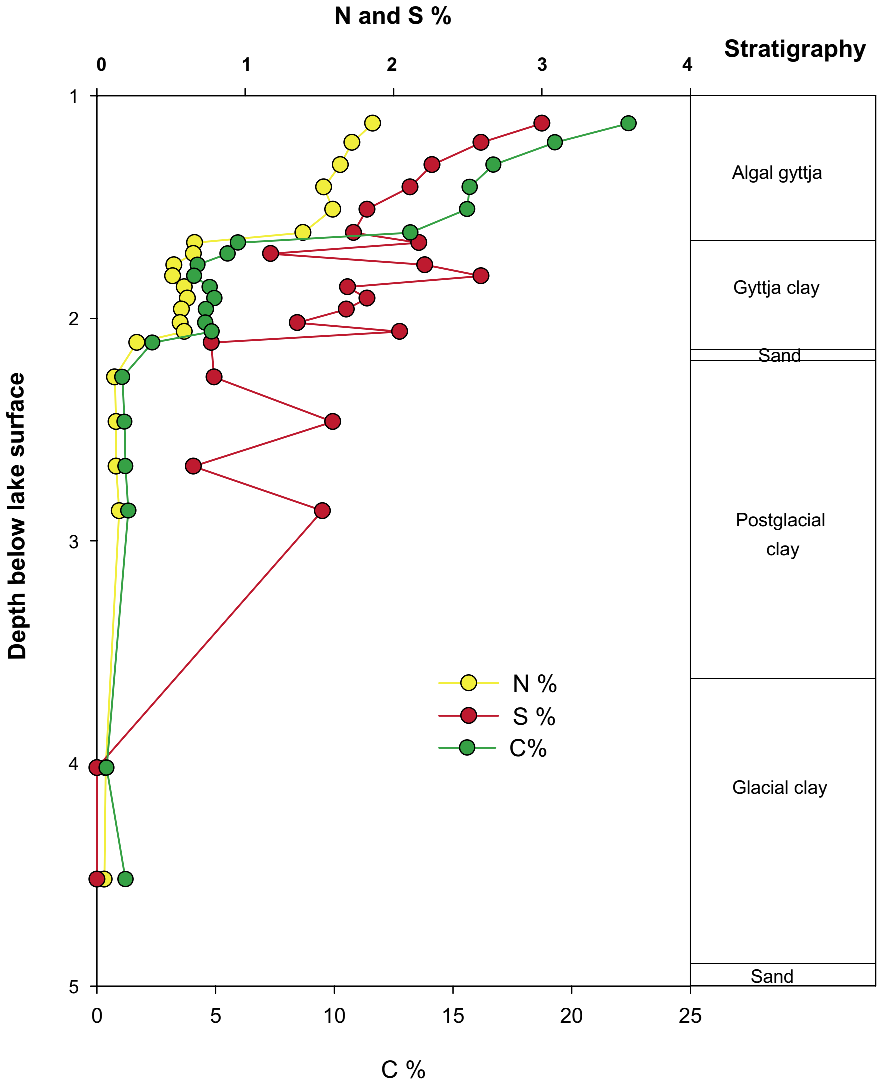

Figure 3-42. *The distribution of C, N and S in marine and lacustrine sediments from Lake Fiskarfjärden (PFM004204). The stratigraphy is shown in the right column.*

Some samples have, however, a higher C/N ratio indicating the presence of $CaCO_3$. Higher productivity in lagoons and lakes compared to the open sea probably caused the relatively high content of organic carbon and nitrogen preserved in sediments deposited in these environments.

The results from analyses of calcium carbonate show that the content of this mineral is low in sediments were S and N were analysed. The glacial clay underlying the gyttja sediments in many lakes have an average $CaCO_3$ content of 26%. In some lakes the $CaCO_3$ content is high in the youngest sediments formed during the present lake stage. The highest calcite contents, over 60%, were recorded in the calcareous gyttja from Lake Stocksjön and Lake Eckarfjärden. The calcium carbonate in these lake sediments has been precipitated due to the high concentration of dissolved calcium carbonate in the lake water (see Section 3.4). The carbonate in the water has been leached from the soils in the surroundings due to chemical weathering of calcite. During the growing season, the CO_2 concentration in the water decreases and causes precipitation of calcite, that later accumulates in the sediments.

Sulphur in the sediments may partly be associated with organic material, but most sulphur in postglacial organic rich sediments is bound in iron sulphides /cf Sternbeck and Sohlenius, 1997/. The 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 clays in the Forsmark area contain any significant amounts of iron sulphides.

Results from mapping of QD show that many of the wetlands constitute of clay gyttja in the surface /Sohlenius et al. 2004/. It is likely that gyttja clay shown on the map of QD have similar contents of C, S and N as recorded in gyttja clay from the lakes. As mentioned above the high content of S in the gyttja clay reflects the occurrence of iron sulphides. Iron sulphides can easily oxidise if the groundwater table is lowered, due to e.g. ditching or isostatic land upheaval. Oxidation of iron sulphides may cause acid soil condition and increased leaching of trace elements /e.g. Åström and Björklund, 1995/.

The results from the XRD analyses show similar distribution of clay minerals in glacial and postglacial clay, which is in accordance with other clay-mineralogical studies in Uppland /Persson, 1985; Snäll, 2004/. Illite is the dominating clay mineral followed by chlorite and small amounts of kaolinite. The results imply that the clay only to a small degree have been affected by chemical weathering /cf Snäll, 2004/.

Chemistry in peat

A stratigraphical and chemical characterisation of peat have been carried out in two peatlands, Stenrösmossen (AFM001245) and one wetland 4 km south-west of Forsmark (AFM001246) /Fredriksson, 2004/. Stenrösmossen was selected since it is situated close to the candidate area, whereas the other peatland was chosen to represent an older and more developed peatland.

It has not been possible to perform studies of peat in the candidate area since the wetlands in that area are too young for the development of a peat layer /Sohlenius et al. 2004/. The results from the investigation of peat are used to understand the historical and future development of wetlands in the area. The chemical composition of the peat may be used for a better understanding of the groundwater chemistry of the area and to predict future land use of the peatlands.

Stenrösmossen is a horizontal forest fen developed from a shallow stagnant water body. The main part of the mire is influenced by minerotrophic, nutrient rich ground water from surrounding QD. Also AFM 001246 is a shallow forest fen, but is partly characterised as a pine bog. Some of the results from /Fredriksson, 2004/ have been summarised and compared with the mean and median values for Swedish peatlands (Table 3-12). The peat in Stenrösmossen is influenced by the occurrence of calcium carbonate in surrounding soils, which is reflected by a high ash content of calcium oxide (47%). The other peatland (AFM001246) has CaO contents (Table 3-12) closer to the average for Swedish peat /Fredriksson, 1984/.

The contents of trace elements in the two peatlands are normal except for lead (Pb) and zinc (Zn). The uppermost general sample from AFM001246 has high content of Pb and the Zn content is high in both the investigated peatlands. The reason for these anomalies is not known, and both peatlands are situated far from any present industrial activities. The mires are, however, situated in an area, which earlier has been subjected to mining and Forsmarks Bruk is situated only a few kilometres from the mires.

There is a relatively high content of sulphur in peat from Stenrösmossen (Table 3-12).

Table 3-12. Concentration of some selected elements in two peatlands from Forsmark /Fredriksson, 2004/. The values can be compared with the mean and median values for Swedish peatlands /Fredriksson, 1984/.

		0–1	0–1	1–2	Mean Sweden	Median Sweden	Std dev
CaO	% (in ash)	47.1	20.6	8.2	24.7	21.6	12.9
Pb	mg/kg (in ash)	116.5	1,600	79.5	64	35	93
Zn	mg/kg (in ash)	620	951	1,526	227	170	311
Ash	% DS	9.7	7.7	9.5	5.1	4.3	3.4
Sulphur	% DS	0.72	0.30	0.37	0.27	0.24	0.14

High sulphur contents are common in peatlands along the Baltic Sea coast. The sulphur may emanate from brackish water which have remained since the site was covered by the sea /cf Fredriksson, 2004/. The high sulphur content makes it unlikely that peat from Stenrösmossen will be used as fuel.

3D model of Quaternary deposits

One way of visualising the spatial variations in the thickness of the overburden is the compilation of a 3D model of the QD /Vikström, 2005/. The model is constructed using Geo Editor, a GIS extension in Arc View. The Geo Editor model is compatible with other tools used in the modelling of near surface hydrogeology, such as the Mike Shee, see Section 3.4.

In the areas with low data density, the average soil depth from the data imported to the model was used (1.9 m). The basis for this calculation is the input data used in the Geo Editor modelling, after excluding the bedrock outcrops where the depth to bedrock is 0. In this model version, 1.9 m is used for areas with low data density (Figure 3-43).

The deepest till cover recorded within the modelled area was observed along the profile Forsmark 7 (Figure 3-44). North of Lake Stocksjön, the depth to bedrock was c 13 m. This site is situated within a zone striking NW-SE where the soil depth is deep and there are relatively few bedrock outcrops. This zone continues towards the south east to the Lake Fiskarfjärden basin. The deepest record of soil cover in the Forsmark area is located along this zone at the outlet from Lake Fiskarfjärden (SFM0026). The depth to bedrock was approximately 16 m, consisting mainly of till /Johansson, 2003/. This site, however, is situated outside the area modelled for soil depth. Although outside the model area, it is also evident that thick QD covers the eastern area, at Storskäret.

The small scale bedrock topography in the area close to Drill site 1 is showed as deep soil cover north west of Lake Bolundsfjärden. The data density in Lake Eckarfjärden and Bolundsfjärden is sufficient for the model. The depth data from Lake Fiskarfjärden, however, should be regarded as tentative since the model is based on lake sediment corings, but only one single coring through till and no geophysical data.

New seismic profiles and updated QD depth calculated from seismic profiles will be available for the next model version. Interpretations of soil dept from air-born geophysical investigations will also be used in the next model version.

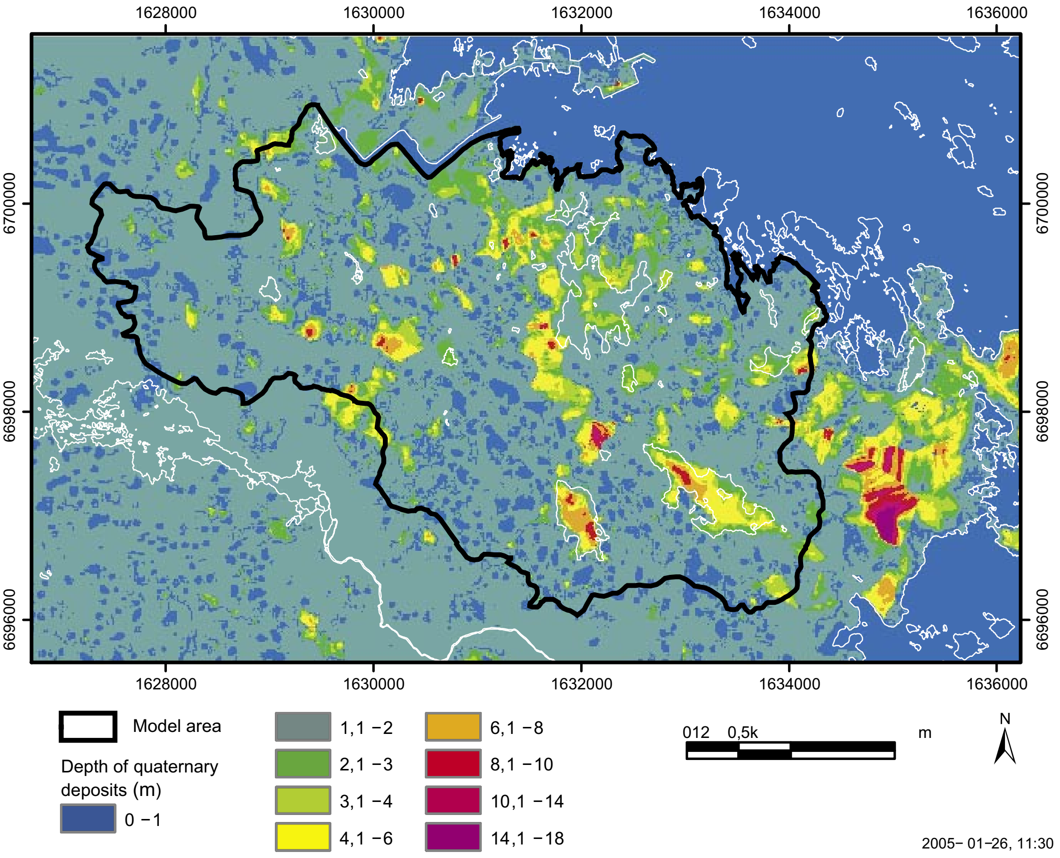

Figure 3-43. *Map showing the depth to bedrock based on the soil depth modelling in Geo Editor. The model is valid for the area within the black solid line, corresponding to the catchment area for Lake Bolundsfjärden.*

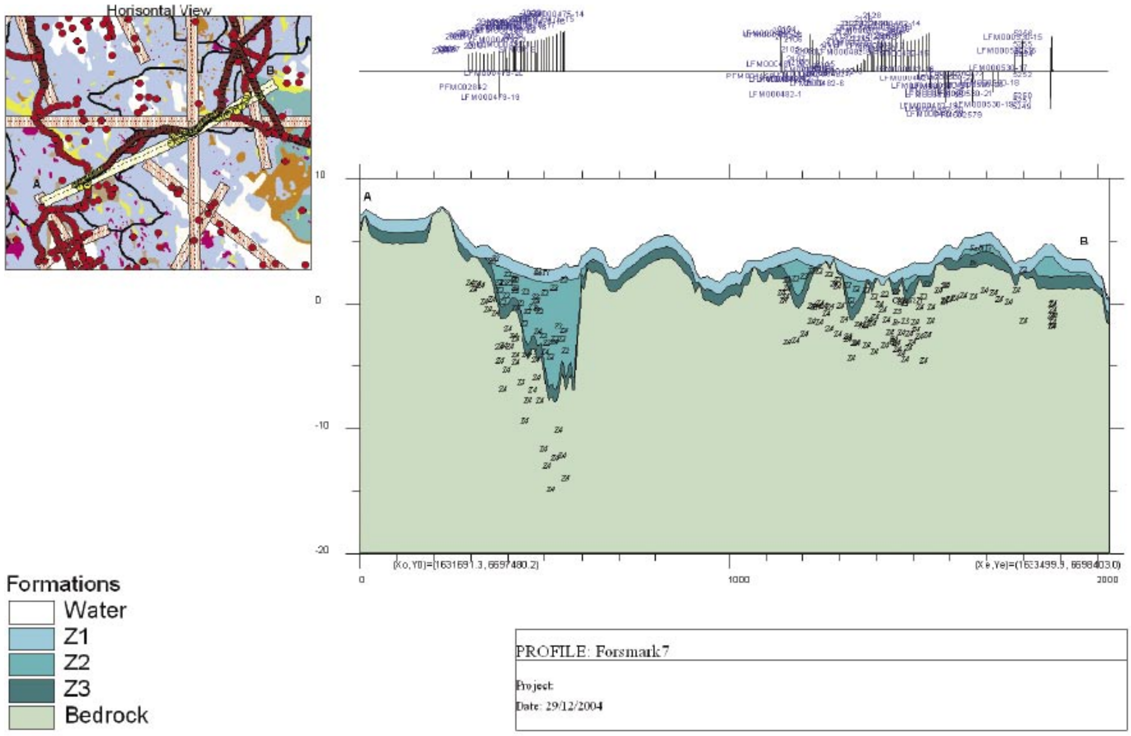

Figure 3-44. *The 3D model of the Quaternary deposits along profile Forsmark 7 has the deepest till cover, c 13 m located north of Lake Stocksjön, from /Vikström, 2005/.*

3.4 Climate, surface hydrology, and near-surface hydrogeology

3.4.1 Introduction

This section presents the meteorological conditions and the modelling of surface hydrology and near-surface hydrogeology performed in support of the Forsmark 1.2 site descriptive model. A detailed description of the methodology, the primary data and the modelling results is presented in a background report /Johansson et al. 2005/.

Concerning these disciplines, it may be noted that they were not covered by background reports in the version 1.1 modelling. However, the available datasets were analysed and the results were integrated and described in the SDM report. The objectives of the modelling reported in this section are to:

- analyse and present the data available in the Forsmark 1.2 dataset,
- update the descriptive model presented in the previous model version /SKB, 2004a/,
- present the results of the initial flow modelling performed in order to support the site description and to provide input data to the ecological system modelling,
- summarise and present the results in the form of an updated site description.

As further described below, the database available at the time for the Forsmark 1.2 "data freeze" (July 31, 2004) contains a relatively large amount of data, including time series of meteorological parameters and surface water and groundwater levels for a 15-month period, and hydraulic parameters from about 50 field tests. Furthermore, the descriptions of, e.g. water courses and Quaternary deposits have been further developed in the version 1.2 modelling, which has contributed to the improved description of surface hydrology and near-surface hydrogeology. In particular, the present model includes results from quantitative flow modelling (no flow modelling was performed in version 1.1).

Since a lot of new data have become available, the version 1.2 modelling effort has to large extent been focused on the presentation and evaluation of site-specific data. Thus, the present knowledge of the site is mainly inferred directly from observations in measurement results. The work conducted to evaluate and generalise these results by use of flow modelling has been limited, especially in terms of the testing of modelling results against site investigation data. It is anticipated that quantitative flow modelling will become a more important component of the modelling work when local discharge measurements and longer time series from local meteorological measurements become available.

Thus, it should be emphasised that although significant steps have been taken in the descriptive modelling, there are still substantial uncertainties in the model description. The main reasons for these uncertainties are the limited amount of local meteorological and discharge data (short time series), and that time has been insufficient for carrying out supporting exploratory analyses and flow modelling exercises. Furthermore, spatial variability, especially the variability in the hydraulic properties of the various Quaternary deposits, remains a potentially important source to uncertainty.

The methodology for the conceptual and descriptive modelling of surface water hydrology and hydrogeology in the overburden was presented in the modelling strategy report for hydrogeology /Rhén et al. 2003/. The strategy report describes the input data, the modelling process and the resulting descriptive model, based on a systems approach in which the descriptive model of the surface and near-surface system is presented as a set of Hydraulic Soil Domains (HSD). The HSDs are to be specified in terms of geometry and hydrogeological parameters, as described in the strategy report.

The description in terms of HSDs provides a suitable framework for conveying the site modellers' interpretation of the site conditions, especially if the result is to be used as a basis for groundwater flow modelling. However, other users may be interested in other aspects of the site descriptive modelling. In particular, the biosphere modelling within Safety Assessment uses "box models", which require input data on the water turnover in the various "biosphere objects" that are modelled. As input to these models, the site descriptive modelling should provide spatial distributions of the total runoff and other components of the water balance, such that, e.g. water turnover times can be calculated for arbitrary spatial objects. Furthermore, a descriptive model organised in terms of "hydrological elements" such as sub-catchments with associated parameters may be more relevant for some applications. This type of data is therefore also presented in the present section.

3.4.2 Investigations and available data

Previous investigations

Two site descriptive models (SDM) of the Forsmark area have been presented before the present version: version 0 (F0, for brevity) /SKB, 2002/ and version 1.1 (F1.1) /SKB, 2004a/.

F0 was developed before the start of the site investigations and was mainly based on data compiled for the Östhammar feasibility study /SKB, 2000/ and related background reports. This model was developed at a regional scale and covered a rectangular area, 15 km by 11 km, surrounding the area identified in the feasibility study as favourable for further study. This area was called the Forsmark regional model area.

The information that provided the basis for the F0 model was mainly 2D in nature (surface data), and general and regional (rather than site specific) in character. However, 3D (depth) information was available from boreholes, shafts and tunnels from the construction of the Forsmark nuclear power plant and the underground low to medium active radioactive waste storage facility, SFR.

Meteorological and hydrogeological data were compiled from nearby stations operated by the Swedish Meteorological and Hydrological Institute (SMHI) /Lindell et al. 2000; Larsson-McCann et al. 2002/, whereas data on catchments were obtained from /SMHI, 1985/ and /Brunberg och Blomqvist, 1998/. The description of the Quaternary deposits (QD) in the feasibility study /SKB, 2000/ formed the basis for the conceptualisation of the hydrogeology of the QD. However, no data on hydraulic properties or groundwater levels in the QD were presented in F0.

At the time for the F1.1 "data freeze", i.e. April 30, 2003, the site investigations, in terms of climate, surface hydrology and near-surface hydrogeology included:

- delineation of catchment areas in the field in the central parts of the model area,
- manual discharge measurements at 8 locations,
- installations of surface water level gauges, drilling of boreholes and excavation of pits in QD,
- installations of groundwater monitoring wells in QD,
- hydraulic tests (slug tests) in these groundwater monitoring wells.

Local meteorological and hydrological stations were not established before the F1.1 data freeze, and there was no time to collect time series of surface water and groundwater levels. The still very limited amount of site specific data implied that also F1.1 was mainly based on generic and/or regional data regarding climate, surface hydrology and near-surface hydrogeology.

Meteorological, hydrological and hydrogeological investigations

Between the F1.1 (April 30, 2003) and F1.2 (Forsmark 1.2; July 31, 2004) data freezes, the meteorological, surface hydrological and near-surface hydrogeological investigations have comprised the following major components:

- Establishment of two meteorological stations and collection of local meteorological data.
- Establishment of one hydrological station and collection of hydrological data.
- First field survey of lake thresholds, and brook gradients and cross-sections (parts of the model area).
- Manual discharge measurements in brooks.
- Installations of additional surface water level gauges.
- Installations of additional groundwater monitoring wells in QD.
- Supplementary slug tests in groundwater monitoring wells.
- Collection of surface water level and groundwater level data.
- Installation of BAT-type filter tips.
- Installation of two pumping wells in QD.
- Pumping tests in the two installed pumping wells.

Other investigations contributing to the modelling

In addition to the investigations listed above, the modelling is based on data from the SKB databases SICADA and SKB-GIS on:

- topographical and other geometrical data,
- surface-based geological investigations of QD and the soil type mapping,
- composition and stratigraphy from boreholes and pits in QD,
- data on the hydrogeological properties of the bedrock,
- soil and water chemistry.

Summary of available data

Table 3-13 gives references to site investigations and other reports that contain meteorological, surface hydrological and near-surface hydrogeological data used in the F1.2 modelling. Table 3-14 provides the corresponding information with respect to other disciplines and types of investigations. Table 3-15 specifies the references to SKB-reports referred to in Tables 3-13 and 3-14.

In general, the site investigation data are available in SKB's SICADA and GIS databases. However, due to technical problems the time series data from SKB's meteorological stations, surface water level gauges, and groundwater monitoring wells were not available in SICADA when the final version of the present report was produced (June, 2005). Instead, quality assured data from SKB's HMS (Hydro Monitoring System) database were used in the analyses of time series data presented herein.

Table 3-13. Available meteorological, hydrological and near-surface hydrogeological data and their handling in F1.2 (HMS = SKB's Hydro Monitoring System database, see text).

Available site data, data specification	Ref	Usage in F1.2 analysis/modelling	Not utilised in F1.2 arguments/comments
Meteorological data			
Regional data			
Summary of precipitation, temperature, wind, humidity and global radiation up to 2003	R-99-70 TR-02-02	Basis for general description and quantitative modelling of groundwater and surface water flow.	
Site Investigation data			
Precipitation, temperature, wind, humidity, global radiation and potential evapotranspiration June 2003–July 2004 from the meteorological stations at Högmasten and Storskäret	HMS	Comparison with regional meteorological data.	
Snow depth, ground frost and ice cover	P-03-117 P-04-137	Validation of snow routine in quantitative modelling.	
Hydrological data			
Regional data			
Catchment characteristics	SKB-GIS	Delineation of catchment areas.	
Regional discharge data	R-99-70 TR-02-02	Specific discharge in conceptual and quantitative modelling.	
Site Investigation data			
Geometric data on catchment areas, lakes and water courses	SKB-GIS P-04-25	Delineation and description of catchment areas and lakes.	
Automatic discharge measurements	HMS		Only < 3 months time series from one station is available.
Manual discharge measurements in water courses	SICADA P-03-27 P-04-146	General description of temporal variability in surface water discharge.	
Installation of surface water level gauges	P-03-64 P-04-139	Basis for surface water level measurements.	
Level measurements in lakes and the sea	P-04-313 HMS	Surface water-groundwater level relations, test of quantitative modelling with MIKE SHE.	
Hydrogeological data			
Inventory of private wells	R-02-17	Description of available hydrogeological information.	No attempt is made to infer hydraulic parameters from these data.
Data on installed groundwater monitoring wells, abstraction wells and BAT filter tips	P-03-64 P-04-136 P-04-138 P-04-139	Description of QD type and depth to bedrock, basis for groundwater level measure-ments and hydraulic tests.	
Hydraulic conductivity of QD	P-03-65 P-04-136 P-04-138 P-04-140 P-04-142	Basis for assigning hydraulic conductivity of QD in conceptual and quantitative models.	
Groundwater levels in QD	P-04-313 HMS	General decription, conceptual and quantitative modelling.	

Table 3-14. Input data from other disciplines and their handling in F1.2.

Available site data, data specification	Ref	Usage in F1.2 analysis/modelling	Not utilised in F1.2 arguments/comments
Topographical data			
Digital Elevation Model (DEM)	SKB-GIS P-04-03	Conceptual and quantitative modelling (GIS and MIKE SHE).	
Vegetation and land use data			
Vegetation map	SKB-GIS P-03-83	Conceptual and quantitative modelling (MIKE-SHE).	
Surface-based geological data			
Soil type map	SKB-GIS R-04-08	Conceptual modelling and quantitative modelling with MIKE-SHE.	
Geological map of QD	SKB-GIS P-03-11 P-03-14 R-04-39	Basis for the conceptual hydrogeological model of QD and for the quantitative modelling (MIKE SHE).	
Geophysical data	P-04-78 P-04-99 P-04-156	Conceptual and quantitative modelling with MIKE SHE.	
Geological data from boreholes and pits			
Stratigraphical data of QD	P-03-24 P-04-34 P-04-86 P-04-111 P-04-127 P-04-148	Basis for the conceptual hydrogeological model of QD and for the quantitative modelling (MIKE SHE).	
Hydrochemical data			
Surface water	P-03-27 P-04-146	Conceptual modelling (in part).	Limited use due to time constraints.
Shallow groundwater	SICADA	Conceptual modelling.	
Hydrogeological properties of the rock			
Modelled hydraulic conductivity and pressure distributions in the upper part of the rock – results of Darcy-Tools modelling for Forsmark 1.1	R-04-15	Quantitative modelling (MIKE SHE) – parametrisation and identification of boundary conditions.	

Table 3-15. Reports in the SKB P, R and TR series referred to in Tables 3-13 and 3-14.

P-03-11	**Sohlenius G, Rudmark L, Hedenström A.** Mapping of unconsolidated Quaternary deposits. Field data 2002.
P-03-14	**Sohlenius G, Rudmark L**. Mapping of unconsolidated Quaternary deposits. Stratigraphical and analytical data.
P-03-24	**Hedenström A.** Investigation of marine and lacustrine sediments in lakes. Field data 2003.
P-03-27	**Nilsson A-C, Karlsson S, Borgiel M.** Sampling and analyses of surface waters. Results from sampling in the Forsmark area, March 2002 to March 2003.
P-03-64	**Johansson P-O.** Drilling and sampling in soil. Installation of groundwater monitoring wells and surface level gauges.

P-03-65	**Werner K, Johansson P-O.** Slug tests in groundwater monitoring wells in soil.
P-03-83	**Boresjö Bronge L, Wester K**. Vegetation mapping with satellite data of the Forsmark, Tierp and Oskarshamn regions.
P-03-117	**Aquilonius K, Karlsson S.** Snow depth, frost in gorund and ice cover during the winter 2002/2003.
P-04-03	**Brydsten L.** A method for construction of digital elevation models for site investigation program at Forsmark and Simpevarp.
P-04-25	**Brunberg A-K, Carlsson T, Blomqvist P, Brydsten L, Strömgren M.** Identification of catchments, lake-related drainage parameters and lake habitats.
P-04-34	**Sundh M, Sohlenius G, Hedenström A.** Stratigraphical investigation of till in machine cut trenches.
P-04-78	**Marek R.** Ground penetration radar survey 2003.
P-04-86	**Hedenström A.** Investigation of marine and lacustrine sediments in lakes. Stratigraphical and analytical data.
P-04-99	**Bergman B, Palm H, Juhlin C.** Estimate of bedrock topography using seismic tomography along reflection seismic profiles.
P-04-111	**Hedenström A, Sohlenius G, Albrecht J.** Stratigraphical and analytical data from auger drillings and pits.
P-04-127	**Fredriksson D.** Peatland investigation Forsmark.
P-04-136	**Johansson P-O.** Undisturbed pore water sampling and permeability measurements with BAT filter tips. Soil sampling for pore water analyses.
P-04-137	**Heneryd N.** Snow depth, ground frost and ice cover during the winter 2003/2004.
P-04-138	**Werner K, Lundholm L, Johansson P-O.** Drilling and pumping test of wells at Börstilåsen.
P-04-139	**Werner K, Lundholm L.** Supplementary drilling and soil sampling, installation of groundwater monitoring wells, a pumping well and surface water level gauges.
P-04-140	**Werner K.** Supplementary slug tests in groundwater monitoring wells in soil.
P-04-142	**Werner K, Lundholm L.** Pumping test in well SFM0074.
P-04-146	**Nilsson A-C, Borgiel M.** Sampling and analyses of surface waters. Results from sampling in the Forsmark area, March 2003 to March 2004.
P-04-148	**Hedenström A.** Stratigraphical and analytical data of Quaternary deposits.
P-04-156	**Marek R.** A co-ordinated interpretation of ground penetrating radar data from the Forsmark site.
P-04-313	**Nyberg G, Wass E, Askling P, Johansson P-O.** Hydromonitoring program. Report for June 2002-July 2004.
R-99-70	**Lindell S, Ambjörn C, Juhlin B, Larsson-McCann S, Lindquist K.** Available climatological and oceanographical data for site investigation program.
R-02-17	**Ludvigsson J-E.** Brunnsinventering i Forsmark.
R-04-08	**Lundin L, Lode E, Stendahl J, Melkerud P-A, Björkvald L, Thorstensson A.** Soils and site types in the Forsmark area.
R-04-39	**Sohlenius G, Rudmark L, Hedenström A.** Mapping of unconsolidated Quaternary deposits 2002-2003. Map description.
R-04-15	**SKB.** Preliminary site description. Forsmark area – version 1.1.
R-05-07	**Vikström M, 2005.** Modelling of soil depth and lake sediments. An example from the Forsmark site.
TR-02-02	**Larsson-McCann S, Karlsson A, Nord M, Sjögren J, Johansson L, Ivarsson M, Kindell S.** Meteorological, hydrological and oceanograpical information and data for the site investigation program in the communities of Östhammar and Tierp in northern part of Uppland.

3.4.3 Description of primary data

This section provides a brief description of the primary data used in the F1.2 modelling. For a more detailed presentation and evaluation of the primary data, the reader is referred to the preceding section and to /Johansson et al. 2005/.

Meteorological data

The regional meteorological conditions in the Forsmark area were described in /Larsson-McCann et al. 2002/. Meteorological stations of interest for the Forsmark regional area were listed, and long-term average data for selected meteorological stations considered to be representative for different meteorological parameters for the Forsmark area were presented. These data were used in F1.1 to characterise the Forsmark area in terms of climate.

During 2003, two meteorological stations were established in the Forsmark area, one in the northern part of the candidate area at the existing mast at the Forsmark nuclear power plant (Högmasten) and one in the southern part at Storskäret (Figure 3-45). Site-specific meteorological data for F1.2 were available from May 2003 up to the data freeze at the end of July 2004. The measurements performed at each station are summarised in Table 3-16.

For the characterisation of the meteorological conditions in F1.2, mainly long-term regional data compiled during the version 0 modelling are used. Local meteorological data from the site investigation are presented for the period May 2003–July 2004 and compared with nearby SMHI stations for which also long-term measurements exist.

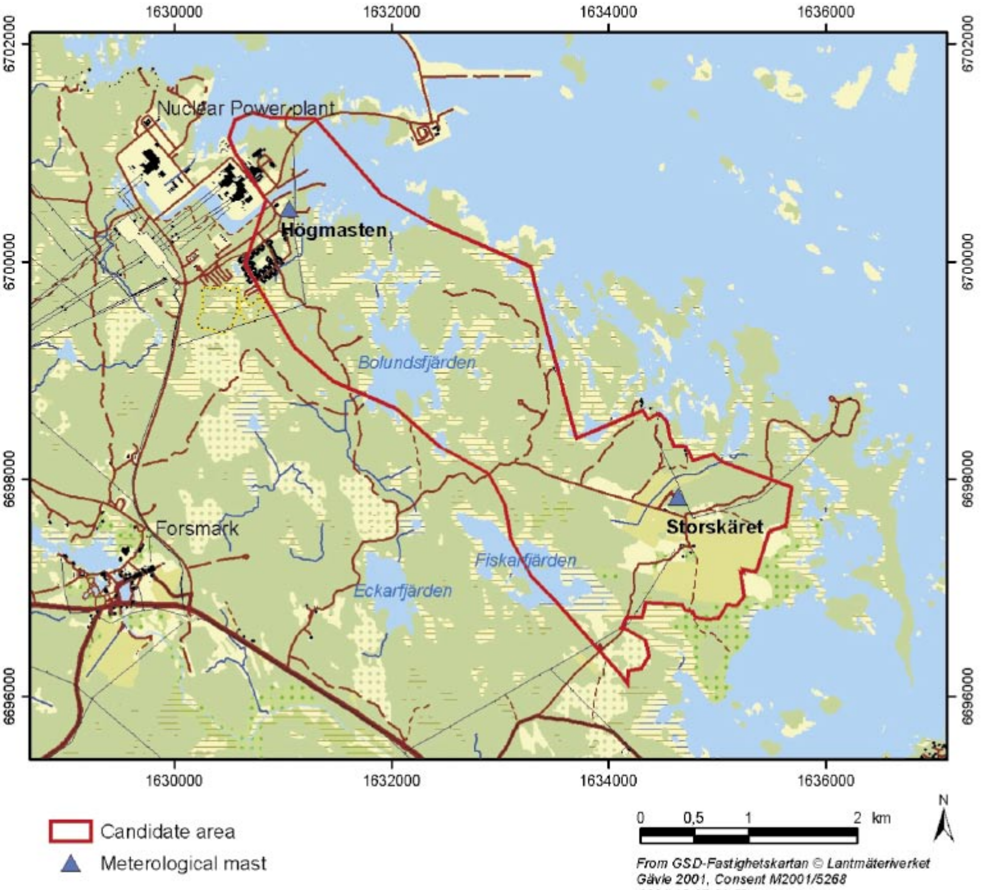

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Figure 3-45. Locations of the two new meteorological stations in the Forsmark area.

Table 3-16. Meteorological measurements at Högmasten and Storskäret.

Parameter	Registration interval	Högmasten	Storskäret
Precipitation	30 min (sum)	x	x
Air temperature	30 min (mean)	x	x
Wind direction and wind speed (10 m above ground)	30 min (mean)	x	x
Humidity	30 min (mean)	x	x
Air pressure	30 min (mean)	x	–
Global radiation	30 min (mean)	x	–

Hydrological data

Surface water level gauges have been installed in six lakes (SFM0039-42, SFM0064 and SFM0066) and at two locations in the Baltic Sea (at the Forsmark harbour, SFM0038, now changed to PFM010038, and at Kallrigafjärden, SFM0043), see Figure 3-46. SMHI also independently measures the sea level in the Forsmark harbour, in the immediate vicinity of the SKB station (SFM0038/PFM010038).

Manual discharge measurements have been performed in water courses at eight locations since March 2002 /Nilsson et al. 2003; Nilsson and Borgiel, 2004/. The measurement locations are shown in Figure 3-47, and the available data from the manual discharge measurements are summarised in Table 3-17. The measurements were performed one to five times per month, except during periods when the water courses were dry or covered with ice, and when the flow was too small to allow for measurements.

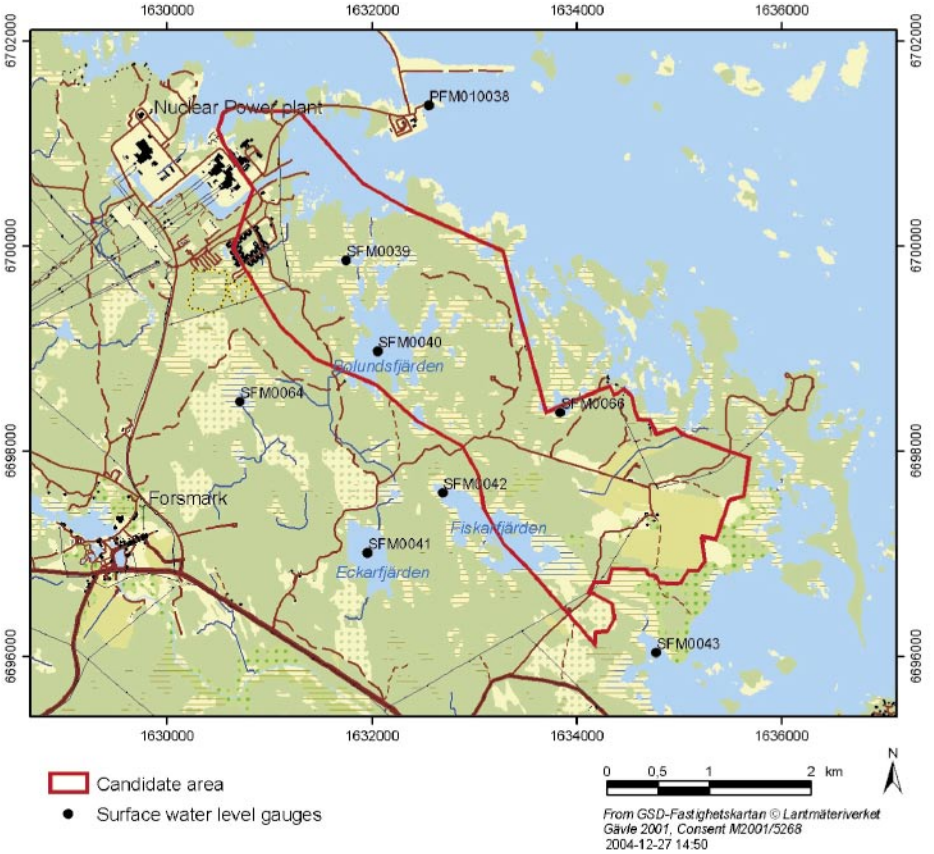

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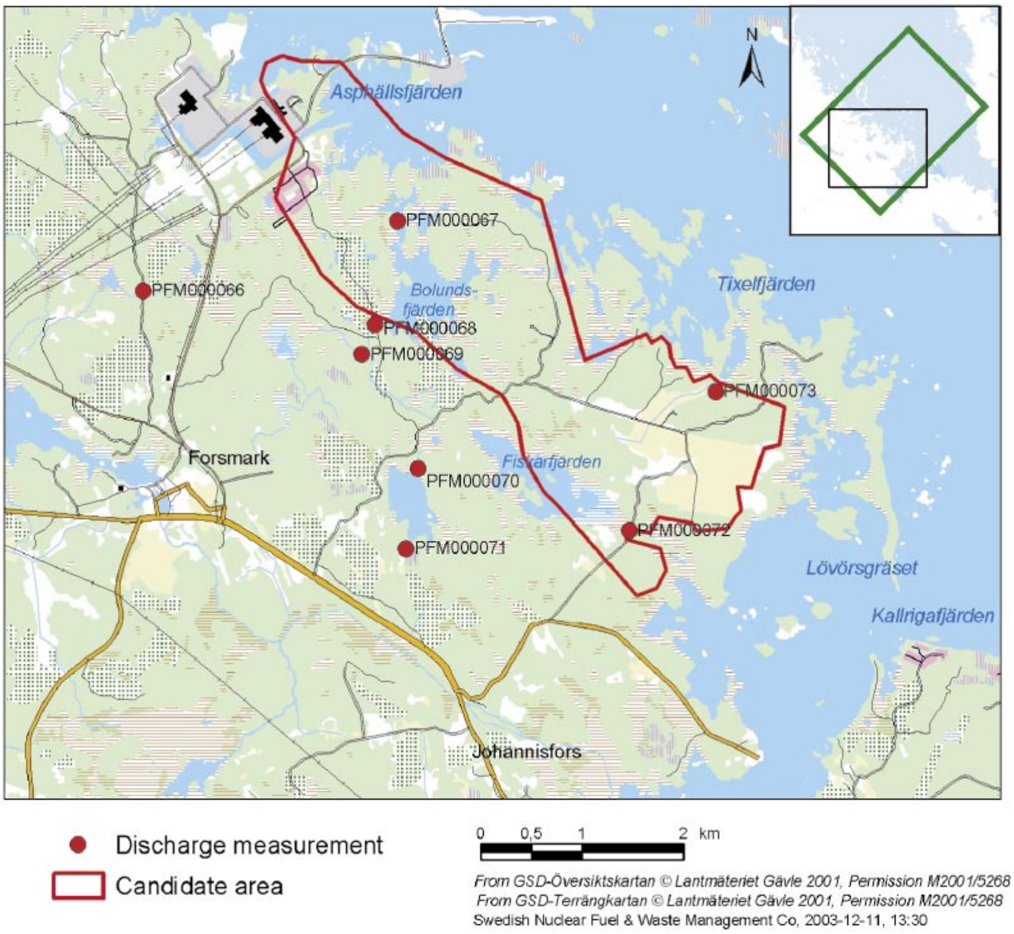
Figure 3-46. Surface water level gauges.



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Swedish Nuclear Fuel & Waste Management Co, 2003-12-11, 13:30

Figure 3-47. *Stations for manual discharge measurements.*

Table 3-17. Summary of manual discharge measurements in water courses.

Station	Location	Measurement period (YYYY-MM-DD)	Number of measurements
PFM000066	East of Gunnarsboträsket	2002-04-15 – 2004-07-06	48
PFM000067	Lillputtsundet	2002-11-26 – 2004-06-29	40
PFM000068	Kungsträsket	2002-04-15 – 2004-10-11	47
PFM000069	Bolundsskogen	2002-04-17 – 2004-10-11	52
PFM000070	North of Eckarfjärden	2002-04-02 – 2004-08-16	40
PFM000071	South of Eckarfjärden	2002-04-16 – 2004-06-29	25
PFM000072	Flottbron	2002-04-15 – 2004-06-29	23
PFM000073	South of Bredviken	2002-04-15 – 2004-06-29	31

Hydrogeological data

At the time of the F1.2 data freeze, a total of 54 groundwater monitoring wells were installed in the Quaternary deposits (QD) /Johansson, 2003; Werner and Lundholm, 2004a/. Of these wells, 12 were located in the vicinity of the core-drill sites. Seven wells were placed in till below the bottom of some of the lakes or below the Baltic Sea. Furthermore, two abstraction wells were installed to enable pumping tests /Werner et al. 2004; Werner and Lundholm, 2004b/. After installation, the groundwater monitoring wells were used for determination of the hydraulic properties of the QD and the QD/rock interface. Furthermore, the monitoring wells are used for groundwater level measurements and water sampling.

For determination of hydraulic properties and water sampling, also six BAT-type filter tips were installed /Johansson, 2004/. The locations of the groundwater level monitoring wells and abstraction wells (all referred to as just "monitoring wells"), and the BAT-type filter tips are shown in Figure 3-48. A full list of the wells and the filter tips, including also the surface water gauges, is given in /Johansson et al. 2005/.

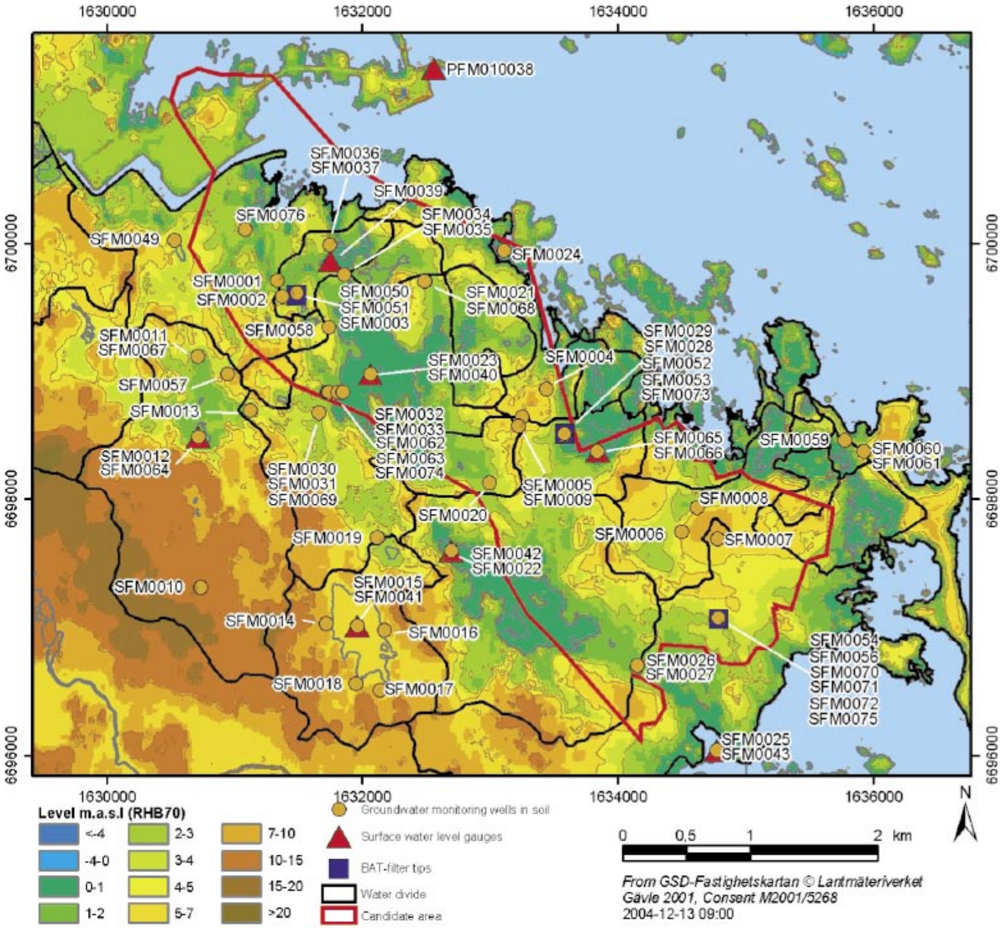

Figure 3-48. *Locations of groundwater monitoring and abstraction wells (shown as one group, referred to "monitoring wells"), BAT-type filter tips, and surface water level gauges.*

3.4.4 Conceptual and descriptive modelling

Introduction

According to the definitions given by /Rhén et al. 2003/, the conceptual model should define the framework in which the problem is to be solved, 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 parameters assigned to these domains.

The aim of the present section is to provide a conceptual and descriptive model of the surface-hydrological and near-surface hydrogeological system of the Forsmark area. The model should, based on site-specific, regional and generic data, describe this system and provide the necessary input for the quantitative model. The model of the system should include descriptions of

- boundaries,
- flow domains and their interfaces,
- infiltration and groundwater recharge,
- flow systems and discharge.

The database for the conceptual and descriptive model is mainly the data described in the preceding sub-sections (Sections 3.4.2–3). However, examples will also be given of supporting evidence from other disciplines of the site investigation. Furthermore, regional and generic data are used in the development of the model. The uncertainties related to the presented model are discussed in Section 3.4.6.

/Rhén et al. 2003/ describe SKB's systems approach to hydrogeological modelling. The division into three types of hydraulic domains (overburden /QD, rock mass, conductors in rock) constitutes the basis for the quantitative flow modelling. From a hydrogeological perspective, the geological data and related interpretations constitute the basis for the geometrical modelling of the different hydraulic domains.

A complete conceptual and descriptive model of the surface hydrology and the hydrogeology at a site involves a description of the integrated (continuous) hydrological-hydrogeological system, i.e. surface waters, groundwater in QD and groundwater in bedrock. The focus of the modelling presented here is on the surface and near-surface conditions. The hydrogeological properties of the bedrock and the bottom boundary condition used in the quantitative modelling are therefore not described in the present conceptual model and descriptive model. However, the bedrock properties and the interaction between QD and bedrock, as adopted in the quantitative modelling, are described in Section 3.4.5.

Boundaries

The conceptual and descriptive model covers the area northeast of the main water divide to the catchment area of Forsmarksån, between the nuclear power plant in the north and Kallrigafjärden in the south, see Figure 3-49. In the present modelling, it is assumed that surface water and near-surface groundwater divides coincide. The boundary towards Forsmarksån is considered as a surface water and groundwater divide, i.e. as a no-flow boundary. Also the north-western boundary is modelled as a surface water and groundwater divide. The boundary along the cooling water canal and the Baltic Sea is a flow boundary, normally an outflow boundary. However, as indicated by the water level measurements presented in Figure 3-50 the flat topography allows for sea water inflow to some of the lakes during periods of very high sea water levels.

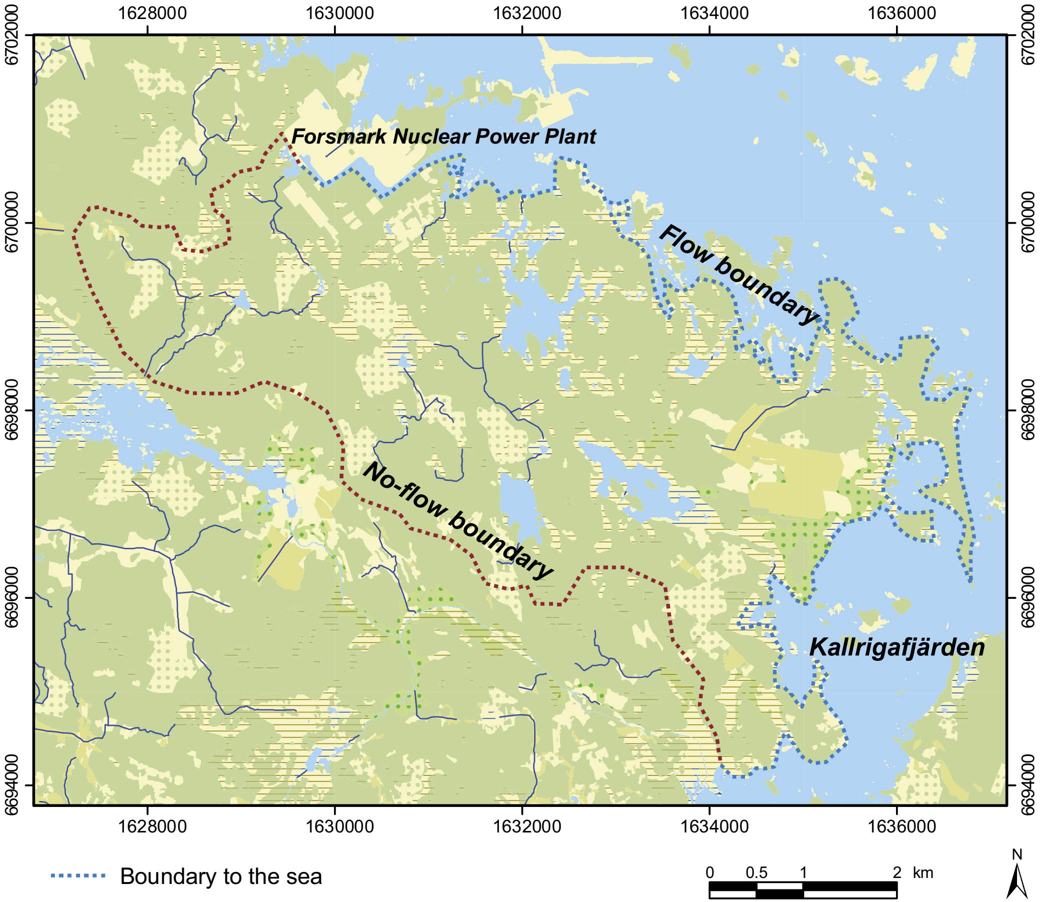

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Figure 3-49. *Area covered by the conceptual and descriptive model.*

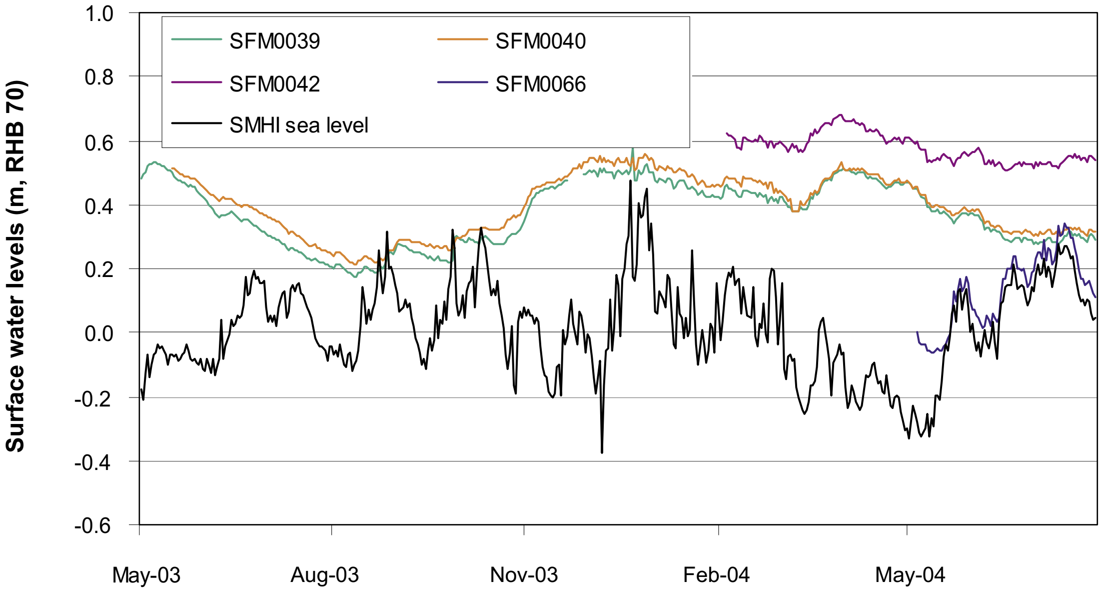

Figure 3-50. *Comparison of the water levels in the Baltic Sea, Lake Lillfjärden (SFM0066), Lake Norra Bassängen (SFM0039), Lake Bolundsfjärden (SFM0040), and Lake Fiskarfjärden (SFM0042).*

In general, the groundwater levels in the groundwater monitoring wells show very weak correlations to the sea water level, whereas the correlation to the cumulative difference between precipitation and potential evapotranspiration (P-PET) is strong for most wells (Figure 3-51). Only the wells SFM0024 and SFM0025, located below open water directly influenced by the sea water level show strong correlations to the sea water level. In addition, SFM0059 and SFM0061 at the Börstilåsen esker, which are not shown in the figure (since time series are too short), are correlated to the sea level. From existing time series it is evident that the sea water level is sometimes higher than the groundwater levels measured in these wells, which implies that sea water intrusion may take place during these periods.

Flow domains and their interfaces

With reference to the three types of hydraulic domains in the SKB systems approach to hydrogeological modelling, cf above, the focus of the description below is on surface water and near-surface groundwater in the QD (HSD) and their interfaces to the two types of bedrock domains (HCD and (HRD).

Catchments and lakes

The area is characterized by a low relief with a small-scale topography. Almost the whole area covered by the conceptual model is below 20 m a s l (metres above sea level). In total, 25 "lake-centered" catchments and sub-catchments have been delineated, ranging in size from 0.03 to 8.67 km^2 (Figure 3-52). Detailed data on the catchments are presented by /Brunberg et al. 2004/, see also summary in /Johansson et al. 2005/.

The 25 mapped lakes range in size from 0.006 km^2 (lake in sub-catchment 7:3) to 0.752 km^2 (Lake Fiskarfjärden). The major lakes besides Lake Fiskarfjärden are Lake Bolundsfjärden (0.609 km^2), Lake Eckarfjärden (0.282 km^2) and Lake Gällsboträsket (0.185 km^2). The lakes are shallow with mean depths and maximum depths ranging from approximately 0.1 to 1 m and 0.4 to 2 m, respectively. The lakes are described in /Brunberg et al. 2004/.

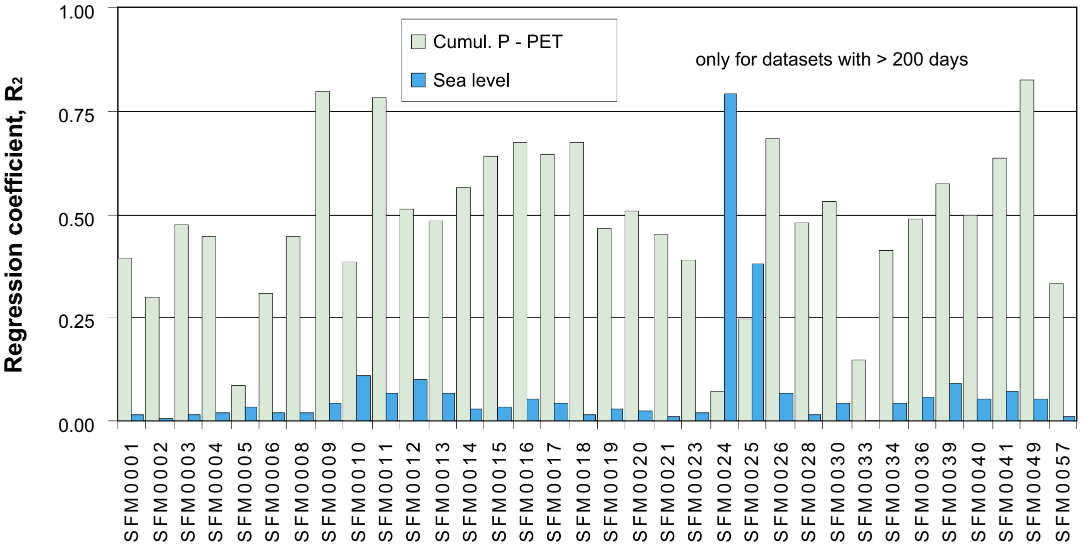

Figure 3-51. *Correlation coefficients for groundwater level data to sea level data and cumulative difference between precipitation and potential evapotranspiration (P-PET) /Johansson et al. 2005/.*

Water courses

No major water courses flow through the area considered in the descriptive modelling. The most important brooks are those dewatering the catchments Forsmark 1 and 2, i.e. sub-catchments 1:1–1:4 and 2:1–2:11, respectively, in Figure 3-52. The water courses downstream Lake Gunnarsboträsket in catchment Forsmark 1 and downstream Lake Eckarfjärden and Lake Gällsboträsket in catchment Forsmark 2 carry water most of the year, but still they can be dry for long time periods during dry years such as 2003 (see Figure 3-53 as an example).

In the F1.2 data freeze only manual discharge measurements were available, but four stations for automatic, continuous discharge measurements have now been established. Many of the brooks in the area have been deepened over considerable distances for drainage purposes. However, still the riparian zone is wide at many locations and relatively large areas are inundated during periods of high water levels. A detailed survey of slopes and cross-sections along the major brooks has been initiated; parts of this survey are reported in the F1.2 data freeze /Johansson et al. 2005/.

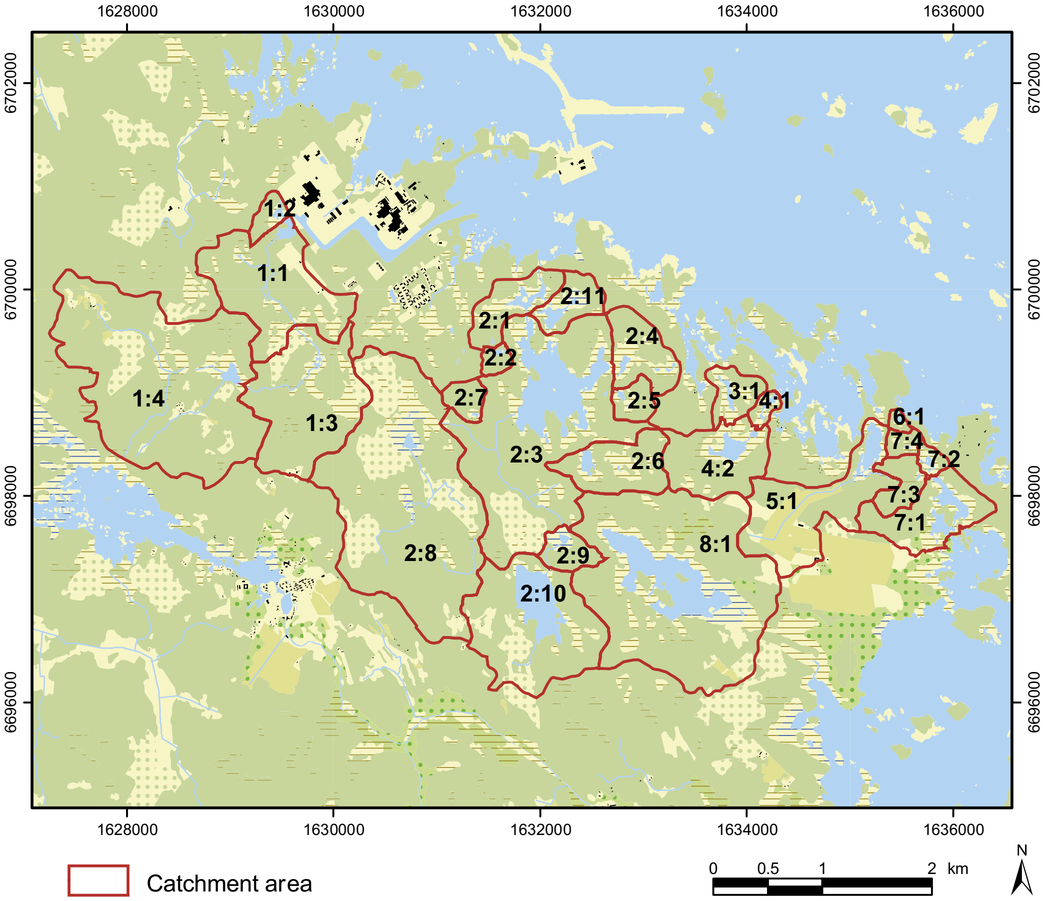

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Figure 3-52. *Delineated catchment areas /Brunberg et al. 2004/.*

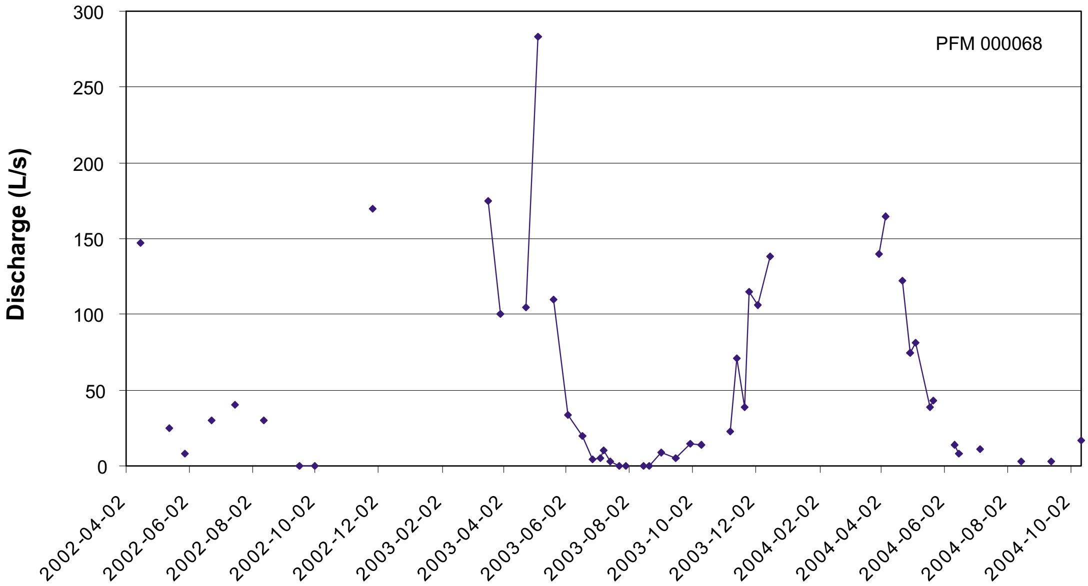

***Figure 3-53.** Discharge from manual measurements in the brook dewatering the catchment upstream of Lake Bolundsfjärden (station no PFM000068).*

Wetlands

Wetlands are frequent and cover 10%, 12% and 17% of the major catchments Forsmark 1, 2 and 8, respectively. In some of the sub-catchments, wetlands cover between 25% and 35% of the area. The distribution of wetlands according to the vegetation map is shown in Figure 3-54.

From a hydrological point of view it is useful to distinguish between bogs, fens and marshes /Kellner, 2003/. Bogs are peat covered areas where the vegetation is supplied with water from precipitation only (ombrotrophic). Bogs only exist in the most elevated parts of the area. These bogs are small and the peat cover is not very thick (< 3 m) /Fredriksson, 2004/. Fens are peat-covered areas where the vegetation at least partly is supplied by inflowing surface water and/or groundwater. Marshes are wetlands with little or no peat. Fens and marshes are frequent in the more low-lying parts of the area.

No comprehensive investigation of the stratigraphy or hydrology of the wetlands has been performed so far. The two fens studied in detail by /Fredriksson, 2004/ were both located in the western most elevated part of the area. These fens were about one metre deep. From existing borings /Johansson, 2003; Werner and Lundholm, 2004a/ it is known that the peat in the wetlands can rest directly on till or be underlain by gyttja and/or clay above the till. This means that the hydraulic contact with the surrounding groundwater system varies.

Quaternary deposits

A map of the Quaternary deposits (QD) in Forsmark is presented in Section 3.3. This detailed map, compiled within the site investigation, is produced to be presented in the scale 1:10,000. It does not completely cover the area considered in the present modelling; a part in the north-west is excluded. For the parts not covered by the detailed mapping, the existing map in 1:50,000 scale from SGU (Geological Survey of Sweden) /Persson, 1985, 1986/ must be used.

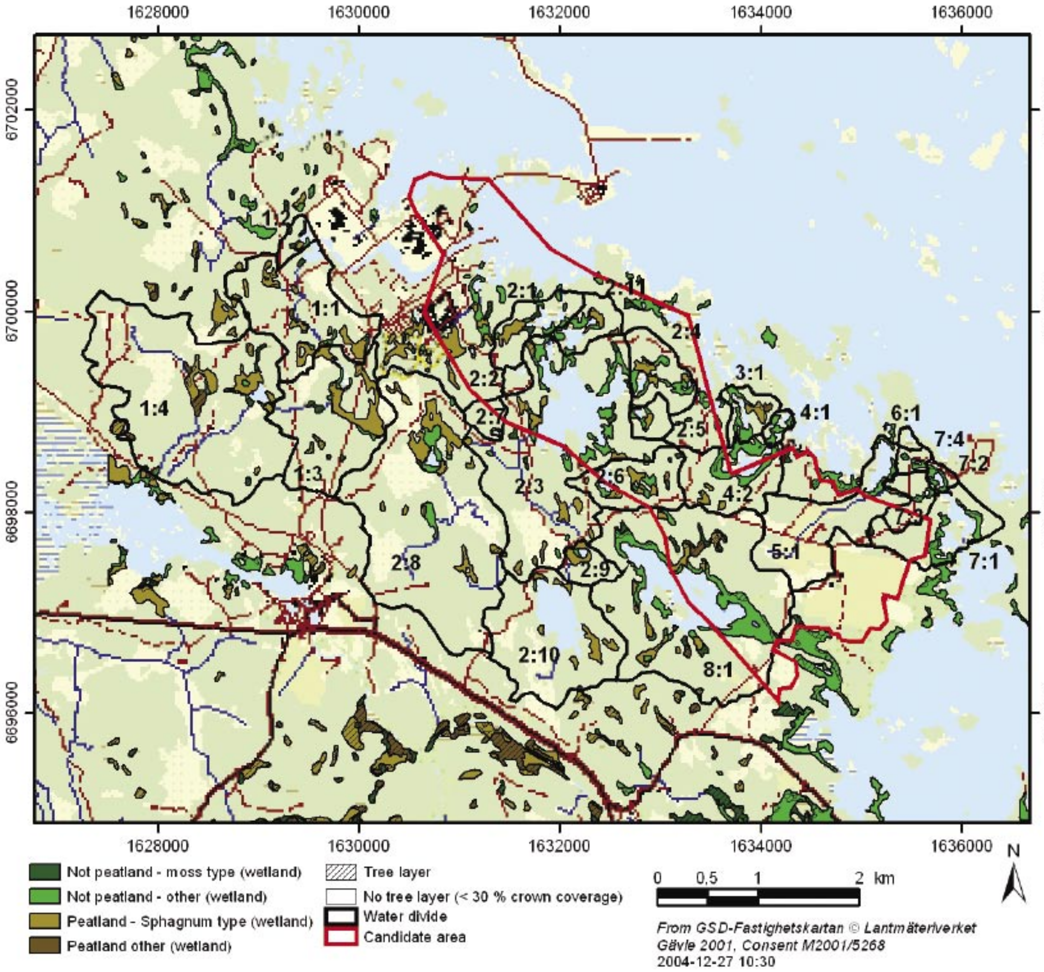

Figure 3-54. *Wetlands of different types within the Forsmark area based on the vegetation map /Boresjö Bronge and Wester, 2003/.*

The geological map shows that till is the dominating QD, covering approximately 75% of the mapped area. Bedrock outcrops are frequent, but cover only approximately 5% of the area. Wave-washed sand and gravel, clay, gyttja clay and peat cover 3–4% each. The only glaciofluvial deposit, the Börstilåsen esker, runs in a north-south direction along the coast (the "green belt" on the map). In general, the QD are shallow, usually less than 5 m deep. The greatest depth to bedrock, recorded in a drilling south-east of Lake Fiskarfjärden, is 16 m.

Three areas with different types of till have been distinguished /SKB, 2004a; Sohlenius et al. 2004/. In the western and northern parts, sandy till is dominating, whereas clayey till dominates at Storskäret and east of Lake Fiskarfjärden. In the easternmost part of the area, close to the Börstilåsen esker, the till has a high frequency of large boulders. In general, the till deposits seem to be deeper in the south-east, in areas covered by clayey till. A preliminary, spatially distributed model of the depth of the QD has been developed for the area included in the quantitative flow modelling, based on drillings and geophysical investigations /Vikström, 2005/, see Section 3.4.5. The median calculated QD depth, subareas with outcropping bedrock excluded, is 1.9 m.

The hydraulic properties of the till are mainly determined by the grain size distribution, the compactness, and structures such as lenses of sorted material. The hydraulic conductivity values from the slug tests in till are summarised in Figure 3-55; a detailed presentation is given by /Johansson et al. 2005/. The measured hydraulic conductivities varied between 5.6×10^{-8} and 7.0×10^{-4} $m\times s^{-1}$. The geometric mean was calculated to 6.0×10^{-6} $m\times s^{-1}$ (arithmetic mean 6.0×10^{-5} $m\times s^{-1}$, median 6.7×10^{-6} $m\times s^{-1}$), and the standard deviation of log K (base: 10) was 1.07. Assuming a log-normal distribution, the 95% confidence interval for the mean was 3.0×10^{-6}–1.2×10^{-5} $m\times s^{-1}$ and the 95% confidence interval for a new observation was 4.9×10^{-8}–7.4×10^{-4} $m\times s^{-1}$.

In the upper approximately one metre of the QD, the saturated hydraulic conductivity and effective porosity are much higher than further down in the profile /Lundin, 1982; Johansson, 1986, 1987a,b; Espeby, 1989; Lind and Lundin, 1990/. This is mainly due to soil forming processes, probably with ground frost as the single most important process, resulting in higher porosity and macro-pores. However, wave washing also implies that the till at exposed locations is coarser at the ground surface, and at some location coarse out-washed material has been deposited.

Based on generic data, the saturated hydraulic conductivity in the upper one metre can be estimated to 10^{-5}–10^{-4} $m\times s^{-1}$ and the effective porosity to between 10% and 20%, with the higher values close to the surface (effective porosity is here used as a common term for specific yield and kinematic porosity). The total porosity can typically be estimated to 30–40%, mainly depending on depth. Only very few site specific data exist for the hydraulic conductivity of the uppermost part of the QD profile. This implies that the quantitative modelling of unsaturated and saturated flow in the uppermost part of the profile in F1.2 must rely mainly on generic data. Some additional site specific data on hydraulic conductivities and water retention properties will be available for the next model version.

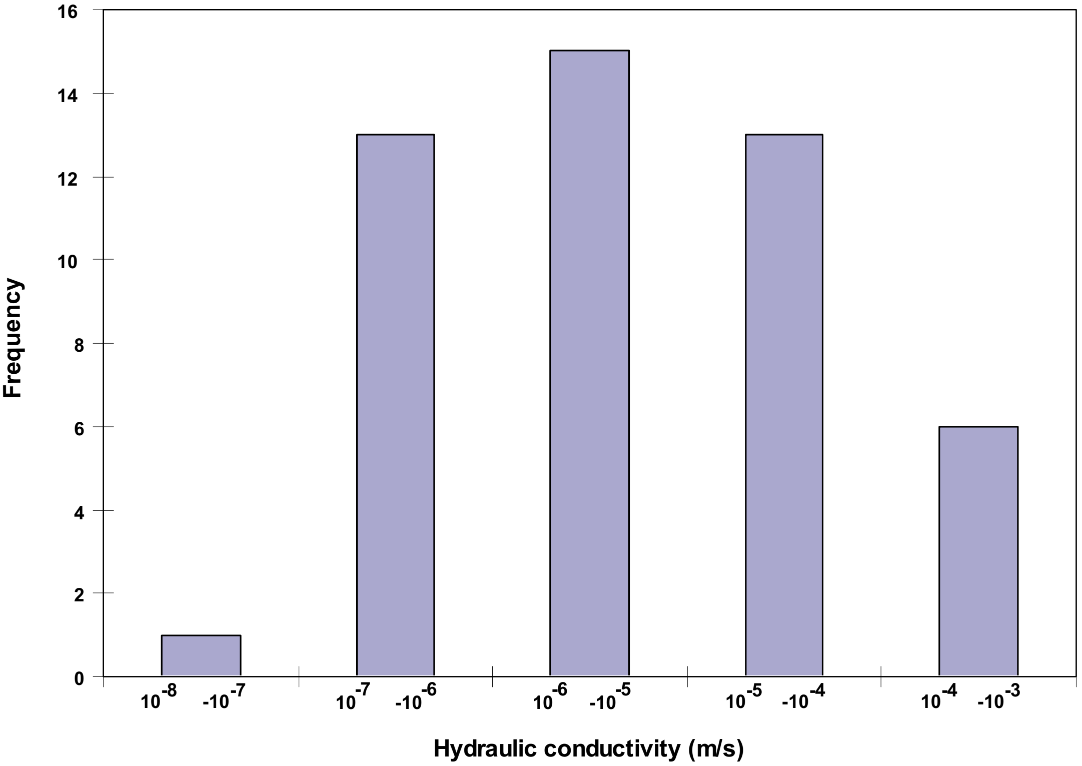

Figure 3-55. *Histogram for the hydraulic conductivities of the QD obtained from slug tests in 48 groundwater monitoring wells /Werner and Johansson, 2003; Werner, 2004/.*

Below the depth interval strongly influenced by the soil forming processes, the hydraulic conductivities and the porosities of the till are considerably lower. The results from the slug tests indicate a higher hydraulic conductivity in the QD/rock contact zone than in the till itself, with geometric mean values of 1.3×10^{-5} and 7.2×10^{-7} $\text{m}\times\text{s}^{-1}$, respectively (Figure 3-56).

Comparing the hydraulic conductivity values from slug-tests to the values calculated from grain-size distributions, the slug-test values are considerably higher in the QD/rock contact zone (from less than one order of magnitude for coarse till up to 3 orders of magnitude for fine-grained tills), whereas they are almost the same for tests in the till itself. Also, if a division is made into coarse till (sandy, gravelly) and fine-grained till (clayey, silty) of the slug tests in the QD/rock contact zone, the geometric means of the conductivities are almost the same. These results indicate that the relatively high values in the contact zone between QD and rock are mainly caused by the bedrock properties. However, in the zone between the upper one metre and the QD/rock contact zone, it is motivated to make a distinction between the coarse till and the fine-grained till.

The old very compact till found at the bottom of the profile at some locations in the area, cf /Sundh et al. 2004/, most probably has a very low hydraulic conductivity. However, since this material so far has been found only at a few locations, it is suggested not to include it as a separate unit in the quantitative modelling in version 1.2. According to generic data, the total and effective porosities in the till below the upper one metre typically can be estimated to 20–30% and 2–5%, respectively.

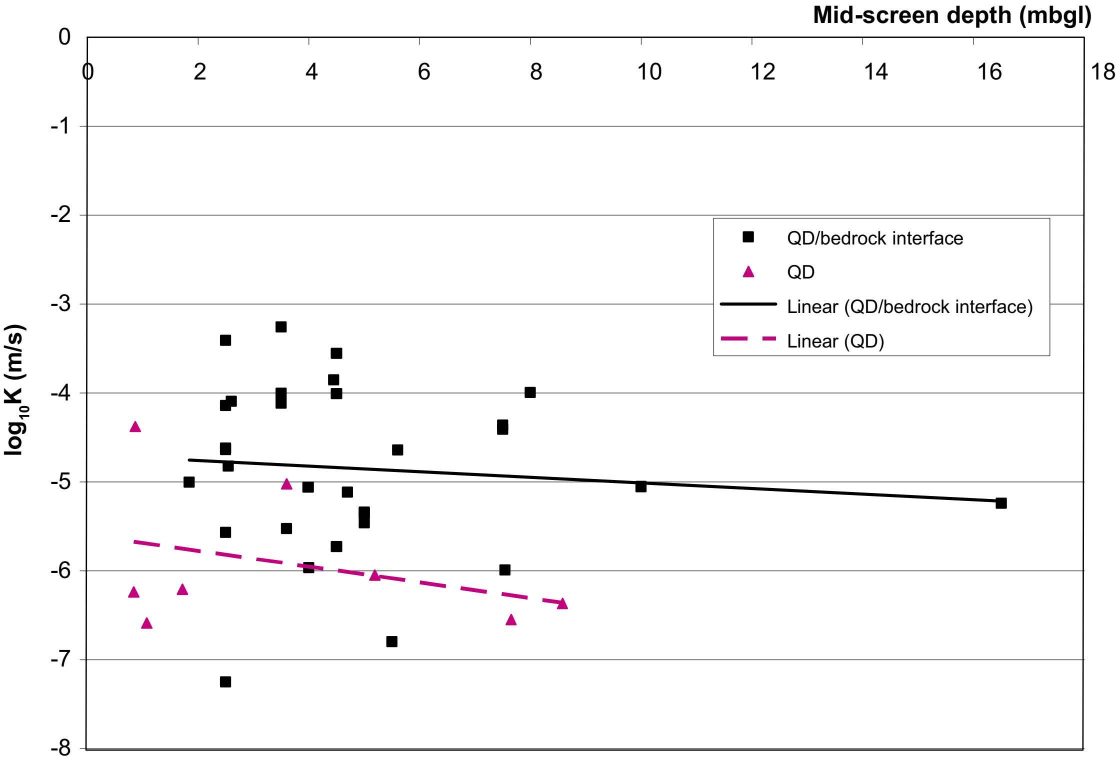

Figure 3-56. Hydraulic conductivities (logarithmic scale) of the QD, obtained from slug tests in wells installed on land (i.e. wells installed below open water are not included). The data are plotted as a function of depth (m b g l; metres below ground level). Squares are data for wells with the screen at the QD/rock interface, whereas the triangles are data for wells with the screen in QD only. The lines are linear fits to the measured data.

All site specific hydraulic conductivity data are from tests measuring the horizontal conductivity. The primary sedimentary structures of till have been shown to influence the hydraulic conductivity /Lind and Lundin, 1990; Lind et al. 1994/. The consistency of these structures depends on the genesis of the till; the consistency is higher in lodgement till than in meltout till and flow till. No systematic classification of the till genesis has been conducted so far. For the present model version it is recommended that sensitivity analysis is used to investigate the influence of anisotropy in the hydraulic conductivity. Generic data indicate that the hydraulic conductivity can vary with more than one order of magnitude in different directions /Lind et al. 1994/.

Based on the presented site-specific and generic data the mean values of saturated hydraulic conductivity, porosity and effective porosity shown in Table 3-18 are proposed for a simplified three-layer model of a till profile (including the QD/rock contact zone), as a starting point for the quantitative modelling. The hydraulic conductivities obtained from the slug tests show a high variance (see Figure 3-55), and the values should be considered as type values. A schematic profile illustrating the conceptual and descriptive model is shown in Figure 3-57.

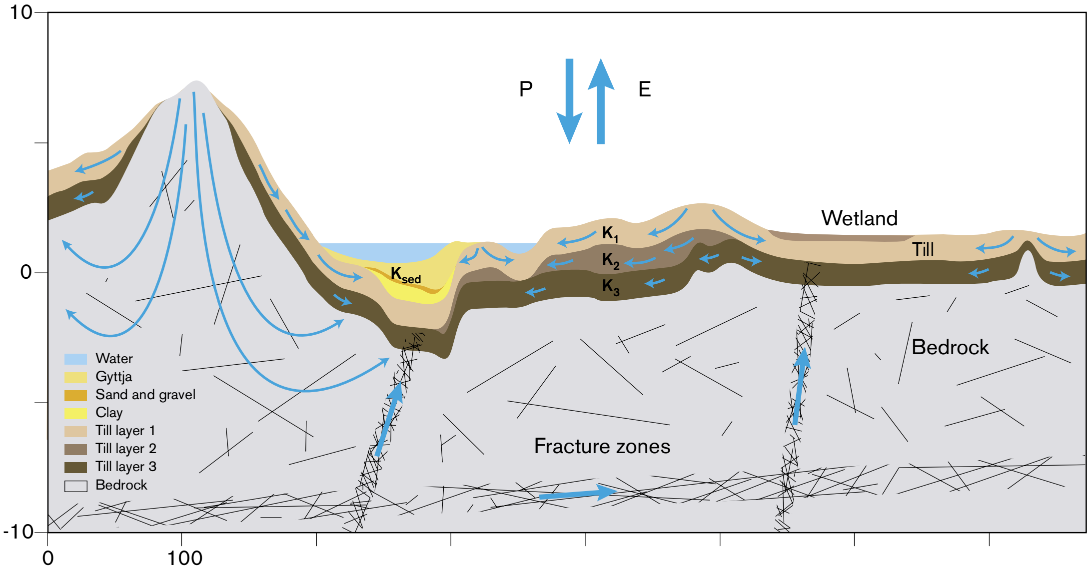

Figure 3-57. *Schematic profile illustrating the conceptual and descriptive model.*

Table 3-18. Proposed mean values of horizontal saturated hydraulic conductivity, total porosity and effective porosity for a simplified three-layer till profile.

Layer	Horizontal saturated hydraulic conductivity (ms^{-1})	Total porosity (%)	Effective porosity (%)
0 to1 m below ground	1.5×10^{-5}	35	15
Middle layer			
Coarse till	1.5×10^{-6}	25	5
Fine-grained till	1.5×10^{-7}	25	3
0 to 1 m above the bedrock	1.5×10^{-5}	25	5

For the only glaciofluvial deposit in the area, the Börstilåsen esker, the hydraulic conductivity of 2×10^{-4} m×s^{-1} that was obtained in a pumping test can be regarded as relatively low. The storativity of 2×10^{-3} indicates mainly confined conditions. In a simplified model, consistent with the present knowledge of the site, the small areas with shallow deposits of wave washed sand can be given the same hydraulic properties as the superficial till.

Since no site-specific hydraulic data exist for clay, gyttja and peat, the quantitative flow modelling must rely on generic data on these materials, see Section 3.4.5. The existence and hydraulic conductivity of clay and gyttja below wetlands and lakes are important factors for the surface water-groundwater interaction. The stratigraphy of lake bottom sediments has been investigated and representative profiles have been constructed for some of the lakes /Hedenström, 2003, 2004; Vikström, 2005/. Typically, the sediment stratigraphy from down and up is glacial and/or postglacial clay, sand and gravel, and nested layers of gyttja in different fractions. The clay layer is missing in major parts of the area below Lake Bolundsfjärden. However, a pumping test in the vicinity of this lake indicated a very limited hydraulic contact between the lake and the groundwater in the till below the lake /Johansson et al. 2005/.

Infiltration and groundwater recharge

During the one-year period for which local measurements exist, August 1, 2003–July 31, 2004, the corrected precipitation in Forsmark was 630 mm (Figure 3-58). The short period for which overlapping time series were available indicated that the precipitation in the model area is 5–10% higher than at the SMHI station Örskär (Figure 3-59). The annual average corrected precipitation at Örskär is 588 mm, which indicates that the value for the one-year period of 630 mm at Forsmark is close to the average annual precipitation.

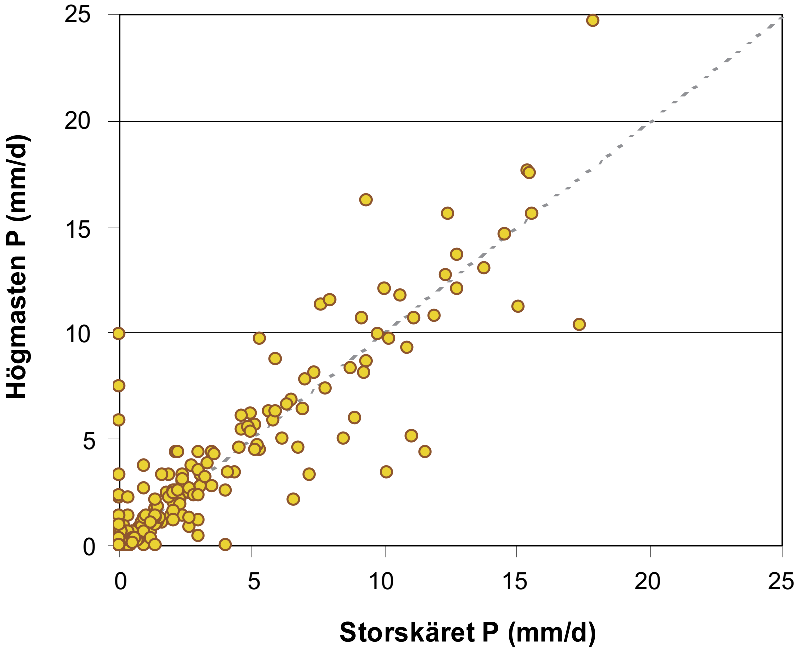

Figure 3-58. *Monthly values for corrected precipitation at Storskäret and Högmasten, and potential evapotranspiration at Högmasten.*

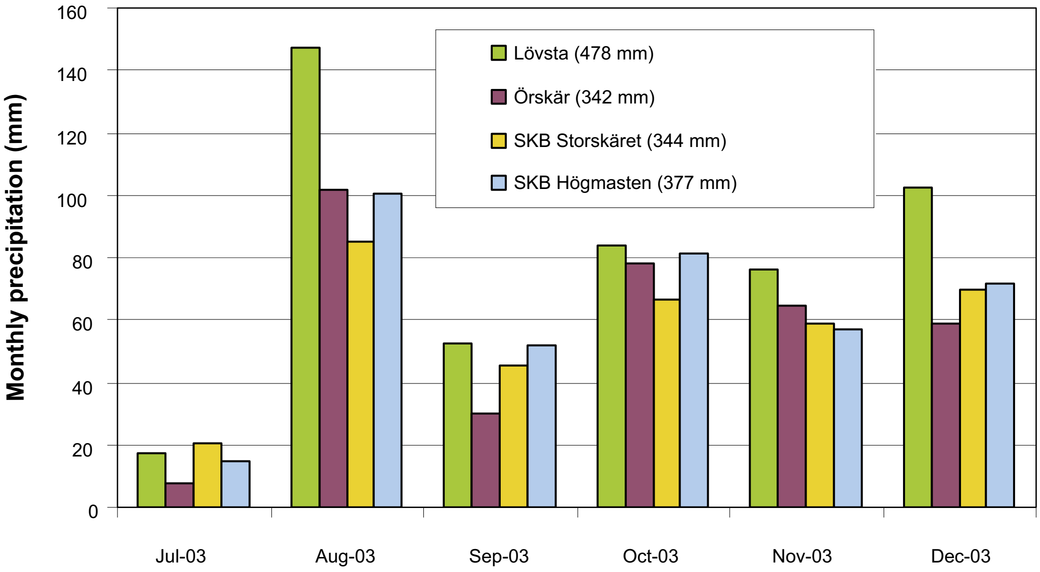

***Figure 3-59.** Comparison of precipitation data from Storskäret and Högmasten with regional SMHI data from Lövsta and Örskär.*

The total "potential evapotranspiration" for a short crop, calculated by the Penman equation, was 472 mm. According to simulations with the CoupModel, using the Penman-Monteith equations, the actual evapotranspiration for the same one-year period was slightly more than 400 mm for a mature coniferous forest in fresh to dry areas, and much smaller, approximately 330 mm, in wet areas /Gustafsson et al. 2005/. The lower values for the wet areas are caused by the limited transpiration taking place when the groundwater level is very close to the ground surface.

In the calculations referred to above, the same root depth was assigned under dry, fresh and wet conditions. If an adaptation of the root depth in wet areas had been made, the difference in transpiration between dry and wet areas probably would have been smaller. The evaporation directly from interception was approximately 130 mm. Typically, the total annual actual evapotranspiration does not differ very much for a forest and an agricultural crop, but the seasonal patterns differ /Gustafsson et al. 2005/. Due to higher interception evaporation, the evapotranspiration is higher in the forest during the cold parts of the year.

In forested areas, constituting approximately 75% of the area covered by the conceptual model, the interception value presented above indicates that approximately 500 mm was available for infiltration. The infiltration capacity exceeds rainfall and snowmelt intensity with few exceptions. Unsaturated (Hortonian) overland flow may appear over short distances mainly on agricultural land covered with clayey till, and on frozen ground where the soil water content is high during freezing. Also on outcropping bedrock unsaturated overland flow may appear, but just over very short distances before the water reaches open fractures or the contact zone between bedrock and QD. In a simplified model, unsaturated overland flow can be assumed to be negligible.

The measured groundwater levels in the area are very shallow, see Figure 3-60. The time series presented show that in most monitoring wells the groundwater level was within one metre below the ground surface all the year, and that on average the groundwater level was less than 0.5 m below ground during 50% of the time. A reservation has to be made regarding the representativity of the monitoring well locations; possibly, topographically low-lying areas are over-represented. However, also in what can be considered as typical recharge areas the average groundwater level is not more than approximately one metre

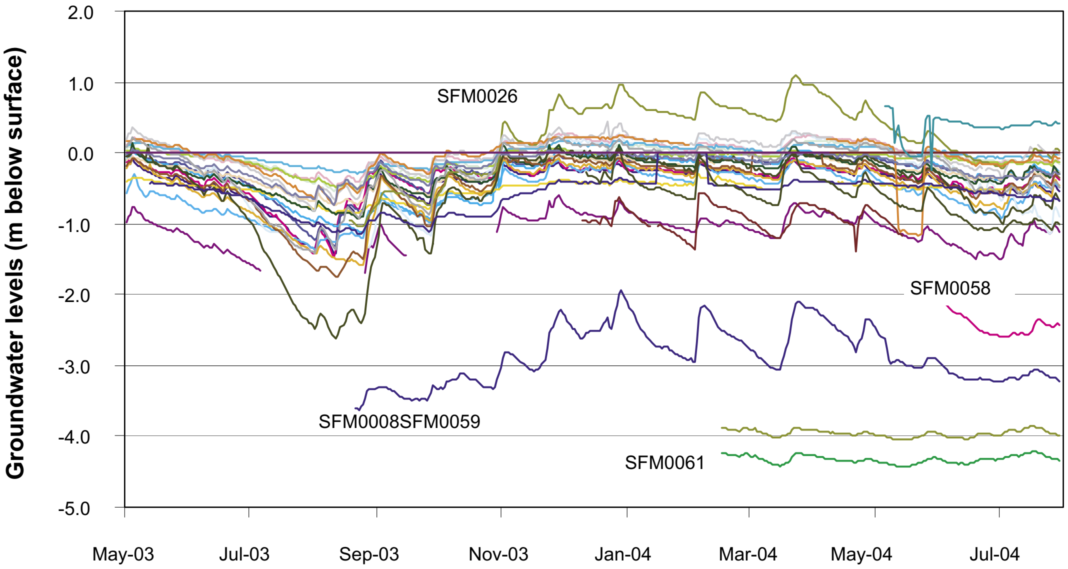

Figure 3-60. *Daily average depth below ground surface for groundwater monitoring wells in QD, excluding wells below water.*

below ground. Only in locally elevated areas with relative steep slopes, considerably deeper groundwater levels can be assumed to exist, see, e.g. SFM0008 in Figure 3-60. The annual groundwater level variations are often less than 0.5 m in low-lying areas and approximately 1 m in typical recharge areas.

The shallow groundwater levels mean that there will be a strong interaction between evapotranspiration, soil moisture and groundwater. This implies that a clear definition of groundwater recharge is required. The common definition is “the process by which water is added to the zone of saturation”. In the present case, however, with very shallow groundwater, there is a large difference between gross and net recharge.

The diurnal groundwater level fluctuations shown in Figure 3-61 clearly illustrate the influence of evapotranspiration on the groundwater zone during dry periods. Of course, this influence is most accentuated in locations with very shallow groundwater, but it is also evident in areas where the groundwater table is at more than two meters depth /Johansson et al. 2005/. The calculated annual evapotranspiration value of slightly more than 400 mm for a forested dry area (typically a recharge area) presented above indicates that the net annual groundwater recharge is approximately 225 mm in such an area.

Direct groundwater recharge from precipitation is the dominant source of groundwater recharge. However, the groundwater level measurements in the vicinity of Lake Bolundsfjärden and Lake Eckarfjärden show that the lakes may act as recharge sources to the till aquifers in the immediate vicinity to the lakes during summer (see Figure 3-62 for Lake Bolundsfjärden; results for other lakes are presented by /Johansson et al. 2005/).

The gradients from the lakes to the surrounding areas are created by direct and indirect groundwater abstraction by evapotranspiration. Due to the low permeability of the bottom sediments the resulting water fluxes can be assumed to be small. Also the Baltic Sea can potentially act as a source of groundwater recharge, especially during periods of high sea water levels. As discussed above, however, there is only very little evidence of correlations between the sea water level and the groundwater levels on land (see Figure 3-51). The influence of this recharge can be assumed to be restricted to areas below the sea and areas in the immediate vicinity of the coast line.

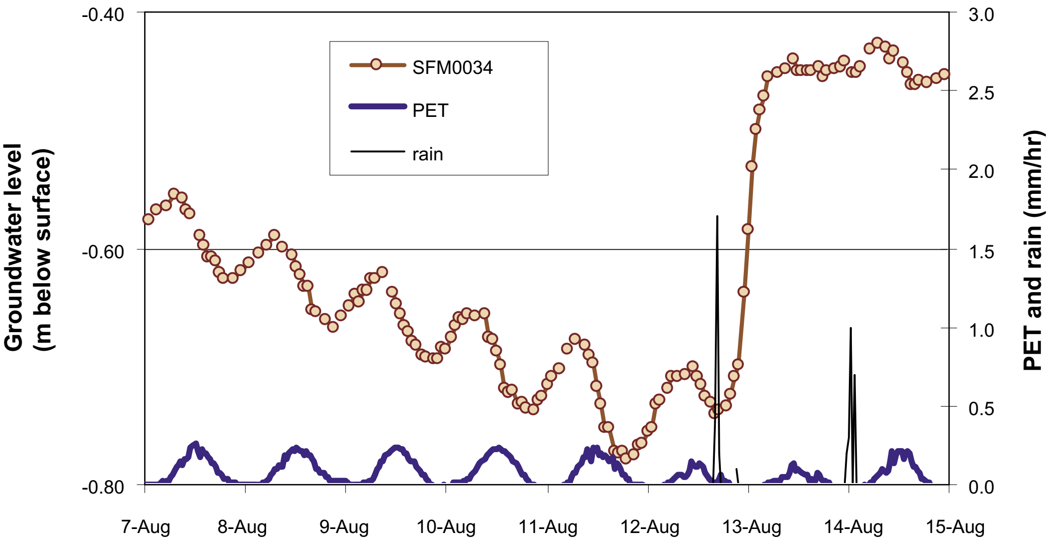

***Figure 3-61.** Diurnal fluctuations in the groundwater level in a typical location with shallow groundwater.*

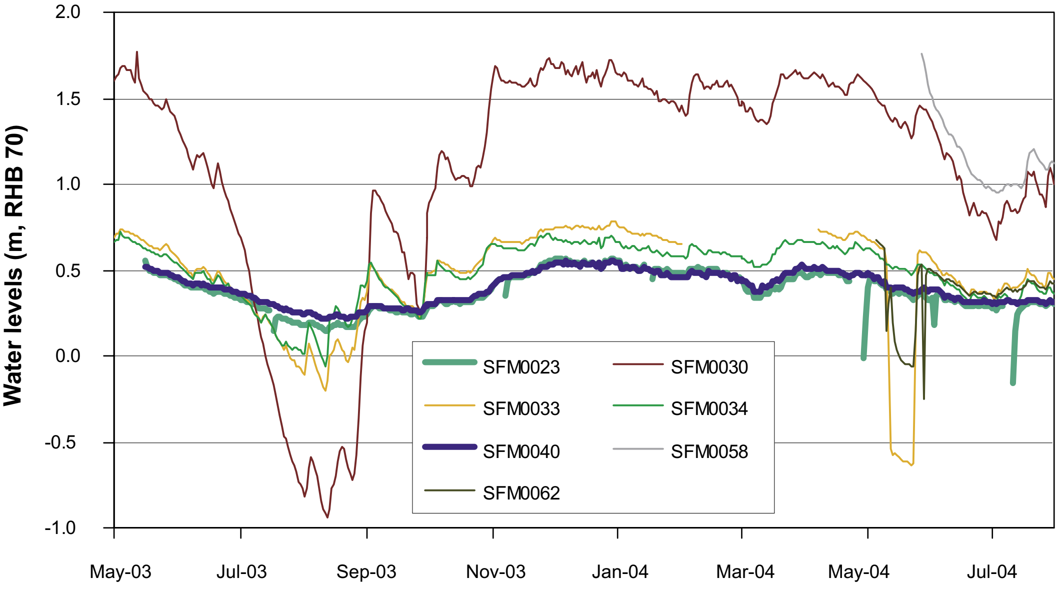

***Figure 3-62.** Lake water level (SFM0040) and groundwater levels near and below Lake Bolundsfjärden (SFM0023 measures the groundwater level below the lake). The disturbances in some wells in May–July, 2004, are caused by a pumping test and water sampling activities.*

Flow systems and discharge

Similar to the external boundaries of the model area, the internal surface water and near-surface groundwater divides are assumed to coincide. The small-scale topography implies that many small catchments will be formed with local, shallow groundwater flow systems in the QD. With reference to the hydraulic conductivity profile of the tills dominating in the area, it is evident that a dominating part of the groundwater will move along very shallow flow paths. These local, small-scale recharge and discharge areas will overlay the more large-scale flow systems associated with groundwater flow at greater depths.

Interesting observations can be made in groundwater level time series from nearby wells in till and bedrock, as illustrated in Figure 3-63. Specifically, the groundwater level in the till seems to be considerably higher than that in rock, both relative to the ground surface and in terms of absolute levels. Relative to the ground surface, the difference is 1.5–2 m. This difference exists even though the screens of the wells in till are installed at the QD/rock interface. The difference between the levels in till and bedrock is much larger than between different sections in the bedrock boreholes sealed off by packers. However, the groundwater levels in the bedrock boreholes are still above the QD/rock interface, indicating that no unsaturated zone exists below the interface.

It can also be noted in Figure 3-63 that a correlation is evident between the groundwater levels in the till and the bedrock. The natural groundwater level fluctuations are, however, much smaller in the bedrock. The prevailing conditions show that the groundwater flow has a downward component at the sites studied, i.e. there is an inflow from the till into the bedrock, although probably small. The measured difference in levels does not agree with the concept of a good hydraulic contact between QD and rock in a zone of relatively high hydraulic conductivity. A possible explanation for the low levels in the bedrock boreholes is that these intersect one/some of the highly conductive horizontal to sub-horizontal zones shown to exist in the shallow bedrock in the Forsmark area /SKB, 2005a – F1.2 SDM/.

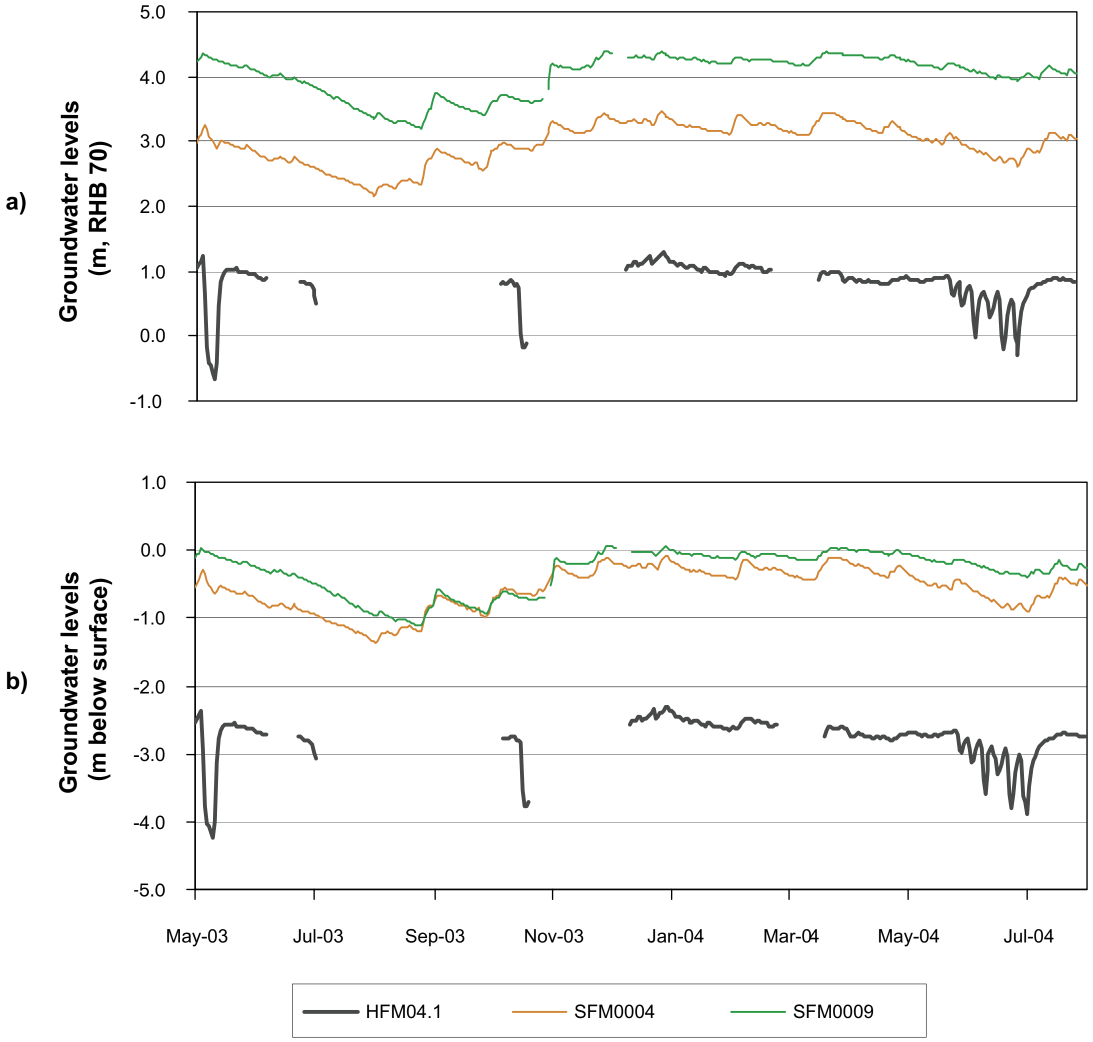

***Figure 3-63.** Groundwater elevations and depths below ground surface for groundwater monitoring wells in QD (SFM) and percussion wells in bedrock (HFM) at Core-drill site 2.*

The permeability and storage characteristics of the materials in the till profile mean that only very little water needs to be added to raise the groundwater table below approximately one metres depth. A groundwater recharge of 10 mm will give a 20 to 50 cm increase in groundwater level. During periods of abundant groundwater recharge, the groundwater level, also in most recharge areas, reaches the uppermost part of the profile where the hydraulic conductivity is much higher than at some depth in the QD. In these situations, a significant lateral groundwater flow will take place. However, the transmissivity of this upper layer is so high that the groundwater level does not reach much closer to the ground surface than 0.5–1 m in typical recharge areas.

In discharge areas, defined as areas where the groundwater flow has an upward component, by definition no groundwater recharge takes place. However, not all discharge areas are saturated up to the ground surface, but water flows in the uppermost most permeable part of the QD profile. In unsaturated discharge areas, the soil water deficit is usually very small and in these areas water levels respond quickly to rainfall and snowmelt and contribute to runoff generation. So-called saturated overland flow appears in discharge areas where the groundwater level reaches the ground level.

In the F1.1 model, the lakes were assumed to be important permanent discharge areas. New data indicate that the situation can be more complicated. The groundwater level time series from Lake Bolundsfjärden and Lake Eckarfjärden discussed above (see Figure 3-62) show flow gradients from the lakes to the riparian zones during parts of the summer.

The hydraulic contact between the lakes and the groundwater zone is highly dependent on the hydraulic conductivity of the bottom sediments. Borings in the lake sediments show relatively thick sediments of gyttja and thin layers of clay at most locations. In Lake Bolundsfjärden, the clay layer appears to be missing under large parts of the lake. However, the groundwater level time series in the vicinity of both Lake Eckarfjärden and Lake Bolundsfjärden, as well as the pumping test near Lake Bolundsfjärden /Johansson et al. 2005/, indicate low-permeable bottom sediments.

The brooks are considered to be permanent discharge areas, although dry during parts of the year. The wetlands can either be in direct contact with the groundwater zone and constitute typical discharge areas or be separate hydrological systems with tight bottom having little or no hydraulic contact with the groundwater zone. Information should be gathered to clarify the hydraulic contact between major wetlands and groundwater. The flat terrain within the model area and the associated relatively small hydraulic gradients mean that the spatial extents of recharge and discharge areas may vary during the year. The time dependence of the recharge and discharge pattern is further discussed in Section 3.4.5.

Hydrochemical data for interpretation of flow systems

By use of oxygen-18 as a tracer, information can be obtained on the runoff generation process as well on groundwater reservoir volumes /Lindström and Rodhe, 1986; Johansson, 1987b; Rodhe, 1987/. In particular, /Rodhe, 1987/ studied the runoff generation process by oxygen-18 in several small Swedish catchment areas. The results showed that also in peak runoff events groundwater (pre-event water) often constitutes the dominating fraction of the discharge. The infiltrating water pushes the “old” water downstream to form the peak runoff.

Also in areas with relatively thin QD, like the Forsmark area, the total reservoir volume in the till is larger than the annual groundwater recharge. The water stored in a 3 m thick saturated till profile corresponds to 3–4 years of groundwater recharge. In traditional hydrological linear reservoir modeling, the active storage used is usually much smaller than the total storage. However, in hydrochemical and contaminant transport modelling also the total storage is of major interest.

Several other hydrochemical parameters, e.g. parameters derived from hydrogen and chloride isotope concentrations, are often used to characterise hydrogeological conditions. Such parameters are also included in SKB's programme for sampling and analyses of surface water and near-surface groundwater, but the results available in the F1.2 data freeze were limited.

A first attempt on coupled hydrochemical and hydrogeological modelling of shallow groundwater has been performed as a part of the hydrogeochemical modelling /SKB, 2005b/. The data presented and discussed below are from this report. In Figure 3-64, Piper diagrams for water samples from groundwater monitoring wells in QD and from percussion drilled boreholes in the bedrock are shown. From Figure 3-64 it is evident that both Ca-HCO$_3$ and Na-HCO$_3$,Cl type waters are represented among the samples from the groundwater monitoring wells in QD, whereas all the bedrock samples are of the Na-HCO$_3$,Cl water type.

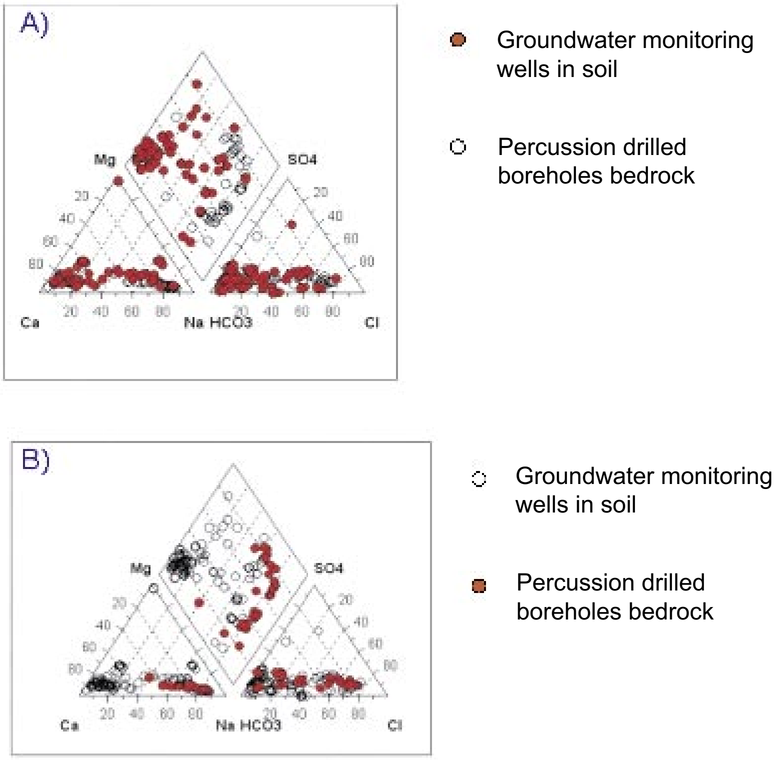

Figure 3-64. *Piper diagrams for groundwater samples from groundwater monitoring wells in QD (red-marked in A) and from percussion drilled boreholes in bedrock (red-marked in B) /SKB, 2005b/.*

The locations of the groundwater monitoring wells in QD with water clearly belonging to one of the two different water types are shown in Figure 3-65, together with the wells where the water can be characterised as "intermediate" in relation to these two types. It can be seen that the wells with the Na-HCO_3,Cl type water are all located at local topographic minima and that several of them are below lakes or the Baltic Sea.

In Figure 3-66 and Figure 3-67, chloride concentrations measured in precipitation samples and samples from groundwater monitoring wells in QD are plotted versus tritium and oxygen-18, respectively. The lowest tritium concentrations are found below Lake Bolundsfjärden, Lake Gällsboträsket and Lake Eckarfjärden. However, the chloride concentrations below the lakes are quite different. In Figure 3-67, it can be seen that the groundwater below the lakes plots along a hypothetical mixing line between the Litorina water and the wells on land.

In a recharge-discharge area perspective, it can be assumed that groundwater samples from both recharge and discharge areas in the local and very shallow systems in the QD belong to the Ca-HCO_3 type of water. Due to the high calcite content in the QD, the water will quickly be calcite saturated or oversaturated.

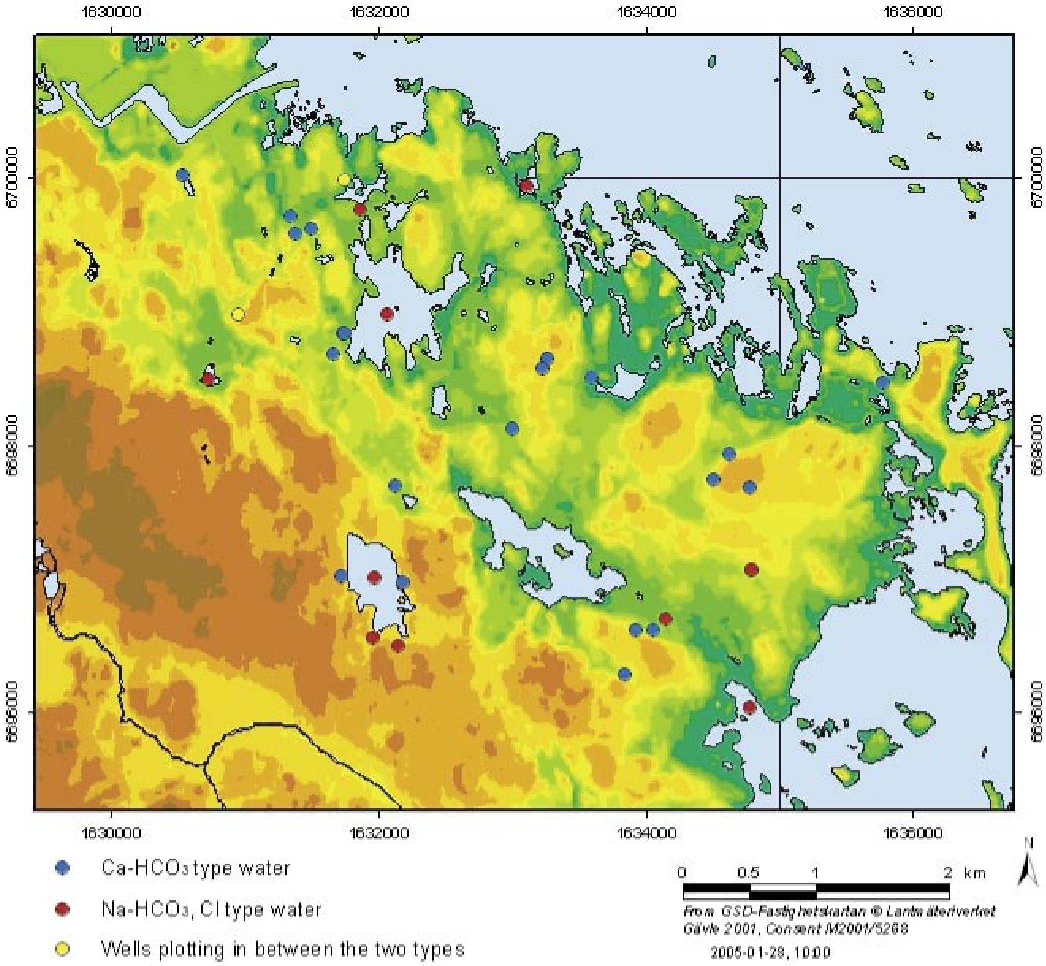

Figure 3-65. *Location of the groundwater monitoring wells in QD with Ca-HCO_3 (blue) and Na-HCO_3, Cl type water (red), and wells plotting in between the two types (yellow) /SKB, 2005b/.*

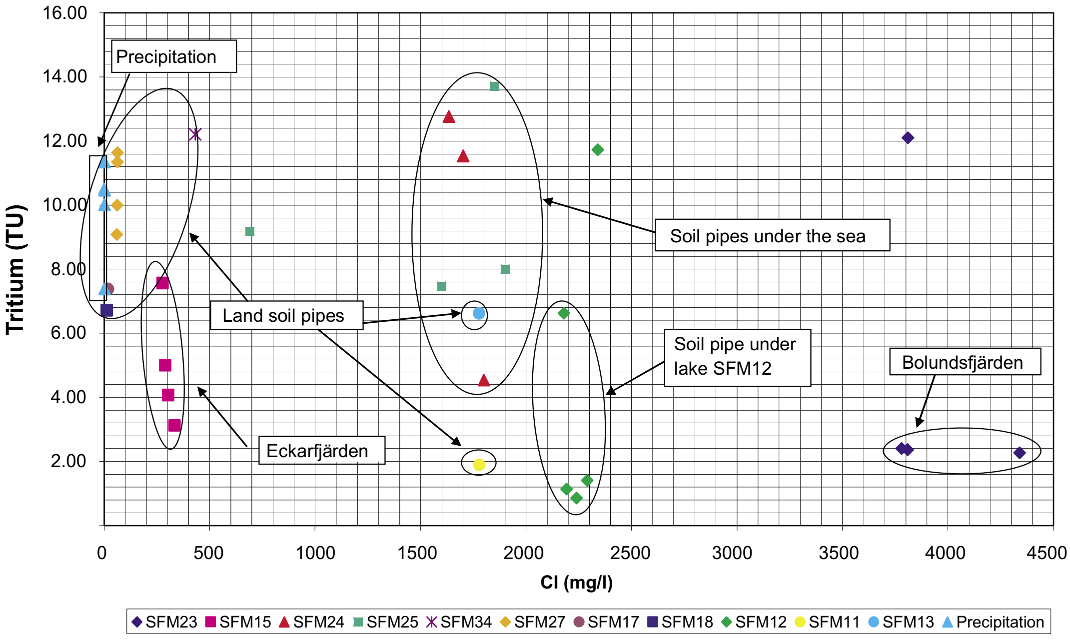

Figure 3-66. *Tritium versus chloride for some groundwater monitoring wells in QD /SKB, 2005b/.*

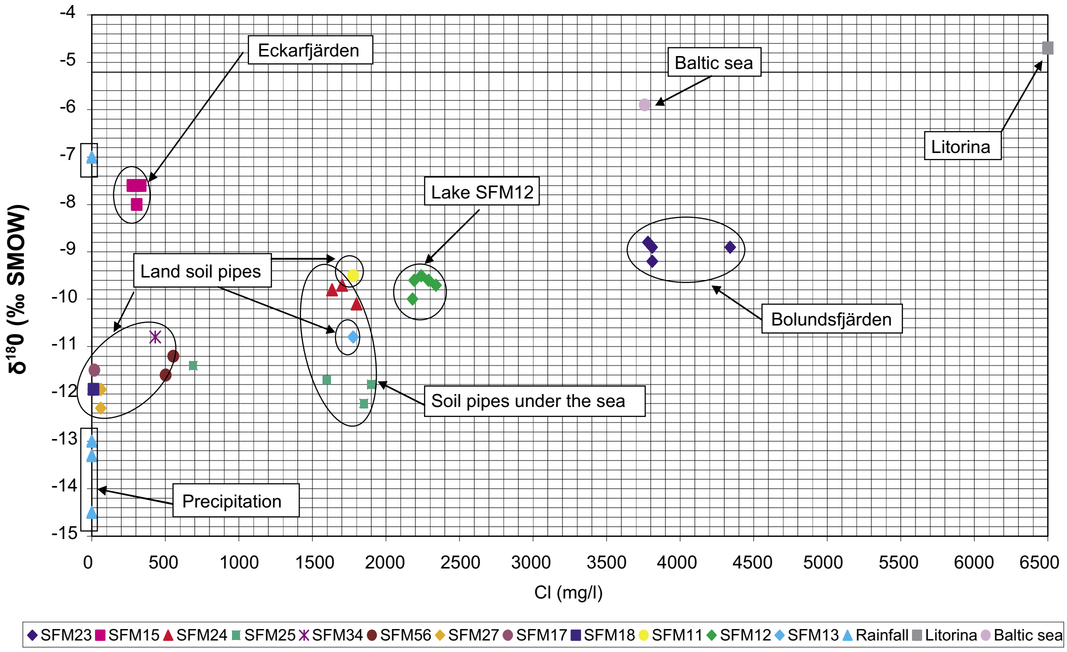

Figure 3-67. *Oxygen-18 versus chloride for some groundwater monitoring wells in QD /SKB, 2005b/.*

The "old" water with high chloride content that has been found below the lakes (and also in some wells in the immediate vicinity of the lakes) can be interpreted in two alternative ways. It can either be interpreted as typical discharge areas for deeper systems with a continuous flow of old, more saline water from below, or as areas with more or less stagnant water, perhaps even underlain by younger and less saline water in the highly conductive horizontal to sub-horizontal zones of the shallow bedrock. For the overall understanding of the hydrogeology in the area, it is important to resolve which of these two interpretations that is correct.

3.4.5 Quantitative flow modelling

Introduction and general objectives

As described by /Rhén et al. 2003/, quantitative flow modelling is performed as an integrated part of the site descriptive modelling. Specifically, the flow modelling serves three main purposes (see also /SKB, 2004a/):

Model testing: Simulations of different geometric interpretations and boundary conditions are carried out in order to try to disprove a given geometric interpretation or boundary condition, and thus reduce the number of alternative conceptual models of the system.

Calibration and sensitivity analyses: Flow modelling performed in order to explore the impact of different assumptions related to initial and boundary conditions and hydraulic properties.

Description of flow paths and flow conditions: Model calculations aimed to enhance the general understanding of the site-specific groundwater flow system.

In view of these main purposes and the present status of the surface hydrological and near-surface hydrogeological modelling, the overall objectives of the quantitative flow modelling in F1.2 were to

- start developing the site understanding by testing some selected aspects of the descriptive model,
- deliver specific output data to the ecological systems modelling,
- test selected modelling tools within the SKB environment.

Although the flow modelling is presented separately and without detailed references to the conceptual and descriptive modelling, the activities related to conceptual/descriptive and quantitative modelling have been integrated. However, the first-attempt character of the modelling work, in combination with the limited time available, has implied less interactions (and iterations) between the conceptual/descriptive and quantitative modelling than in a "complete" modelling process. This has also been the case for the interactions with other modelling disciplines, such as the hydrogeological and hydrogeochemical modelling of the rock.

Short descriptions of modelling tools

This section gives a brief description of the tools used in the F1.2 quantitative flow modelling, and the objectives of each model application. For a more detailed description of the tools, see /Werner et al. 2005/.

GIS-based models

Relatively simple, topography-driven steady-state hydrological models can be developed using the Hydrological Modelling extension in ArcGIS 8.3. This type of modelling requires a Digital Elevation Model (DEM) as the sole input to the calculation of water flow directions and so-called "flow accumulation". In addition, an estimate of the specific discharge (constant in space and time in these calculations) is needed for calculating the discharge (total runoff) in the grid cells in the model. The F1.2 GIS-based modelling also included calculations with the PCRaster-POLFLOW tool, in which meteorological, geological and land use data can be used to calculate a spatially variable specific total runoff and to divide it into different components. The results of the PCRaster-POLFLOW modelling are reported by /Johansson et al. 2005/; all results presented are from the ArcGIS modelling.

The main objective of the F1.2 GIS modelling was to provide input to the ecological systems modelling in terms of the spatial distribution of the total runoff. Furthermore, the GIS modelling aimed to illustrate the overall flow pattern within the Forsmark area and to estimate the mean annual discharge in the main water courses. Another objective was to evaluate uncertainties related to the DEM. Selected results addressing these objectives are presented in the following. A more comprehensive presentation and discussion is given in /Johansson et al. 2005/.

The MIKE SHE model

MIKE SHE (SHE = Système Hydrologique Europeen) is a physically based distributed model that simulates the whole land-based hydrological cycle. For simulation of surface-water flow, MIKE SHE is integrated with the channel-flow program MIKE 11. The exchange of water between MIKE SHE and MIKE 11 takes place during the whole simulation. MIKE SHE is primarily developed to model groundwater flow in porous media. However, the F1.2 modelling also considers groundwater flow in the near-surface bedrock using data from the F1.1 groundwater flow modelling with the DarcyTools code /SKB, 2004a/. Specifically, the "deep rock" and "near-surface" groundwater models are coupled through a head boundary condition at the bottom of the MIKE SHE model.

The main objective of the MIKE SHE modelling was to perform transient, process-based flow modelling of the integrated surface hydrological and near-surface hydrogeological system, thereby supporting the development of site understanding. Furthermore, the process-based modelling provided numerical results on detailed water balances that were used within the ecological systems modelling. Thus, the aim was to simulate the water movement in the QD and the interaction between surface water and groundwater. As described above, the modelling also addressed the coupling of the near-surface groundwater and the deep groundwater in the bedrock.

Results from the GIS modelling

Recharge and discharge areas

Recharge and discharge areas have been identified with the GIS model. In these calculations, cells within recharge areas were defined as having a zero value in the "accumulation grid" (i.e. no upstream cells contributed to the recharge cells). These areas are marked with red in Figure 3-68. Discharge areas were defined as consisting of cells with accumulation grid values higher than 500 (i.e. 500 contributing upstream cells, or more). These discharge areas are marked with blue in the figure. As the grid cells have a size of is 10 m by 10 m, this means that areas receiving water from an area larger than 0.05 km^2 were defined as discharge areas.

Figure 3-68 illustrates the local flow systems described in the conceptual and descriptive modelling (cf, Section 3.4.4). Although recharge areas are restricted to cells of zero accumulation only, it can be seen that they occupy a relatively large part of the total area. Obviously, the relations between recharge areas, "intermediate areas" and discharge areas are determined by the arbitrarily chosen definitions of recharge and discharge areas. However, the results are still of interest as an illustration of the overall recharge-discharge pattern. It can also be noted that the locations of recharge and discharge areas are strongly influenced by the local topography.

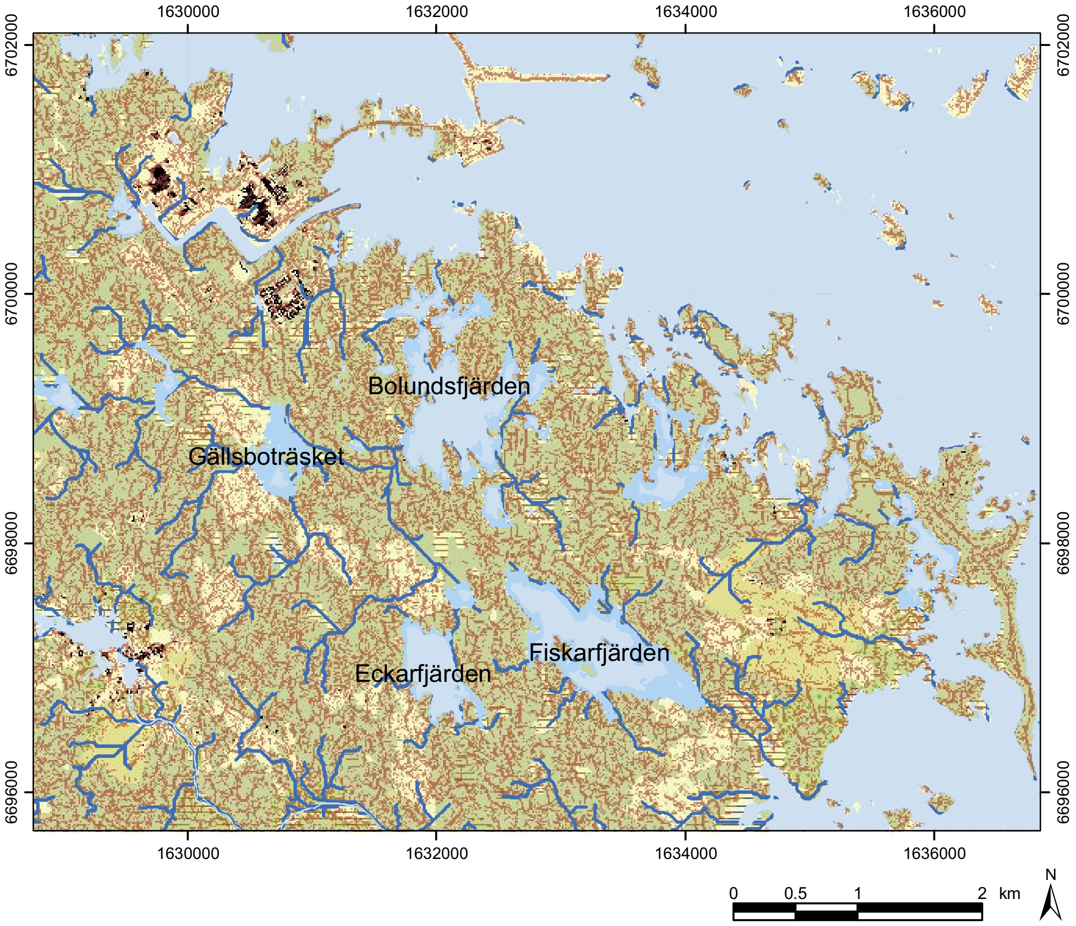

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Figure 3-68. *Identification of recharge and discharge areas using the GIS model. In the model, areas receiving water from an area larger than 0.05 km^2 are defined as discharge areas.*

Identification of catchments

The GIS-based model can be used to identify sub-catchments, e.g. the catchment area of a specific wetland area or some other object considered in the Safety Assessment modelling. In the main part of the model area, the modelled catchments coincide with the field-controlled catchment boundaries of /Brunberg et al. 2004/, cf Figure 3-69. In the figure, the field-controlled boundaries are marked with dashed lines and the number of each catchment is indicated. The modelled sub-catchments are indicated (covered) by different colours.

With the GIS-model it was possible to locate all the 25 catchment areas identified by /Brunberg et al. 2004/, see Section 3.4.4 (Figure 3-52). In the GIS model, sub-catchments no 2:4 and 3:1 consist of two subareas each. The total areas of these two subareas are, however, in both cases almost the same as the areas for the corresponding field-controlled sub-catchments.

As shown in Figure 3-69, there was an obvious divergence between the field-controlled and GIS-modelled catchment boundaries between catchments Forsmark 1 and Forsmark 2 (along the boundary between sub-catchments no 1:3 and 2:8). The water flow in the GIS model crossed the field-controlled boundary from Forsmark 1 to Forsmark 2, such that

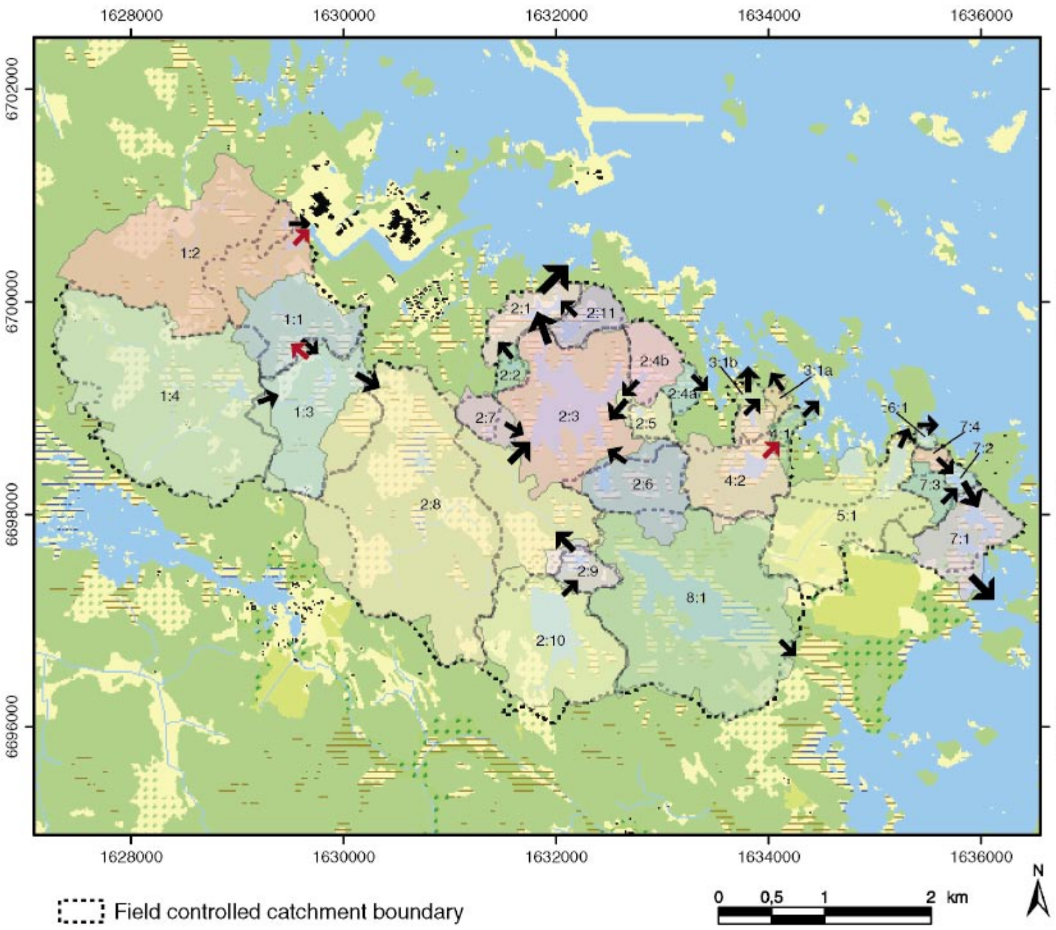

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Figure 3-69. *Modelled and field-controlled catchment boundaries. Black arrows indicate the flow pattern obtained from the GIS model, and red arrows the flow directions corresponding to the field-controlled catchment boundaries.*

the discharge from parts of Forsmark 1 reached the sea through different outlets in the two descriptions. According to /Brunberg et al. 2004/, there is a no-flow boundary between catchments no 1 and 2, and the outlet from Forsmark 1 is just south of the nuclear power plant. Conversely, the GIS model indicates that the water from most of Forsmark 1 flows into Forsmark 2.

Figure 3-69 illustrates these differences using black and red arrows. The black arrows indicate the flow pattern according to the GIS model, whereas the red arrows show how the water flows in reality (i.e. according to the field-controlled boundaries). It is evident that the differences between modelled and “real” flow patterns will have a significant impact on, e.g. estimates of discharges in the outlets to the sea in the northern part of the model area.

As shown in Figure 3-69, differences between modelled and field-controlled catchment boundaries exist also in other parts of the model area. A quantification of these differences, providing an estimate of potential uncertainties caused by errors in the DEM, is presented in /Johansson et al. 2005/. Furthermore, the PCRaster-POLFLOW modelling reported in /Johansson et al. 2005/ shows that a lowering of the topography along the mapped water courses leads to an improved agreement between observed and modelled water divides.

Results from the MIKE SHE modelling

The MIKE SHE modelling was based on meteorological data from the SMHI station Örskär. High-resolution data from 1988 were used in the simulations, since 1988 has been identified as a statistically representative year for the period 1961–2000 /Larsson-McCann et al. 2002/. The annual corrected precipitation for the modelled year was 674 mm and the potential evapotranspiration was calculated to 538 mm. Thus, it should be noted that all results presented below are based on these input data, and not on the site data from 2003–2004 described in Sections 3.4.3–4. Furthermore, all references to "dry" and "wet" periods concern different parts of the modelled year (1988), not long-term extreme values.

Water balance

The regional runoff for the area is estimated to 6.5 l$\times$s$^{-1}\times$km^{-2} /SKB, 2004a/, which corresponds to 205 mm$\times$year^{-1}. The modelled specific runoff in MIKE SHE (averaged over the model area) was 7.1 l$\times$s$^{-1}\times$km^{-2}, corresponding to 226 mm$\times$year^{-1}. The total actual transpiration was calculated to 441 mm$\times$year^{-1}. Thus, the calculated water balance agrees with the estimates presented in connection with the descriptive model of the flow system in Section 3.4.4. Figure 3-70 illustrates the calculated water balance and the exchanges of water between different compartments in the model. There was a small error in the water balance (c 1 mm$\times$year^{-1}). The water balance is calculated in all the compartments of the model. Thus, there are arrows labelled "evaporation" both in the overland (OL) compartment and in the unsaturated zone (UZ) compartment.

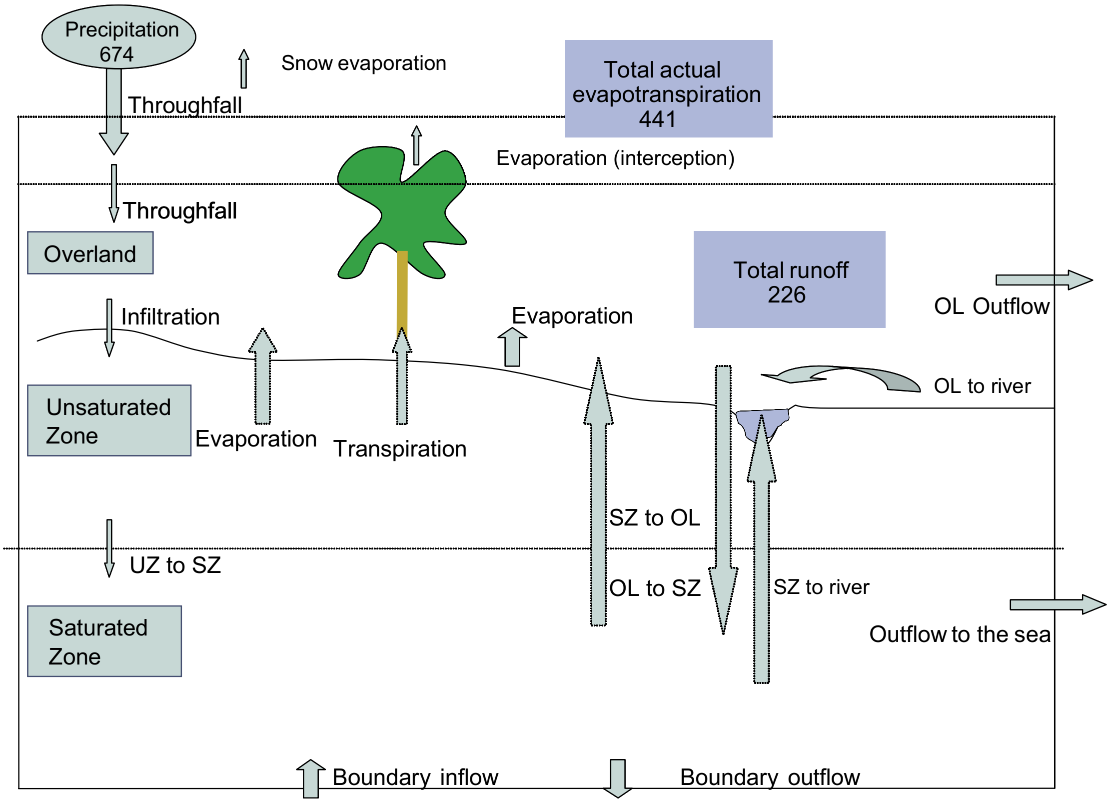

***Figure 3-70.** Water balance for the model area, and water exchanges between the different compartments in the model.*

The total actual evapotranspiration is the sum of evaporation from snow, interception, soil surface, ponded water and transpiration. The calculated interception is 163 mm×year^{-1}. This value is somewhat higher than the interception calculated with the CoupModel (130 mm×year^{-1}), see Section 3.4.4. The total transpiration averaged over the whole area is calculated to 70 mm×year^{-1}. If the water balance is calculated for areas covered by vegetation only, the corresponding value is 102 mm×year^{-1}, which is larger because lakes and areas with ponded water do not generate transpiration.

In the model, the runoff is calculated as the net flow of water to the MIKE 11 model plus the water that leaves the model area as overland flow. MIKE 11 calculates the actual discharges and water levels in the water courses. Figure 3-71 shows the hydrograph in three different water courses in the model area, i.e. the outlets of the Forsmark 1 catchment, Lake Bolundsfjärden in Forsmark 2, and the Forsmark 8 catchment. The hydrograph calculated for Forsmark 1 has many peaks and is highly transient during the year.

The results for the discharge from Lake Bolundsfjärden indicate that the lake reduces the temporal variations in the flow in the water course. The discharge in the water course that constitutes the outlet of Forsmark 8, downstream of Lake Fiskarfjärden, is smaller than the discharge from Lake Bolundsfjärden, due to the smaller catchment area, but shows a similar pattern of temporal variability. The maximum calculated discharge in the three water courses during the simulation period, approximately 80 l×s^{-1}, occurs in the water course from the Forsmark 1 catchment. However, Figure 3-71 shows that the total annual discharge from Lake Bolundfjärden in Forsmark 2 is much larger than that from Forsmark 1.

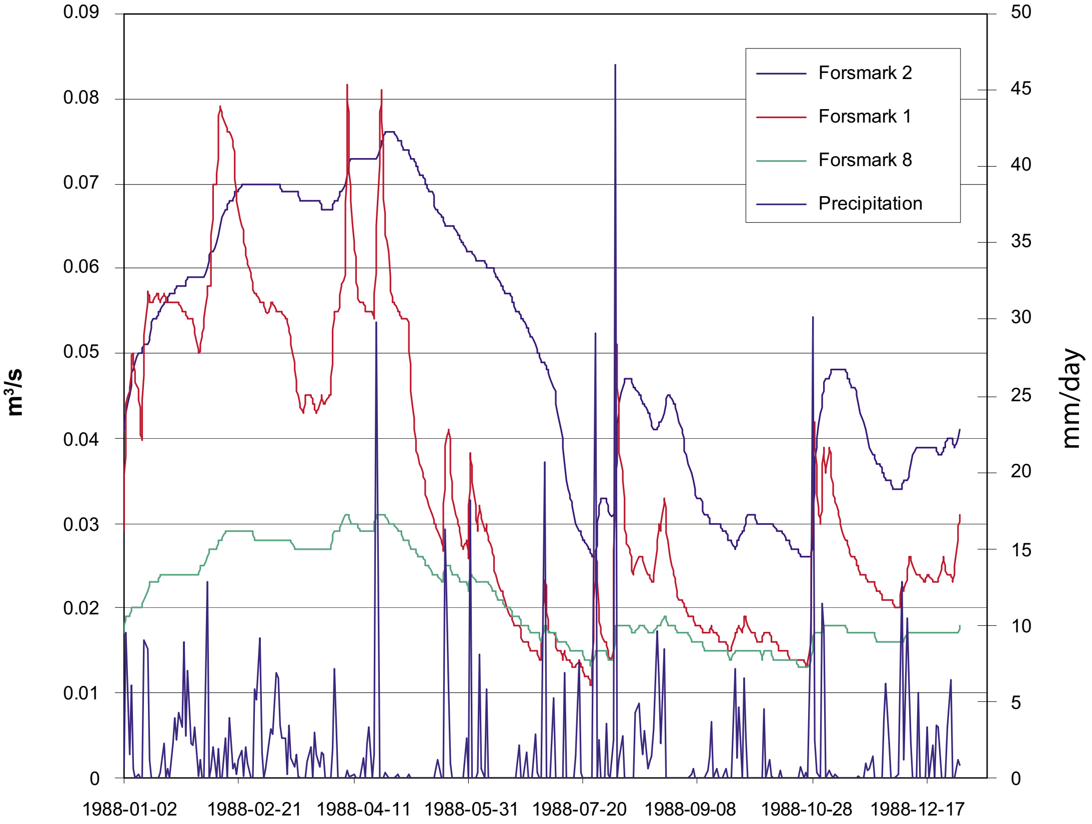

Figure 3-71. *Calculated discharges in three water courses during the modelled year.*

Generally, the calculated groundwater level within the model area was close to the ground surface. For example, the mean groundwater level (i.e. spatially averaged over the model area) in the end of June was 0.2 m below the ground surface, see Figure 3-72. However, there was a certain temporal variation during the year. As shown in the figure, the calculated depth to the groundwater table in the end of June varied within the model area. The maximum depth was approximately 7 m below the ground surface, and was found at the topographic heights south of Lake Gällsboträsket.

The contours of the mapped lakes and wetlands within the model area are marked in Figure 3-72; the lakes are marked with black lines and the wetland areas are marked with dashed lines. Yellow, orange or red colours indicate ponded water on the ground surface. It was found that the simulated water depths in the lakes were in accordance with measured depths. However, the water depths in some wetlands were 0.5–1 m, implying that shallow lakes, rather than wetlands, were obtained in the model.

As described in Section 3.4.4, the model area in Forsmark consists of many small catchment areas, and the groundwater table is generally very shallow. Thus, the model results support these aspects of the descriptive model. Since the area is very flat, water is accumulating on the ground surface in the low points, i.e. in wetland areas and lakes. As described above, the modelling resulted in too much water ponding on the ground surface in some wetland areas. This result can to some extent be related to errors in the DEM and to man-made structures that not are included in the present model. For example, there may be ditches or man-made redirections of the surface waters that cause a more effective runoff than that simulated by the river network in the present MIKE 11 model. Another factor that may have contributed to the ponding of water is the hydraulic conductivity values, i.e. that the values assigned to the QD were incorrect (too low).

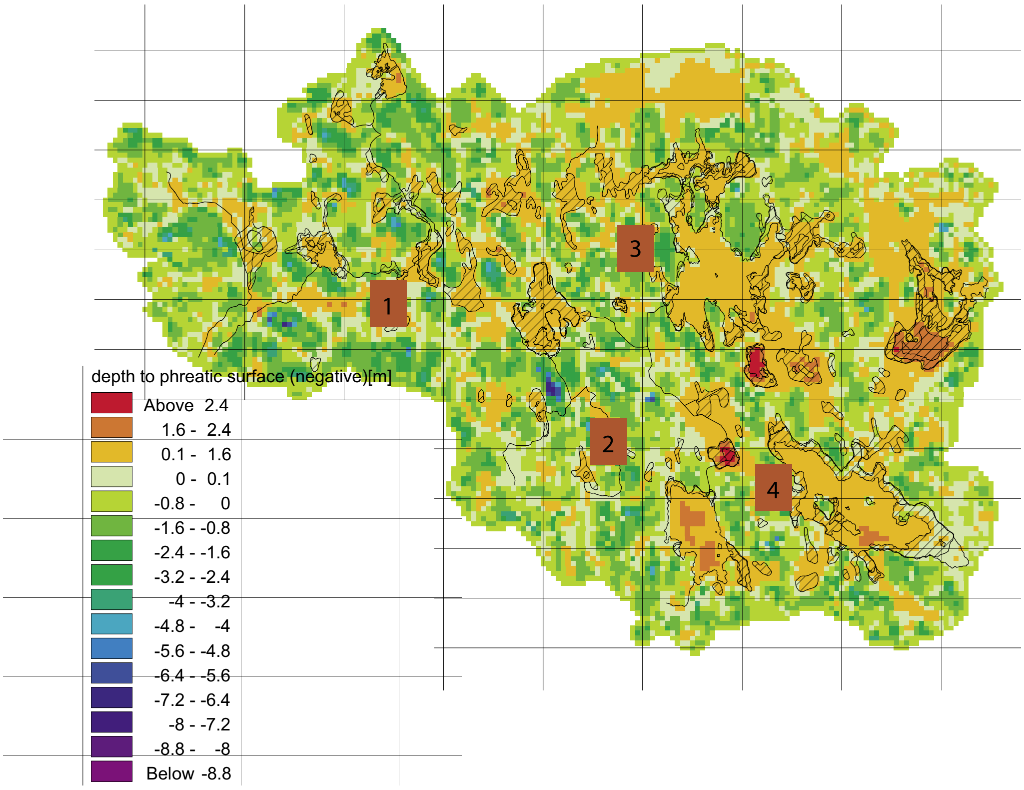

***Figure 3-72.** Simulated depth to the groundwater table (depth relative to the ground surface) in the end of June during the modelled one-year period. The mapped lakes are marked with black lines and the wetland areas are marked with dashed lines; yellow, orange or red colours indicate ponded water on the ground surface.*

Time series showing the fluctuations of the groundwater levels at the points numbered 1 through 4 in Figure 3-72 have been evaluated, see /Johansson et al. 2005/ for details. Points no 3 and 4 are at locations characterised by shallow groundwater tables, whereas points no 1 and 2 are located at topographic heights where the depth to the groundwater table is larger. Comparing the results, it was noted that the two groups of observation points showed somewhat different patterns of temporal variability.

In the points with shallow groundwater, the groundwater level was above or very close to the ground surface during spring, and lower during the summer and autumn. The levels at these points showed short-term variations not observed where the groundwater depth was larger, indicating a sensitivity to the meteorological conditions. The calculated groundwater levels below the topographic heights showed smoother variations, with increasing levels during spring and early summer and decreasing levels during autumn.

In accordance with the conceptual model presented in Section 3.4.4, the QD consisted of three till layers in the MIKE SHE model, except for in areas below lakes and where the total depth of the QD was small. The details of the model setup are described by /Johansson et al. 2005/. The till layers are here referred to as Layer 1, 2 and 3, respectively, with Layer 1 being the uppermost layer. Simulation results in terms of flow directions for saturated groundwater flow in Layer 1 and 2 are presented in Figures 3-73 to 3-75, which means that only the saturated part of the flow system is considered in grid cells that are not fully saturated.

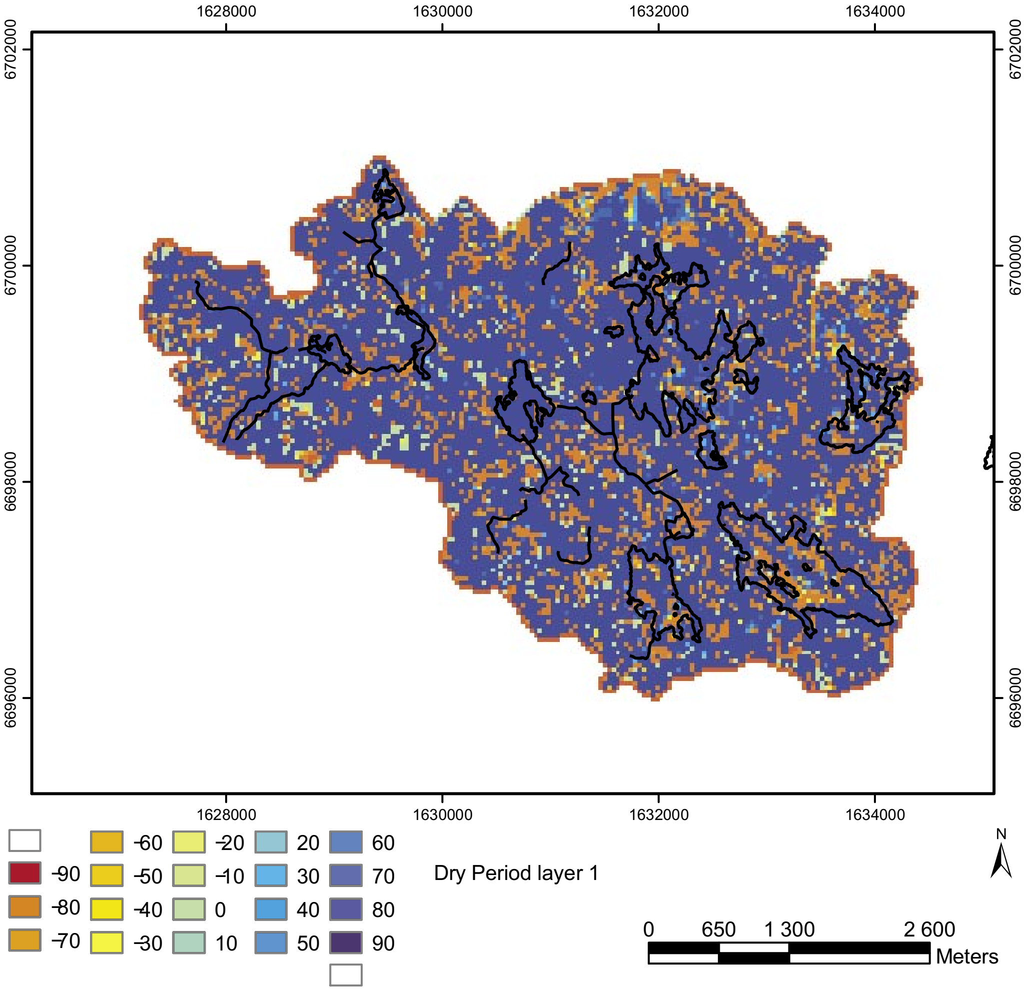

Figure 3-73. Flow direction in Layer 1 during a dry period. The legend refers to the angle of the flow vector relative to the horizontal plane; +90 (degrees) is up and –90 is down.

The figures illustrate the angle between the groundwater velocity (Darcy velocity) in the xy-plane and the groundwater velocity in the z-direction, thereby showing if the flow in each grid cell is horizontal or vertical. In particular, the water flow is vertical and directed upwards if the calculated angle is 90 degrees. If the angle is between –45 and 45 degrees, the groundwater flow is dominated by the horizontal component. Yellow and turquoise areas are areas where the groundwater flow is mainly in the horizontal direction, whereas blue and red areas have vertical upward and downward flow, respectively.

The results in Figures 3-73 and 3-74 show that the calculated groundwater flow in Layer 1 was dominated by its vertical component. During a dry period (in the summer), the evapotranspiration had a strong influence on the water movement in the uppermost layer, see Figure 3-73, such that the uptake of water by the roots in the unsaturated zone led to an upward groundwater flow. The results for Layer 1 during a wet period, Figure 3-74, showed that the groundwater flow was dominated by vertical flow directed downwards. Areas with upward flow, blue areas, coincide with lakes and areas near the water courses.

These two figures illustrate how the local topography and the meteorological conditions influence the locations of recharge and discharge areas. The topographic heights were recharge areas in both cases and the areas around the water courses and the lakes were discharge areas during both the dry and the wet periods. The flat areas between the local heights and the topographic minima were recharge or discharge areas depending on the meteorological conditions.

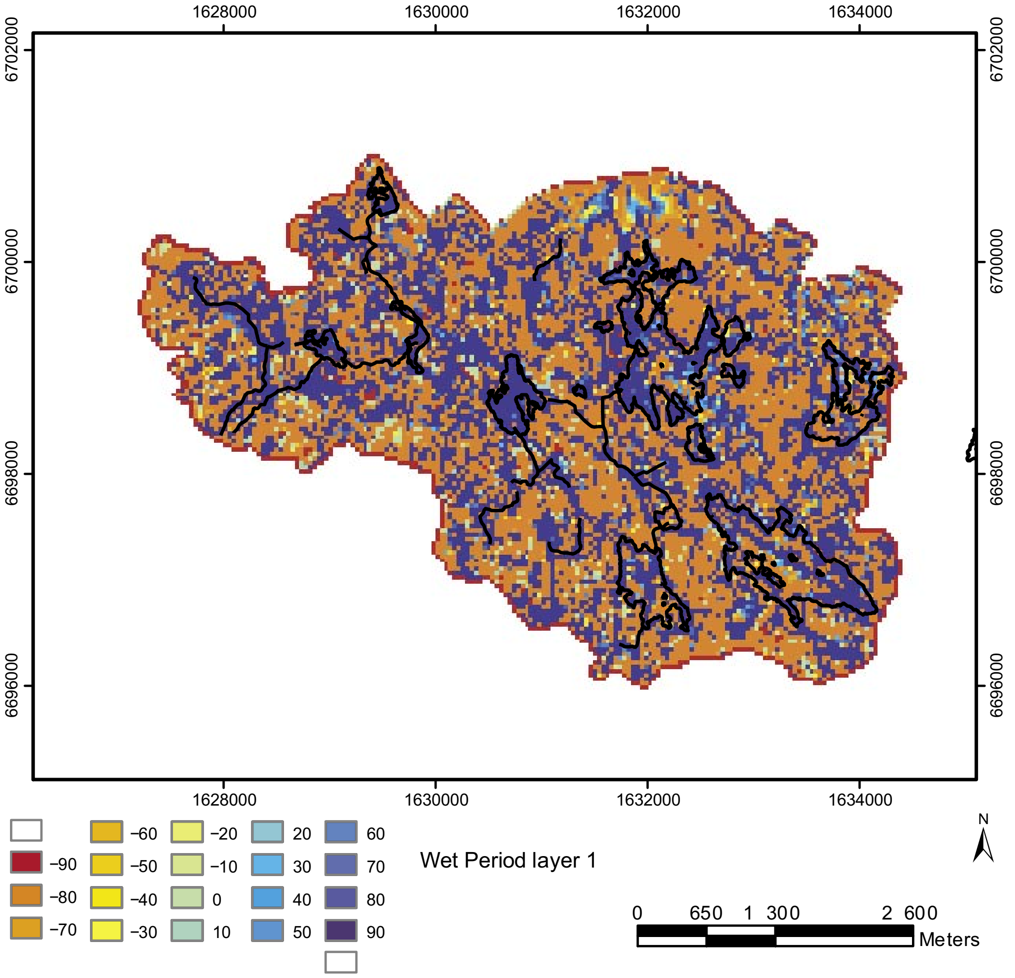

Figure 3-74. *Flow direction in Layer 1 during a wet period. The legend refers to the angle of the flow vector relative to the horizontal plane; +90 (degrees) is up and –90 is down.*

The calculated groundwater flow directions in Layer 2, see Figure 3-75, were also dominated by the vertical component, but there were also some areas dominated by horizontal flow. In Layer 2, the distribution of vertical and horizontal flow areas was almost the same during wet and dry periods; Figure 3-75 illustrates the groundwater flow conditions during a dry period.

Figures 3-73 to 3-75 illustrate the local character of the near-surface hydrogeology in the Forsmark area, thereby supporting the description in the preceding section. The groundwater flow in the upper part of the QD profile was found to be sensitive to the meteorological conditions and dominated by the vertical component (either upward or downward flow, depending on the meteorological conditions). The patterns of vertical groundwater flow in Layer 1 and Layer 3 (not shown) were almost the same under both dry and wet conditions. The main horizontal flow appeared to occur in Layer 2, whereas it in the conceptual modelling was assumed that most of the flow takes place in the uppermost, more permeable till layer. Whether this apparent difference is due to, for instance, insufficient vertical resolution or a too small hydraulic conductivity contrast, will be investigated in future model versions.

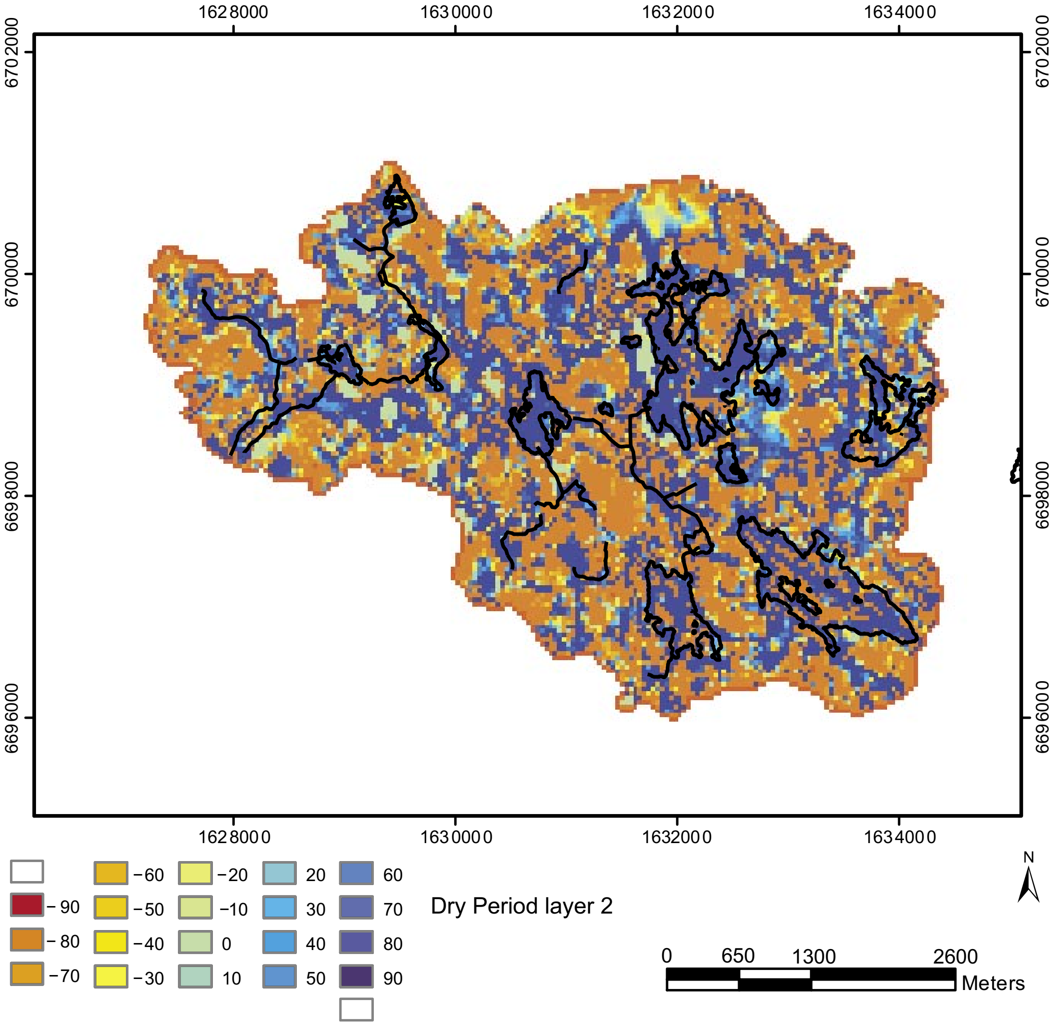

Figure 3-75. Flow direction relative to the horizontal plane in Layer 2 during a dry period. The legend refers to the angle of the flow vector relative to the horizontal plane; +90 (degrees) is up and –90 is down.

Water exchange with deep groundwater

The bottom boundary condition in the MIKE SHE model is a so-called head-controlled flux boundary condition. The prescribed head at the boundary (located at –150 m a s l), taken from the F1.1 DarcyTools model /SKB, 2004a/, generates a flux over the bottom boundary. Thus, results from the modelling of groundwater flow in the fractured rock are used as input to the MIKE SHE modelling, which provides a coupling between the deep rock and near-surface groundwater flow systems.

Figure 3-76 shows the vertical groundwater (Darcy) velocity across the bottom boundary in the MIKE SHE model. Green and blue colours indicate inflow to and yellow and red colours outflow from the model volume. The figure illustrates that the main groundwater flow at the bottom boundary took place in the fracture zones. The groundwater flow pattern reflected the extent of the large fracture zone crossing the model area.

There was a net inflow of water to the MIKE SHE model volume during the simulation period. The accumulated net flow over the bottom boundary during one year was 1.3 mm. The corresponding annual flow rate at this depth in the DarcyTools model was calculated to 2.3 mm (also net upward flow). The vertical discretisation in the two models differs, which implies that it is difficult to make an exact comparison of the two model results. However, it can be concluded that the calculated vertical net groundwater flow rates at the level of the bottom boundary in the MIKE SHE model had the same direction and were of the same order of magnitude.

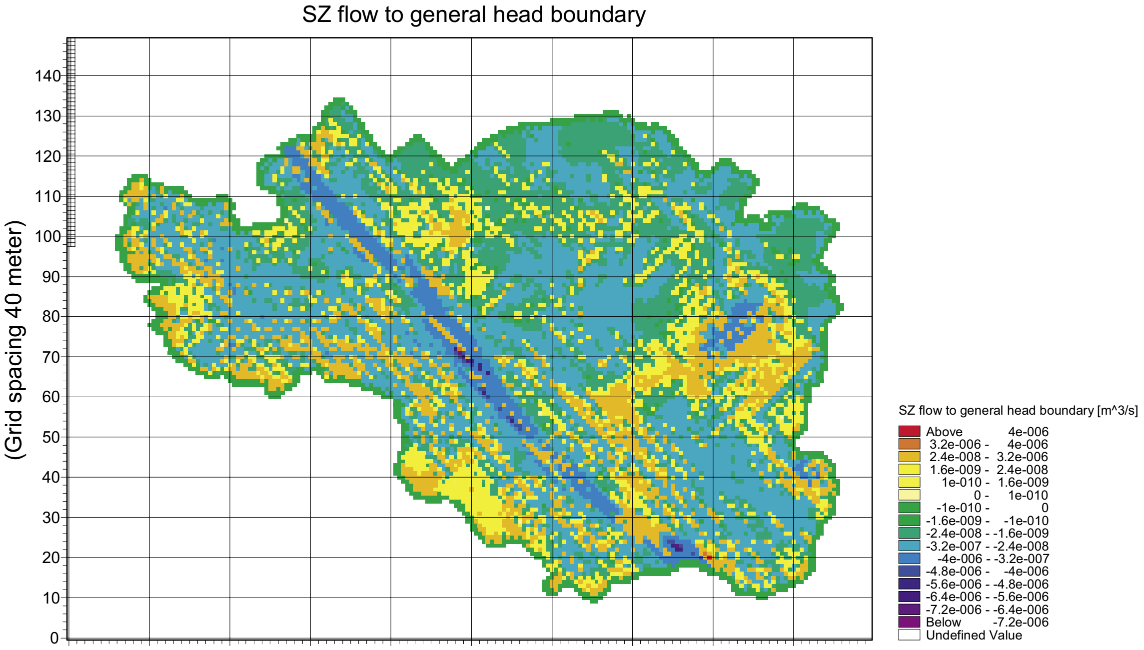

***Figure 3-76.** Water exchange with deep groundwater in each grid cell (40 m×by 40 m) at –150 m a s l.*

Particle tracking

Particle tracking makes it possible to calculate the flow paths of hypothetical particles in the model volume. The calculated, three-dimensional flow field is the basis for the movement of the particles. The particles are transported according to the local groundwater velocity calculated in the MIKE SHE water movement module. The particle tracking only occurs in the saturated zone; particles that leave the saturated zone are not traced further. However, it is possible to identify what kind of sinks the particles have moved to, i.e. whether they go from the saturated zone to water courses, the unsaturated zone, model boundaries, or wells (no wells are included in the present MIKE SHE modelling of the Forsmark area).

Two cases were studied in the particle tracking simulations. In both cases, the particles were introduced in the layer above the bottom lower boundary layer (the second lowest layer in the model; it is not possible to introduce particles in boundary cells). The first case ("Case 1" below) considered a uniform injection, in which eight particles were introduced in each grid cell. In the second case ("Case 2"), the introduction of particles was flow-weighted, which means that the number of particles introduced in a given cell was proportional to the vertical groundwater velocity in that cell. All cells in the injection layer that had an upward flow were assigned at least one particle.

The simulation time was 150 years in both release cases, using the results of transient flow during the modelled single "representative year". Thus, the model results from the MIKE SHE water movement calculation for this single year were cycled 150 times. A number of "registration zones" in the uppermost calculation layer were defined. These zones make it possible for the modeller to study where in the model volume a specific particle emerges, i.e. the arrival of the particle in each pre-defined zone can be monitored. It is also possible to calculate the travel times for a particle to each specific registration zone. In the present modelling of the Forsmark area, each sub-catchment and each lake was defined as a separate registration zone.

In Case 1, 45% of the particles left the model volume through the bottom boundary or through the boundary towards the sea. The Case 2 results showed that only 13% of the particles crossed the model boundaries; the smaller fraction of "escaping" particles is due to the fact that particles were introduced in cells with upward flow only.

Figure 3-77 shows model results from Case 1. The figure illustrates to which catchment the particles moved, i.e. in which of the catchment registration zones each particle left the saturated zone, and where the particles were introduced in the bottom boundary of the model. Thus, the colour of a cell indicates in which catchment the particle injected at that x,y-position left the saturated zone. For example, a cell marked with pink colour indicates that the particles released at that position within the bottom boundary plane was traced to the Forsmark 2 catchment (referred to as "Norra bassängen"). It follows that all the particles that emerged in Forsmark 2 were released within the pink area in the figure.

Each colour in the figure is associated with a catchment area, i.e. a registration zone. Empty (non-coloured) areas in the figure indicate that the particles released there left the model through the bottom boundary. The catchment boundaries, i.e. the boundaries of the different registration zones, are marked with black lines.

The figure shows that the particle transport is mainly vertical, such that, e.g. no particles released in the southern part of the model area travel to the northern part. In both Case 1 and Case 2, the largest amount of particles was registered in the Forsmark 2 catchment. Thus, the particle tracking simulations indicate that Forsmark 2 is the main discharge area for particles injected at depth in the rock within the whole model area. More details on the particle tracking results, such as the number of particles registered in each catchment and the distribution of the particles on the lakes and land parts of the catchments, are reported in /Johansson et al. 2005/.

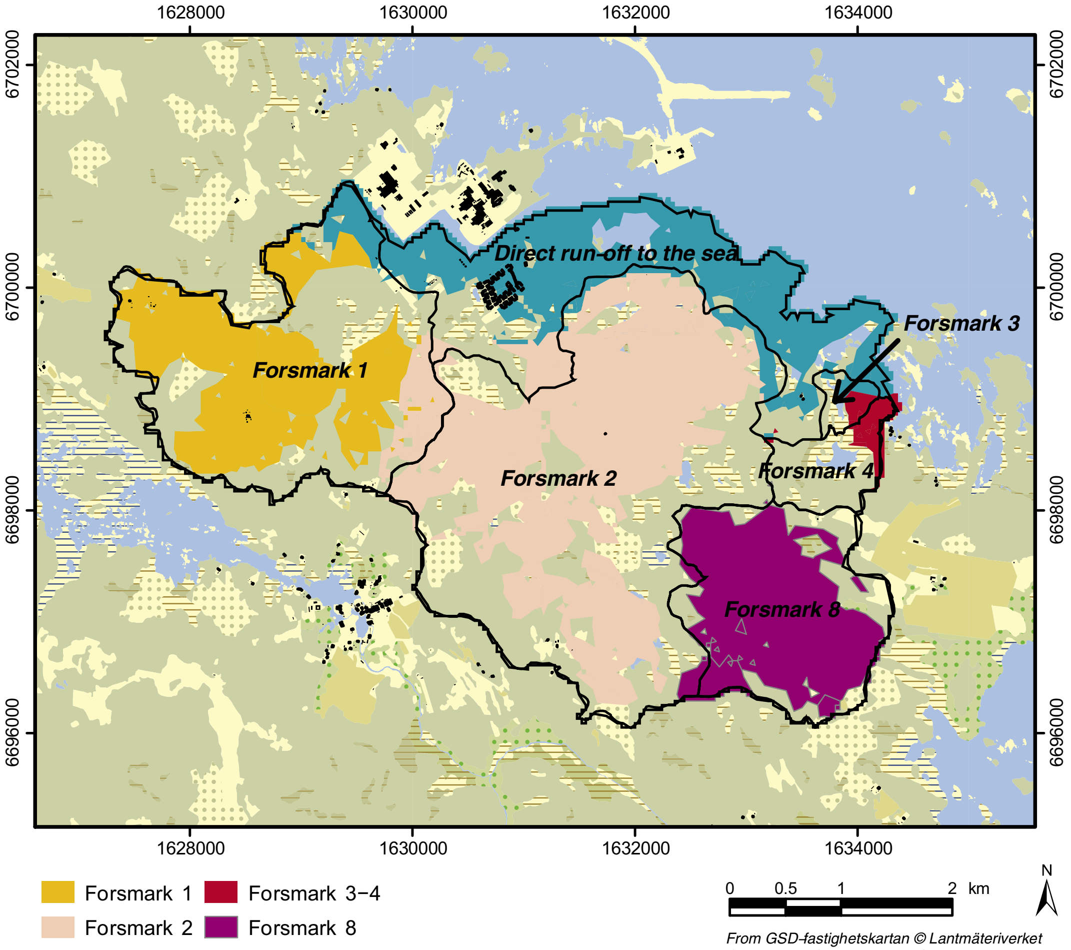

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Figure 3-77. *Results of particle tracking simulations, Case 1 (uniform injection). The colour of a cell indicates in which catchment a particle injected at that x,y-position in the bottom boundary left the saturated zone (particles injected in empty cells left the model through the bottom boundary).*

The calculated advective travel time in Case 1 from each cell to the registration zone, i.e. catchment or lake (the average travel time for all particles injected in the cell), is shown in Figure 3-78. The figure illustrates that the fracture zones had a large influence of the travel times; particles released in the fracture zones had very short travel times to the near-surface system. The red areas in Figure 3-78 are areas where the travel times from the second lowest calculation layer to the uppermost one (Layer 1) were less than 10 years.

Also the areas very close to the sea boundary had short travel times. However, this does not necessarily mean that these particles left the model volume in the uppermost calculation layer. The particles that crossed the model boundary towards the sea were registered in all calculation layers. Therefore, the short travel times near the sea boundary may be related to shorter flow paths, indicating a boundary effect caused by the limited horizontal extent of the model (only land areas were included). Conversely, the particles registered in catchments and lakes had travelled through all layers in the model, i.e. almost 150 m in the vertical direction.

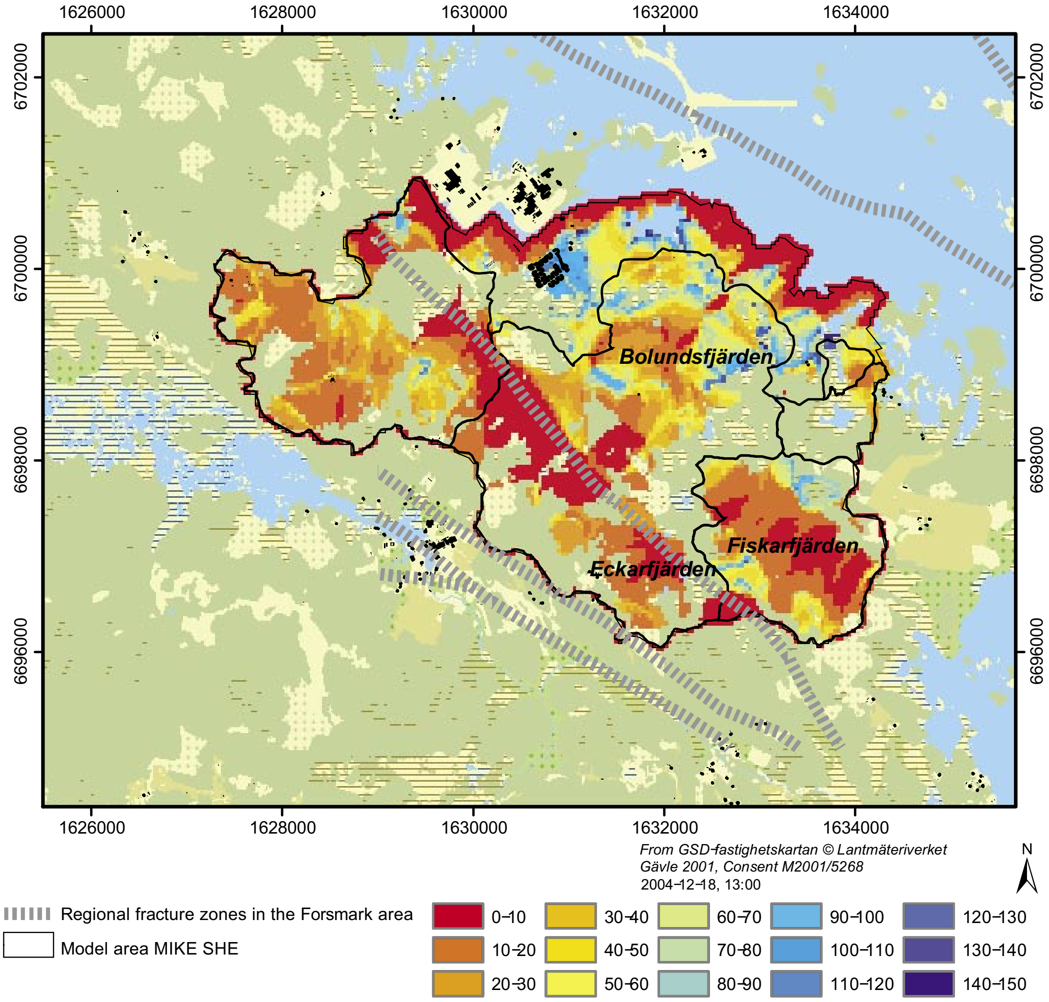

***Figure 3-78.** Advective travel times (years) for particles released uniformly at the bottom boundary of the MIKE SHE model (Case 1).*

In summary, the two particle tracking cases showed similar results. Most of the particles emerged in the lakes. Forsmark 2, the "Norra bassängen" catchment, received most of the particles in both release cases. The largest difference between Case 1 and Case 2 was that most of the particles in Case 1 were traced to Lake Bolundsfjärden, whereas in Case 2 most of the particles were registered in Lake Gällsboträsket. This result was related to the number of particles introduced in the fracture zone under Lake Gällboträsket (more particles were released in the fracture zone in Case 2). The particle tracking results are in agreement with the results shown in Figure 3-73 to 3-75, emphasising the vertical component of the groundwater flow in the near-surface system.

3.4.6 Resulting description of the Forsmark site

Development since previous model version

Site-specific data on meteorological conditions, surface hydrology and near-surface hydrogeology were very limited in Forsmark 1.1 (F1.1). For the present Forsmark 1.2 (F1.2) model version the following additional site-specific data have been available:

- Local meteorological data from two stations (time series of approximately one year).

- Results from a first field survey of lake thresholds, and hydraulic gradients and cross-sections in water courses (F1.2 dataset includes data for only a part of the model area).
- Manual discharge measurements in water courses (time series for an additional 15 months).
- Stratigraphy of Quaternary deposits (QD) from additional drillings coupled to installation of groundwater monitoring wells in QD (16 new drillings).
- Hydraulic parameter data from additional slug tests (12) and pumping tests (2).
- Time series of sea, lake and groundwater levels (up to 15 months long).
- Chemical data from near-surface groundwater.

The conceptual and descriptive models have been improved and given more details based on the site-specific data. The three-layer model of the till dominating the QD that was proposed in F1.1 still appears to be a reasonable simplification and has got some additional support from the new hydraulic tests. The available time series of surface and groundwater levels illustrate the close interaction between evapotranspiration, surface water and near-surface groundwater. The water level time series and the hydrochemistry of the near-surface groundwater indicate complex flow patterns in some important discharge areas.

Preliminary quantitative flow modelling has been performed as a part of the F1.2 modelling effort. The modelling activities included GIS-based hydrological modelling, using the hydrological modelling extension in ArcGIS 8.3 and the PCRaster-POLFLOW tool, as well as more detailed process modelling using MIKE SHE. Modelling results have been delivered to the ecological systems modelling, and the modelling has also contributed to and confirmed the site understanding expressed in the descriptive model.

Summary of present knowledge

Conceptual and descriptive model

The present knowledge, as inferred from data evaluations and expressed in the conceptual and descriptive modelling, can be summarised as follows:

- Data from the local meteorological stations and nearby SMHI regional stations indicate an average corrected annual precipitation of 600–650 mm in the Forsmark area.
- The mean annual evapotranspiration in the dominating forested areas can be estimated to a little more than 400 mm, leaving approximately 200 mm for runoff.
- The area covered by the conceptual and descriptive models is characterised by a low relief and a small-scale topography. Almost the whole area is below 20 m a s l.
- In total 25 “lake-centered” catchments, ranging in size from 0.03 to 8.67 km^2 have been delineated within the model area.
- The 25 mapped lakes range in size from 0.006 to 0.752 km^2. The lakes are very shallow with maximum depths ranging from 0.4 to 2 m. The major lakes are Lake Fiskarfjärden, Lake Eckarfjärden, and Lake Bolundsfjärden. The bottom sediments mostly consist of a relatively thick gyttja layer underlain by thin layers of sand and clay. However, in Lake Bolundsfjärden the clay layer is missing under a large part of the lake.
- No major water courses flow through the model area. The brooks downstream of Lake Gunnarsboträsket, Lake Gällsboträsket, Lake Eckarfjärden and Lake Fiskarfjärden carry water during most of the year, whereas the remaining brooks are dry for long periods. No automatic continuous discharge measurements were available for F1.2, but four discharge stations are now in operation.

- Wetlands are frequent and cover 10–20% of the area of the three major catchments and up to 25–35% of some sub-catchments. The stratigraphy of the wetlands has not been investigated in detail. Peat has developed in the more elevated areas but the thickness is mostly less than one metre. In more low-lying areas the peat layer is very thin or missing. The peat is underlain by gyttja and sometimes also by sand and clay layers. The hydraulic contact between the wetlands and the surrounding shallow groundwater largely depends on the stratigraphy. It can be assumed that wetlands that are more or less isolated from the nearby shallow groundwater as well as wetlands continuously fed by groundwater exist within the model area.
- Till is the dominating QD covering approximately 75% of the area. In most of the area the till is sandy. However, at Storskäret in the southeast, clayey till dominates. Bedrock outcrops are frequent but cover only approximately 5% of the area. Wave washed sand and gravel, clay, gyttja clay and peat cover about 3–4% each. The till is relatively shallow, usually less than 5 m thick. The greatest depth recorded is 16 m. A median depth of 1.9 m, excluding areas with outcropping bedrock, was calculated in the "QD depth model" developed using data from drillings, pits and geophysical investigations /Vikström, 2005/.
- Based on site-specific and generic data a three-layer model is proposed for the hydraulic properties of the dominating till, see Table 3-18. The uppermost layer is assigned relatively high conductivity and porosity values due to the impact of soil forming processes. The middle layer is given lower values for both conductivity and porosity, in agreement with both site-specific and generic data. A differentiation is proposed between areas with coarse and fine-grained till. The bottom layer, resting on the bedrock, is in accordance with site-specific data, again assigned a higher conductivity value. However, it is still an open question if the relatively high values obtained in the slug tests are caused by a higher conductivity in the till at the QD/rock interface or mainly depend on the properties of the uppermost part of the bedrock.
- The infiltration capacity exceeds rainfall and snowmelt intensity with few exceptions. Unsaturated (Hortonian) overland flow only appears over short distances on agricultural land covered by clayey till, on frozen ground where the soil water content is high during freezing, and on outcropping bedrock.
- Direct groundwater recharge from precipitation is the dominant source to groundwater recharge. However, groundwater level measurements in the vicinity of Lake Bolundsfjärden and Lake Eckarfjärden show that gradients are from the lakes to the riparian zones during periods of dry summer conditions. Due to the low hydraulic conductivities of the QD materials involved, the flows during these periods can be assumed to be small.
- The groundwater is very shallow, within one metre below ground as an annual mean for almost all groundwater monitoring wells. Also, the annual groundwater level amplitude is less than 1.5 m for most wells. The shallow groundwater levels mean that there will be a strong interaction between evapotranspiration, soil moisture and groundwater. This is clearly illustrated by the measured fast groundwater level decline and diurnal groundwater level fluctuations during dry, warm periods. The present situation implies that it is important to make a distinction between gross and net groundwater recharge (i.e. transients are important).
- Strong correlations were found between the groundwater level variations in different groundwater monitoring wells, and between groundwater level variations and the cumulative P-ET difference (precipitation minus evapotranspiration). Very strong correlations were also obtained between observed groundwater levels and levels simulated based on a simple conceptual hydrological model, see /Johansson et al. 2005/.

- The correlations between the sea water level and the measured groundwater levels were weak, with exception of two wells located below open water directly influenced by the sea water and the two wells at the Börstilåsen esker. The relations between the sea water level and the water levels in Lake Norra Bassängen, Lake Bolundsfjärden and Lake Lillfjärden show that inflow of sea water can occur during periods of very high sea water levels.
- Surface water and near-surface groundwater divides are assumed to coincide. The small-scale topography implies that many local, shallow groundwater flow systems are formed in the QD. The hydraulic conductivity profile of the dominating till means that a dominating part of the groundwater will move along very shallow flow paths. These local and small-scale recharge and discharge areas will overlay more large-scale flow systems associated groundwater flows at greater depths.
- Groundwater level time series from wells in till and bedrock within the same areas show a considerably higher groundwater level in the till than in the bedrock. The observed differences in levels are not fully consistent with the good hydraulic contact between QD and bedrock indicated by the hydraulic tests in the QD. However, the relatively lower groundwater levels in the bedrock may be caused by the horizontal to sub-horizontal highly conductive zones shown to exist in the upper bedrock.
- Not all discharge areas are saturated up to the ground surface, but water flows in the uppermost highly permeable part of the QD profile. "Saturated overland flow" occurs in discharge areas where the groundwater level reaches the ground level. The flat terrain, in combination with the shallow groundwater levels, results in temporal variations in the extents of recharge and discharge areas during the year.
- The sediment stratigraphy of lakes and wetlands is crucial for their function as discharge areas. Low permeability sediments will restrict discharge and result in a relocation of discharge to areas where such sediments are missing.
- "Old water" with high chloride content has been found below Lake Bolundsfjärden, Lake Eckarfjärden and Lake Gällsboträsket. It can either be interpreted as a continuous discharge of deep water or as stagnant water. The two alternative interpretations lead to different conceptual models regarding the role of the lakes as discharge areas for groundwater from greater depths.

Quantitative flow modelling

The observations and conclusions from the quantitative flow modelling with the GIS and MIKE SHE modelling tools can be summarised as follows:

- The results from the GIS modelling support the assumptions and conclusions in the descriptive model. The model is highly sensitive to the topography, as this is the only parameter determining the flow pattern. Consequently, the simulated locations of recharge and discharge areas are strongly influenced by the local topography. In addition, the flat topography means that small errors in the topographical model (the DEM) may have large effects on the modelled flow pattern. The present analysis shows that there are errors in the DEM, especially along the boundary between "Forsmark 1" and "Forsmark 2". If the DEM is used in combination with the field controlled catchment boundaries, boundary effects (flow anomalies) may occur in such areas.
- Ditches, diverted water courses and other human impacts on the flow system are important in some parts of the model area. These and other types of "man-made structures" are not fully considered in the DEM, and therefore need to be investigated further in order to obtain a proper description of the surface water and near-surface groundwater systems.

- The water balance for the Forsmark area, as calculated with the MIKE SHE modelling tool, agrees with the presented conceptual and descriptive models for the flow system. The transient model simulations for the selected reference year result in an annual total runoff of 226 mm and a total actual evapotranspiration of 441 mm. These values are considered to be reasonable for the Forsmark area, but cannot at present be tested against site-specific measurements. The MIKE SHE model produces a shallow groundwater table, which is in accordance with groundwater level measurements within the area, and with the overall conceptualisation of the system.
- The modelling results show that most of the groundwater flow occurs in the QD. During dry summer periods, the evapotranspiration has a strong influence on the groundwater flow. Except from within typical recharge areas, the dominant water flow direction during dry summer periods is upwards. The groundwater flow is dominated by its vertical component. The horizontal flow paths are short, indicating a small-scale local flow system.
- The results also illustrate the importance of the fracture zones for the groundwater recharge to, or discharge from, the bedrock (the model includes the bedrock to a depth of 150 m, based on the Forsmark 1.1 description of rock hydraulic properties). There is a hydraulic contact between the QD and the fracture zones, where the calculated flow is upwards, although the flow rates are small relative to other components of the water balance. The groundwater flow in the bedrock between the fracture zones is very small. There is a small exchange of groundwater across the bottom boundary of the model (at 150 m depth); the flow direction and magnitude is consistent with the results obtained with the corresponding F1.1 DarcyTools groundwater flow model /SKB, 2004a/.
- Similar to the GIS modelling, the process-based modelling with the MIKE SHE model shows that the locations of recharge and discharge areas are strongly influenced by the local topography. Meteorological parameters (precipitation, snow melt and temperature) also affect the locations of recharge and discharge areas. Within the studied area, the model simulates topographic heights as recharge areas and water courses and lakes as discharge areas throughout the year. However, the locations of local recharge and discharge areas in between these two "extremes" are influenced by the meteorological conditions, and may thus vary during the year.
- The results from the particle tracking simulations show that the groundwater flow is dominated by its vertical component. The catchment "Norra bassängen", Forsmark 2, receives the main portion of the introduced particles in both of the particle release cases studied (uniform release and flow-weighted release). The dominant transport of particles occurs in the fracture zones, which makes the results of the two cases similar. The travel time of a particle is highly dependent on its release position. The shortest travel times are observed for the registration/observation areas underlain by large fracture zones. However, when evaluating the particle tracking results it should be noted that the underlying flow model is based on the F1.1 hydrogeological model of the rock, and that relatively large modifications have been made in the F1.2 model. Thus, large changes in the spatial patterns of particle release areas can be expected when the present model is updated with the F1.2 hydrogeological model of the rock.

Evaluation of uncertainties

As described in Section 3.4.2, a relatively large amount of new data has been available for the F1.2 modelling. Specifically, the evaluation of time series of local meteorological data and surface water and groundwater levels, enabling comparisons between different processes and hydrological sub-systems, has lead to an improved understanding of the site that supports some of the fundamental aspects of the descriptive model. However, significant uncertainties still exist regarding the interactions between different sub-systems and the spatial and temporal variability of model parameters. In particular, the site-specific basis for setting boundary conditions in hydrological models (i.e. meteorological data) and for evaluating calculated water balances and surface water discharges (i.e. discharge measurements) is still quite weak.

The main uncertainties in the present descriptive model can be summarised as follows:

- The available local meteorological time series are very short and longer time series are needed to get reliable correlations to nearby regional SMHI-stations that will allow for long-term hydrological and near-surface hydrogeological modelling.
- Local continuous discharge measurements were not available for version F1.2. Time series from these measurements will be most valuable for the derivation of a more accurate total water balance, and can be used for calibration and validation of the quantitative models. Four discharge stations are now in operation, producing data that will be used in forthcoming model versions.
- The groundwater levels in the area are very shallow. However, there is a bias towards local topographical minima in the location of the monitoring wells. The implications of this bias should be analysed and some additional wells should be located to typical local topographical maxima (recharge areas).
- The evident difference in groundwater levels between the QD and the upper bedrock observed at some of the core-drill sites should be further investigated for a better understanding of hydraulic contact between the QD and the rock. The sites studied are considered to be recharge areas. A similar study in a local discharge area is recommended.
- More information on the hydraulic conditions at and below lakes and wetlands is essential since they have been identified as important discharge areas. Further field investigations including drillings and hydraulic tests are recommended to reduce this uncertainty.
- The locations of recharge and discharge areas at different scales are crucial for the understanding of groundwater system. A combination of complementary field investigations, including hydrogeological and hydrogeochemical methods, and modelling exercises using models based on morphological parameters as well as hydrogeological modelling is recommended. The models should be compared with the vegetation map, the soil type map and the QD map.

The present descriptive model of the surface-hydrological and near-surface hydrogeological system is considered to be acceptable in a qualitative sense, which means that the general description of the hydrological and hydrogeological driving forces and the overall flow pattern will not change substantially in future models. Furthermore, there exists a relatively large amount of quantitative information on, primarily, the hydraulic properties of the QD.

However, as described above significant uncertainties remain regarding certain aspects of the model. No systematic or complete quantification of uncertainties has been performed in the present model version. Some sensitivity studies have been reported, for instance, the comparison of field controlled and DEM-based catchment areas and the flow modelling with anisotropic hydraulic conductivity reported in /Johansson et al. 2005/. In addition, the statistics of measured hydraulic conductivities are presented, which gives an indication of the uncertainty associated with spatial variability. It is expected that sensitivity studies with flow models will be an important part of future modelling efforts.

Implications for future investigations

Presentation and evaluation of the existing database has been an important component of the F1.2 modelling of surface hydrology and near-surface hydrogeology. Based on this work, complemented by a first set of flow simulations, the main uncertainties and the investigations required to reduce these uncertainties have been identified (cf above). Thus, the present modelling results will serve as a basis for the continued site investigations. It can be noted that the investigations identified as important for reducing the uncertainties in the descriptive model include both extensions of presently on-going measurements (e.g. continued meteorological, water level and discharge measurements) and new investigations of, for instance, wetlands.

3.5 Coastal oceanography of the Forsmark area

3.5.1 Methodology

The Baltic coastal waters act as an intermediary link of successive advectional and diffusive processes by which waterborne material released from the geosphere may eventually end up in the world oceans, passing through the Baltic (Figure 3-79) on its way. The primary connection with the geosphere is made directly by leakage through the sea bottom of the coastal zone or via water run-off (discharged diffusely by ground currents, or discretely by localized watersheds such as streams or rivers) entering into surface layers of the coastal zone. The coastal waters also comprise aquatic ecosystems in which entered material can be transformed via food chains. For aquatic ecosystems the rate of water exchange is an indisputable basic parameter that sets the externally forced pace of the material turnover. The overall objective of the present task is to quantify the water exchange of the coastal area in the vicinity of the planned repositories in such terms that projection into the distant future is made possible. To this purpose various water circulation models driven by reasonably simplified but adequate forcing are employed, and the massive resulting hydrographic data generated over a one-year cycle of a typical year are condensed into a conceptual form that can serve as a basis for communication with other involved disciplines. For the Forsmark area (Figure 3-80), the year 1988 was chosen as the most representative year /Larsson-McCann et al. 2002/.

To obtain a quantitative estimate of the water turnover, the concept of Average Transit Residence (ATR-) time defined by /Bolin and Rodhe, 1973/ was used. This well-defined concept was independently adapted to water circulation models by introducing its volume-specific counterpart /England, 1995; Engqvist, 1996/. ATR-time denotes the length of time a particular water parcel (or parts thereof) on the average spends within a specified connected body of water.

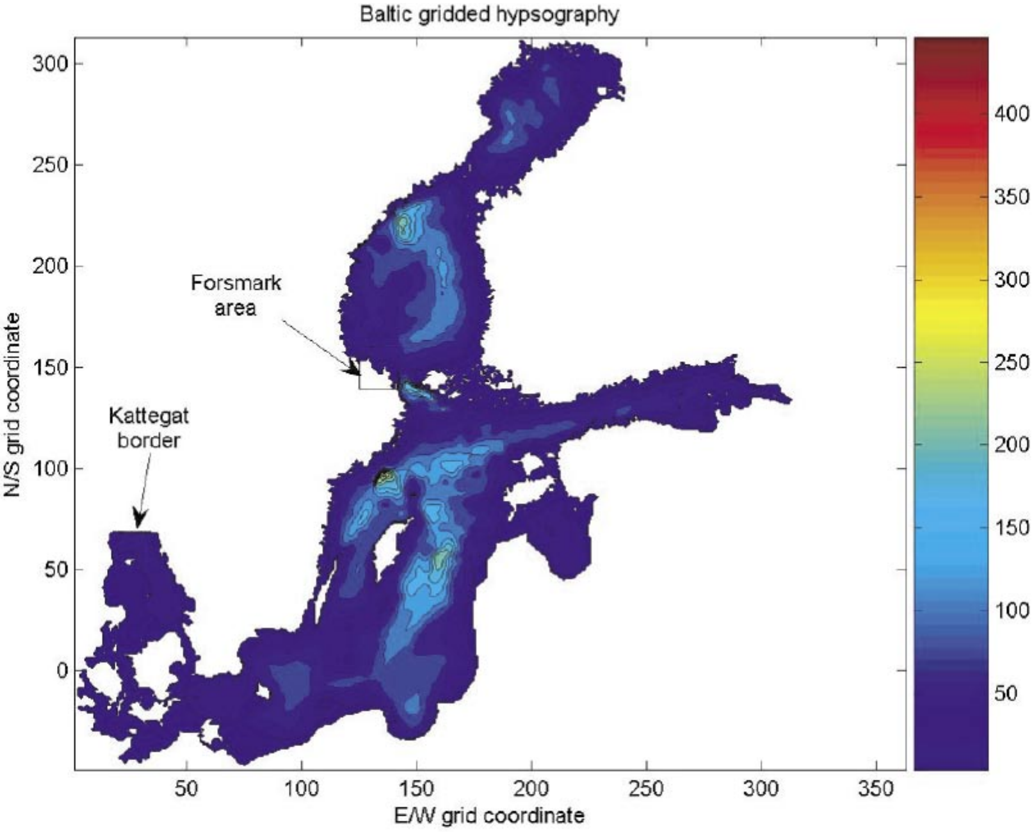

Figure 3-79. The Baltic model grid displaying the Warnemünde hypsographic data. The approximate location of the Forsmark area is indicated, as is the Kattegat model border to the Skagerak.

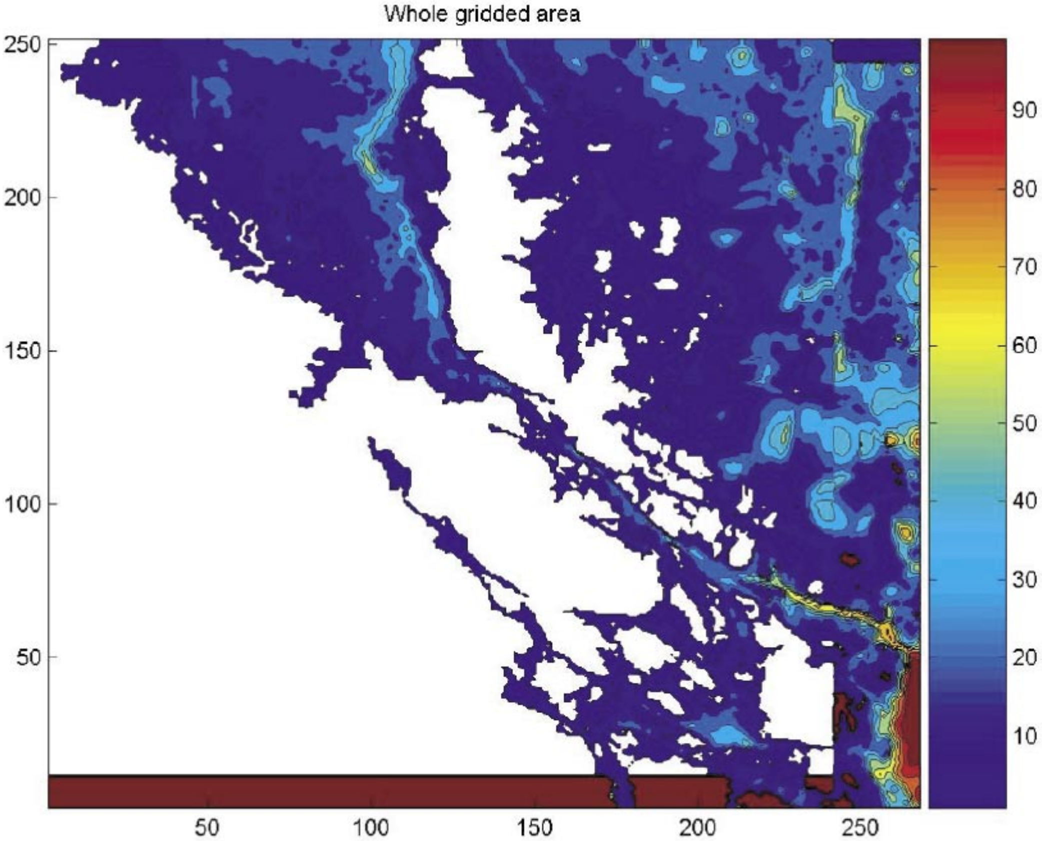

Figure 3-80. The entire gridded Forsmark area with the location of the finally chosen grid indicated as white-coloured land. Along the eastern boundary the transition zone to the adjacent larger-scaled chart is noticeable.

Given information on the mixing time scales in relation to the advective time scales, it is possible to interpret the ATR-times concept for estimating the water exchange over long-term periods, typically one year, by computing its average, maximum and minimum values (together with an appreciation of the variance, e.g. the standard deviation, S.D.) based on computed instantaneous ensembles of the best resolved spatial unit (i.e. grid cell for 3D-models, Figure 3-81). These ATR-times snapshots should be sampled with a shorter time period than the induced inherent temporal variation due to the forcing. Looking at one water parcels present in a reservoir at a given moment and following it individually while measuring the time it takes until it leaves, yields the residence time of this particular water parcel. The ensemble average over all parcels gives the average residence time. Backtracking the same parcels in reverse time until the instant they entered the reservoir /Delhez et al. 2004/ would analogously give the time they already have spent there, which could appropriately be named “age”. The sum of age and residence time thus yields ATR-time. An appreciation of the corresponding water exchange would then be

$$Q_i = \gamma V_i / A_i \qquad \text{(Equation 3-1)}$$

where Q, V and A denote volume flux, volume of the strata and the ATR-time respectively, while the index indicates the stratum’s order number. The parameter γ takes a value of unity for more secluded landlocked areas. In such regimes the water passage is restrained by narrow and shallow straits. This means that the time scales of horizontal mixing increase relative the advective time scale so that horizontally well-mixed conditions ensue.

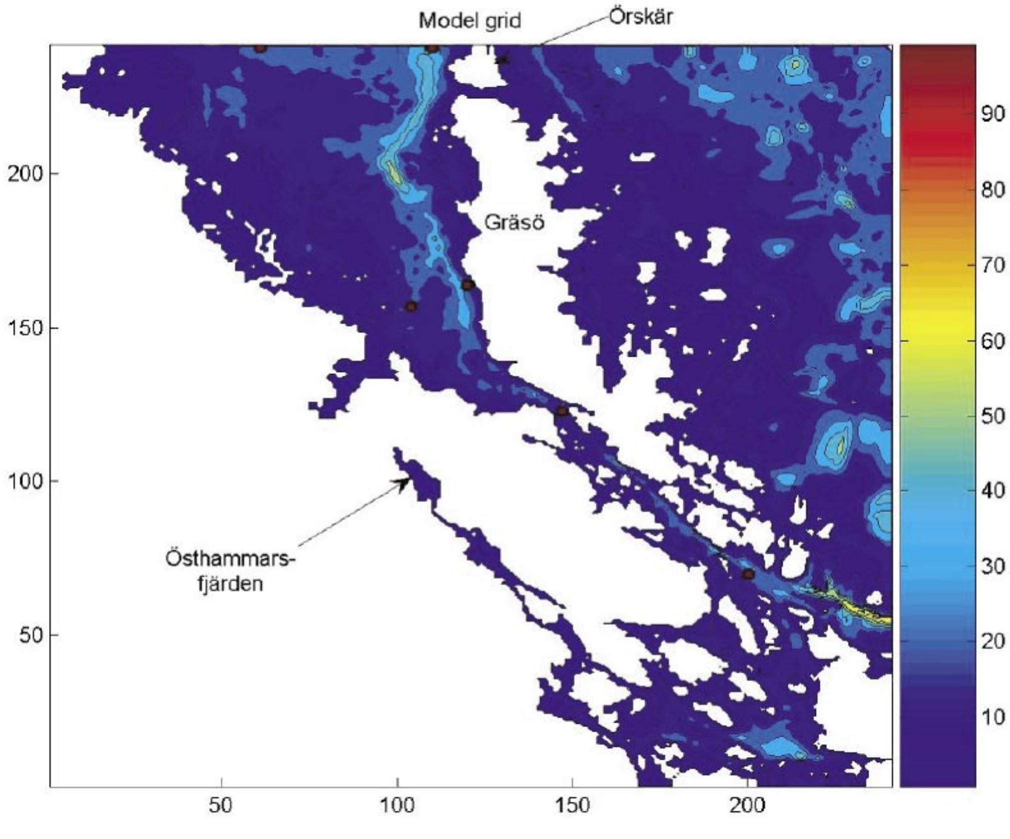

Figure 3-81. The chosen model area with some of the grid cells manipulated manually. In particular the channel connecting Östhammarsfjärden with the southern basins has been made sufficiently wide in a few sections to permit through flow. It is also equipped with a river discharge into this basin with a flow rate that has been modeled in proportion to its catchment area compared to the one of Forsmarksån. The six red spots mark the sites of deployed oceanographic instruments during the validation year 2004.

For plug-flow regimes with insignificant mixing – which would be the typical situation in the open coastal zone – in comparison to the well-mixed regimes, the parameter γ would tend to be closer to 0.5. For pulsating flow regimes, with water being slushed back and forth across the boundaries with the same intensity, a kernel in the center of the region could in principle age indefinitely, making the estimated Q progressively smaller with time, which is in accordance with the decrease of the effective exchange rate. Any level of diffusive mixing in the interior will under such circumstances make the appreciation of Q attain a plateau level.

Computationally, the scalar variable ATR-time of exogeneous water (whether it enters though boundaries or is administered by discharge) is initially set to zero (days/m^3), and the internally contained water is allowed to be aged one (1) time step unit for each time step it resides in the actual domain. Treated as an ordinary passive tracer in the model, the advection and diffusion of this variable will then attain a quasi-steady equilibrium of the water parcels between renewal by entering through the boundaries versus aging by staying resident. Because the exchange of the stratified coastal waters normally follows internal surfaces of constant density (isopycnals) and thus is mainly horizontal, averages in this direction represent a valid data reduction, retaining information on how the various vertical strata are renewed /e.g. Engqvist and Andrejev, 1999/. Vertical mixing, up-/downwelling and other baroclinic processes will act to equalize the age of adjacent strata, but this information is lost so that the full three-dimensional flow structure cannot be recovered. This loss is, however, deemed acceptable since the most intense and lasting vertical mixing takes place in the upper surface layers that will be well-mixed also when entering through the border. The up-/downwelling instances occur with a period time that is normally longer than the ATR-time, mitigating the temporal impact it will have on the long-term average. These circumstances make the appreciation of the volume flux Q attain a plateau level. Thus the ATR-time concept must be used with some caution if the computed values become in parity with the designated one-year cycle time scale that are derived from ecological modeling considerations. The highest a priori likelihood for this eventuality to occur concerns the decisively land-locked areas, which will thus consistently be modelled separately.

The coastal area has been partitioned into a number of non-overlapping sub-basins (SBs) based on the consideration of present underwater structures that in the future with the potential land rise will progressively accentuate the confinement of the water movements to a higher degree. One of these areas is considerably greater than all the others combined, and represents the open coastal section that is regarded as an intermediary stage for the eventual water exchange to the Baltic; this will be referred to as the major coastal SB, Figure 3-82. The computation of ATR-times will be performed with the major coastal SB both excluding and including all the sub-basins to obtain information of how these differ.

The exchange of any of the SBs with the Baltic waters can then be estimated by staging this two-fold exchange in series, an approximation that is valid to the extent that the area of an SB is small in comparison to the total area of the larger computational domain. Some of these SBs are also coincidental, with anticipated leakage points connecting to the geosphere. The water exchange of such a particular sub-basin area relative the Baltic Sea then comes into focus and is achieved in two steps. First, each of these SBs is subjected individually to estimation of their ATR-time, counting all ambient waters including other sub-basins as exogenous. Second, the ATR-time of the major coastal SB relative the Baltic is computed. The uncertainty of this appreciation may be confined within the values using the exclusive and inclusive representation of the coastal basin.

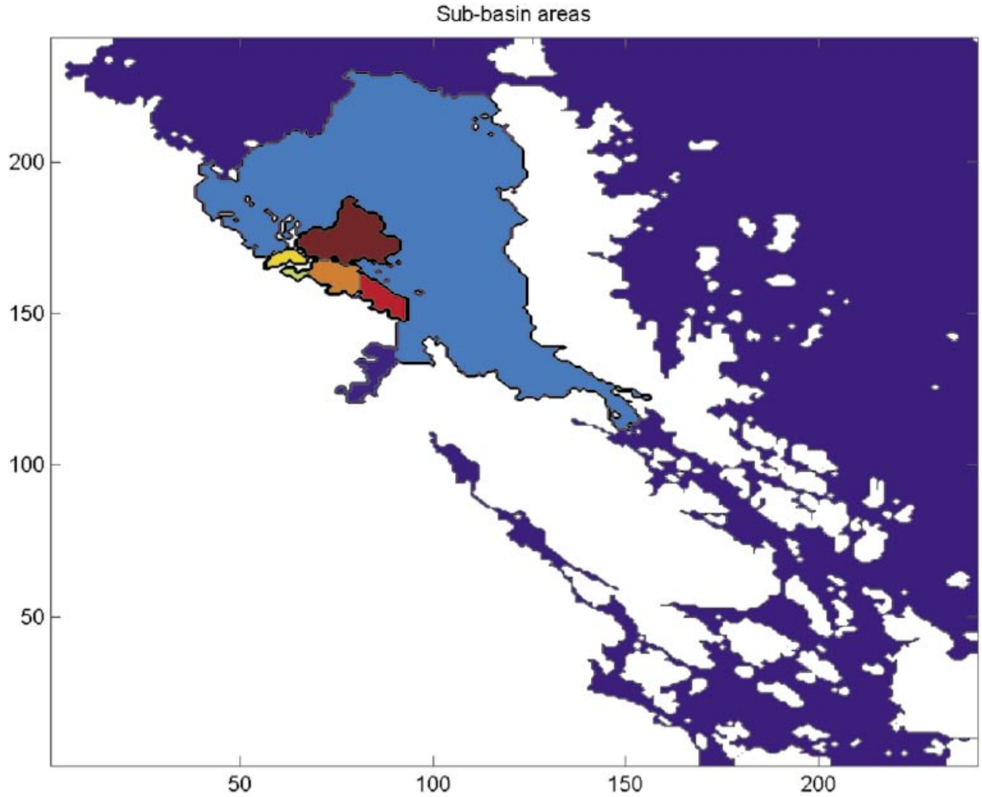

***Figure 3-82.** The location of sub-basins indicated in colors other than dark blue. The coastal major sub-basin is depicted in light blue, and encompasses most but not all of the Öregrundsgrepen embayment.*

3.5.2 Description of conceptual models

The Forsmark area is located in Öregrundsgrepen that appears as a funnel-like open-ended embayment with the wider end toward the north. The narrow southern end is also shallower with a threshold of approximately 25 m. There are notable density fluctuations over a yearly cycle, mainly due to the collective discharge of all the rivers into the Bothnian Bay. Via the strait of Öregrund a connection is made to the southern basins forming an appropriate buffer zone to the area of primary interest. The basins of the buffer zone are connected to the Baltic by one main strait. On its offshore side the long interface to the Baltic contains a few areas that are charted in less detail.

For contemporary coastal oceanography of an open (in contrast to landlocked) coastal section, three-dimensional (3D) models represent the state of the art. When the aspect ratio (vertical scale to horizontal scale quotient) is sufficiently smaller than unity, the hydrostatic approximation applies, and the numerically more efficient shallow water equations can be employed. When more articulated horizontal resolution is demanded, this simplification may eventually need to be abandoned, resulting in considerably increased computational effort. The forcing of the coastal zone model also necessitates providing information about the sea level and density fluctuations at the boundary toward the Baltic. Since only few such measurements are available, this problem can be handled by coupling two 3D-models in a cascade arrangement along simple geometrical interfacial lines so that information of the large-scale Baltic events are transferred into the better resolved fine-scale coastal areas. In any such cascaded coupling arrangement some information must necessarily be lost. A common method also presently employed is to create a buffer zone over which the incoming and outgoing surface waves and similarly two-way internal density wave modes are permitted to be relaxed.

The Baltic model (AS3D) employed in this study /Andrejev and Sokolov, 1989, 1990/ has been developed for the main purpose of providing insight into the circulation of the central Baltic. Its present horizontal resolution is 2'×2' (nautical miles) based on the Warnemünde hypsographic data, Figure 3-79. The horizontal eddy diffusivity is nominally set to 30 (m^2/s), consistent with assuming the grid cells to be well mixed. This model is presently involved in several ongoing Baltic hydrographic studies /e.g. Andrejev et al. 2004a,b/. A thorough testing of this model in comparison to measured data /Engqvist and Andrejev, 2003/ revealed that along an interface to a model area comprising the Stockholm archipelago, the measured salinity and temperature profiles were acceptably well reproduced, with the main difference being an offset in salinity. This evaluation thus strongly increased confidence in the AS3D-model. The heat exchange with the atmosphere is mainly determined by the air temperature; likewise the ice formation and melting processes are formulated in a simple but straightforward manner. This would be a liability if the main concern were to correctly predict the ice situation /e.g. Omstedt, 1999/, but this is not the present objective. For projection into a distant future, climate scenarios could more likely produce a prognosis of shifting air temperatures, while other factors determining the heat exchange (insolation, relative humidity and nebulosity) would probably be more inaccessible. ATR-times of the entire Baltic have been computed by /Meier, 2005/.

The 3D-domain grid has been computed from DEM based on national digitized charts, complemented with shoreline information from economical maps. The grid has been specified in spherical coordinates WGS84 (sweref 99 long lat ellh) with the constraint that to be considered as a wet grid cell at least 50% of the covered area must consist of water. The Forsmark coastal area was resolved horizontally into 0.1×0.1 nautical mile grid cells (Figure 3-80). The final choice of the actual model area (Figure 3-81) includes a large section east of the Gräsö island that would barely seem to influence the strait connection to the southern section of model area that connect to Öregrundsgrepen through Öregrundsund. These waters east of Gräsö are subject to military restrictions and the bathymetry has therefore been only coarsely charted. It is thus advantageous to include these bathymetric uncertainties in a large buffer area that interfaces to the Baltic. The grid resolves the main underwater features of this coastal section, but does more poorly for the near-shore island clusters and for the landlocked waters in the vicinity of Östhammar. In fact when using the objective gridding criterion that at least 50% of area must consist of water meant that these interior waters was disconnected at a few locations. In order attach these to the main computational domain, manual corrections were performed.

3.5.3 Input data and data evaluation

Atmospheric forcing

Synoptically gridded (1°×1°) so-called Müller-data are consistently used from which wind components, air pressure and temperature are extracted every 3 h. One instance of checking the contained wind data against local measurements did not give any reason for concern; on the contrary the local wind measured at Örskär (Figure 3-79) was well represented in the actual synoptic wind /Engqvist and Andrejev, 1999/. For estimates of distant future coastal water exchange, more refined and explicit atmospheric thermal forcing (e.g. humidity, insolation and nebulosity) cannot be relied upon since these will most likely also be associated with large uncertainties. In the place of three unknown parameters it is preferable to have only one unknown, i.e. the surface air temperature.

Kattegat boundary data

For the Baltic model the sea level, salinity and temperature of the Kattegat model border also need to be appreciated. The sea level data are gauged both on the Swedish side (Göteborg) and on the Danish side (Fredrikshavn). The difference between those levels is an important model parameter and provides an appreciation of the geostrophic adjusted flow. It is not possible to reliably reconstruct the absolute vertical position of these gauges from accessible data; instead the long-term average has been used for obtaining this information. The salinity and temperature profiles are mainly determined by North Sea dynamics and display a repeated pattern from year to year /Gustafsson, 2000/; these averages have been used. Aberration from these used averages will have the consequence that a slow drift in the average salinity will be induced which will only marginally affect the dynamics of the surface layers constituting the better resolved local model domain. If sufficient data are available, procedures of data assimilation can be performed.

Freshwater discharge data

The freshwater discharge of the two streams Forsmarksån and Olandsån (retrieval ID: Sicada_04_77) have a discharge capacity (Figure 3-83) that could contribute significantly to the water exchange of the coastal region by inducing estuarine circulation, at least in the spring when the volume fluxes peaks. These fluxes have been calculated from the HBV-model for the actual type-year 1981 (Jenny Ryman, SMHI; pers comm).

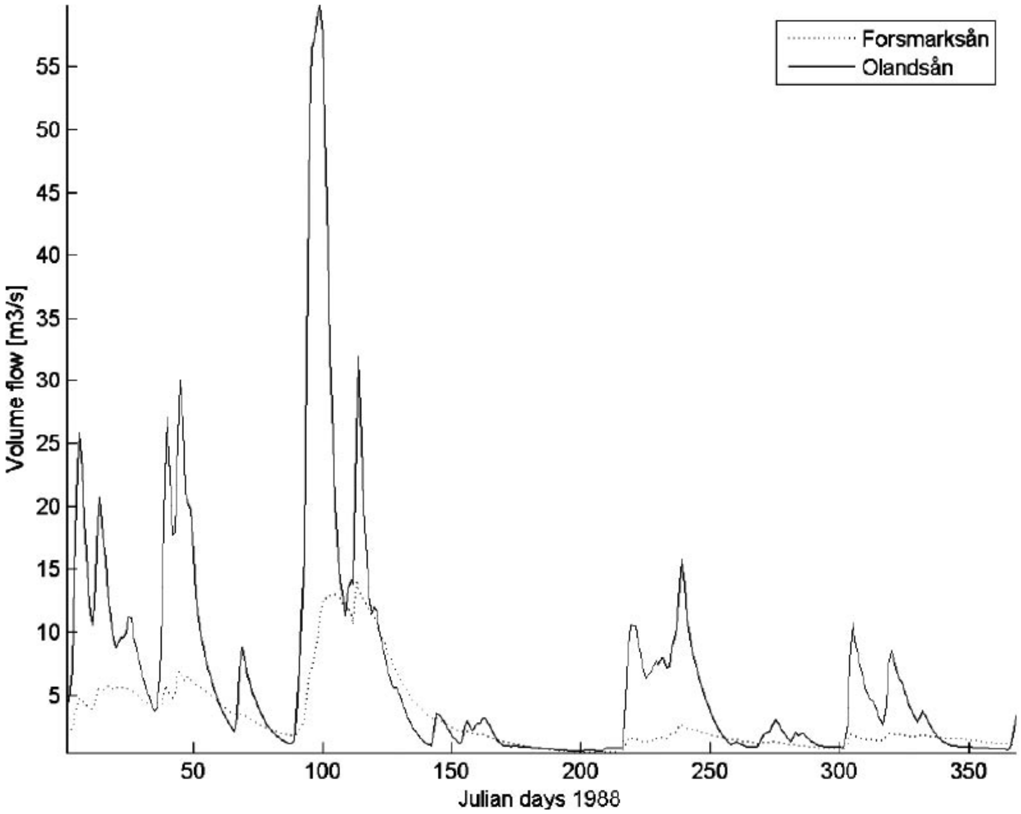

Figure 3-83. *Water discharge of the two major streams Forsmarksån and Olandsån 1988.*

3.5.4 Quantitative models

The complete set of equations of the AS3D-model including boundary formulation and numerical scheme is given in /Andrejev and Sokolov, 1997/, making it superfluous to reiterate them here. In the present version, the Baltic area including the section of its Kattegat boundary is resolved by a 315×363 cell grid. The integration time step is normally 1 hour, except on storm occasions when it has been lowered to 0.5 hour. This model is under continued development and is presently used in several ongoing Baltic hydrograpic studies: /Engqvist and Andrejev, 2003; Andrejev et al. 2004a,b/.

The first coupling of two cascaded AS3D-models was performed by /Engqvist and Andrejev, 1999/, in which previous oceanographic investigations and modelling efforts are also reviewed. The Forsmark area (Figures 3-79 and 3-81) with the planned repository is located centrally in the north/south direction in a grid that contains 241×241 grid cells. The horizontal eddy diffusivity has been set to 20 (m^2/s) and the integration time step has necessarily been set to as low as 1.2 minutes. The basic equations are essentially identical to those of the Baltic model, but one difference is that the interfacial border to the Baltic is affected by the computed sea level, salinity and temperature data of the Baltic model.

The resulting ATR-time estimates are presented in Table 3-19 giving the minimum, average and maximum values over the year cycle together with the standard deviation for each SB. The yearly average of bi-monthly snapshots of the ATR-time (resolved into grid cells) is depicted in Figure 3-84. As exogenous water, in addition to the discharge of the two streams (Figure 3-83), is the resulting area considered that lies outside the conjoined area of all the individual SBs. The corresponding volume fluxes across the interfaces between the SBs have been computed and are used in the section dealing with the Ecological models, Chapter 4.

Table 3-19. ATR-time (days) estimates for seven of the nine SBs. The second is the major coastal basin that to a large extent but not exactly coincides with Öregrundsgrepen. These data are computed with all water outside an individual SB considered as exogenous. The vertically integrated (averaged by volume) statistics for SB15 through SB19 are calculated directly from the 3D-model results, which have a temporal resolution of one hour. Two of the SBs were not sufficiently resolved by the 3D grid and the corresponding calculation will have to wait until their basin and strait hypsographies are available.

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

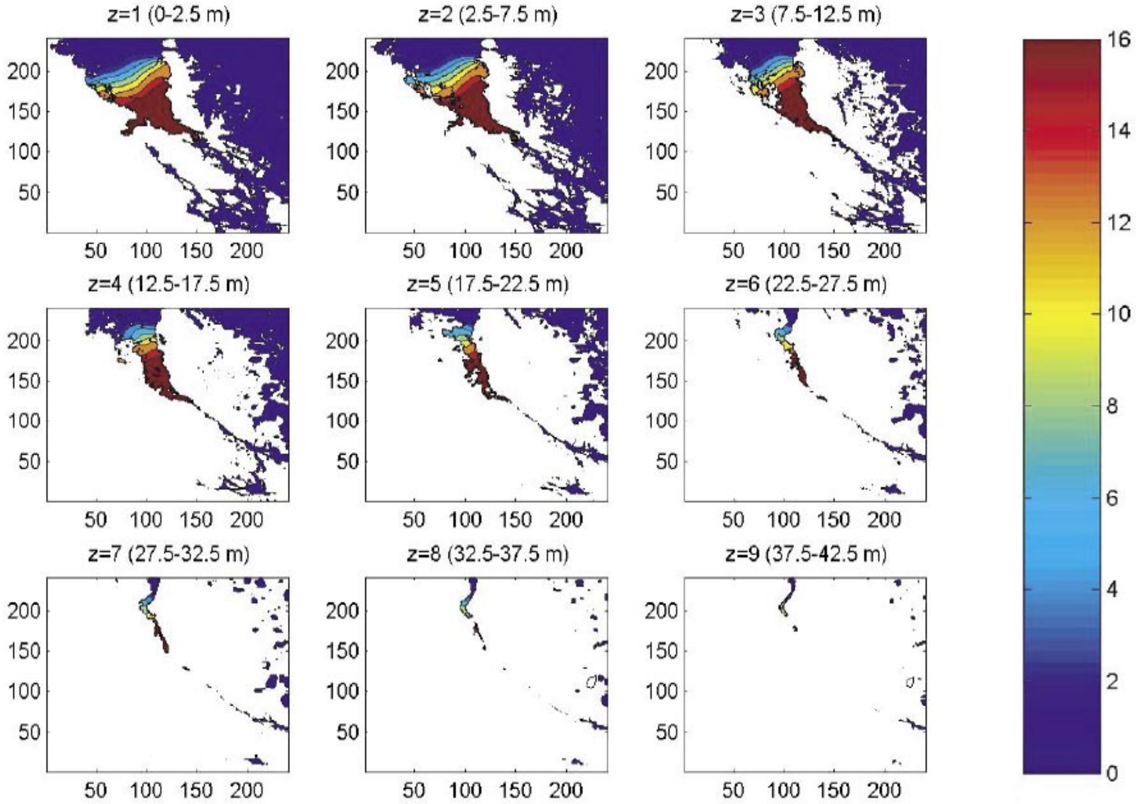

Figure 3-84. *ATR times of individual grid cells calculated as a yearly average of the type-year 1988 considering all SBs individually ventilated relative adjacent basins in order to make the plots comparable to Table 1. Exogeneous water is entering from outside the boundaries of each SB and as the discharge of the two streams, Figure 3-83. The calculation was based on bi-monthly samples of the ATR times for the different strata down to a depth (42.5 m) that approximately corresponds to the deepest part of the conjoined area. Even for the innermost part of the major coastal sub-basin (Öregrundsgrepen) the average ATR times are safely smaller than one year.*

3.5.5 Confidence and uncertainties

No model run is complete without a sensitivity analysis. An encompassing such analysis with regard to sensitivity of ATR-time variations to the forcing factors was performed in /Engqvist and Andrejev, 2000/. An ongoing thorough field data program with the sole aim of collecting systematic validation data (Figure 3-81) over a full-year cycle in the Forsmark area will determine decisively the level of confidence with which these models can be invested. One general point is that scarcity of Baltic salinity and temperature data for initialization or assimilation purposes limits the prospect for differentiating the contemporary interannual Baltic hydrography. For longer time scales, sensitivity analyses of the Baltic dependence on its forcing /Gustafsson, 2004b/ may be used.

3.6 Chemistry

3.6.1 Introduction

A detailed description of the chemical properties in different parts of the ecosystem constitutes necessary background knowledge and serves with input data for the modelling work in many of the other disciplines, i.e. hydrological and transport modelling, understanding of the historical development of the site and for the safety analysis. A comprehensive description of the chemical properties in surface ecosystems will include a wide array of parameters (elements and compounds) and processes, varying both in time and space in several different media (water, regolith and biota). Water is by far the most important medium for transport of elements and matter. The site investigations concerning chemical properties in the surface system have so far been concentrated to analyses of samples from surface water and near-surface groundwater, and to some extent also to samples from the overburden. The site investigation programme for 2005 is planned to include further analyses of chemical properties in the overburden and also in biota. No new information concerning chemical deposition in the Forsmark area is available for the current version of the site descriptive model

The results presented in this chapter represent only a part of the total data produced within the programme for chemistry in surface and near-surface groundwater, and the aim is mainly to give a first characterisation and understanding of the site-specific data. The surface water sampling programme is described in detail in /Nilsson, 2003/, together with a compilation of primary data from the first year of sampling, and a detailed compilation and evaluation of primary data from the period 2002–2004 is given in /Sonesten, 2005/. Data and results from chemical investigations of the overburden is presented in Section 3.3 (Quaternary deposits/overburden).

3.6.2 Input data and methods

Data on surface water chemistry has been collected biweekly to monthly from March 2002, and the sampling programme includes 8 stream, 6 lake and 3 sea sampling sites (Figure 3-85). The stream and lake sampling sites represent 4 different drainage areas in the regional model area. The number of sampling occasions for each sampling site varies for most parameters between 20 and 40, the lower numbers mainly due to weather conditions (storm, unsafe ice-cover, dried up or frozen streams) occasionally preventing sampling of some sites. Analysed parameters include, for most samples, major cations and anions, nutrients, organic compounds and O_2 (Table 3-20). Water temperature, pH, conductivity, salinity and turbidity were determined in the field. Moreover, trace elements and stable and radiogenic isotopes were analysed at 3–4 sampling occasions per year.

Data on near-surface groundwater has been collected from totally 41 groundwater monitoring wells (Figure 3-86). These wells are sampled 4 times per year, and most of the wells have been sampled at more than occasion. The analysed water was sampled from levels situated in the glacial till or at the transition zone between till and bedrock. One of the wells, SFM0060, is situated in glaciofluvial material, which often has a high hydraulic conductivity. Most of the wells are situated on land, but some are situated in lakes or in shallow bays. Till samples from all wells, except from those situated at sites covered by water, were analysed for grain size composition and $CaCO_3$ content. All analysed samples contained more than 5% $CaCO_3$ (see the regolith chapter).

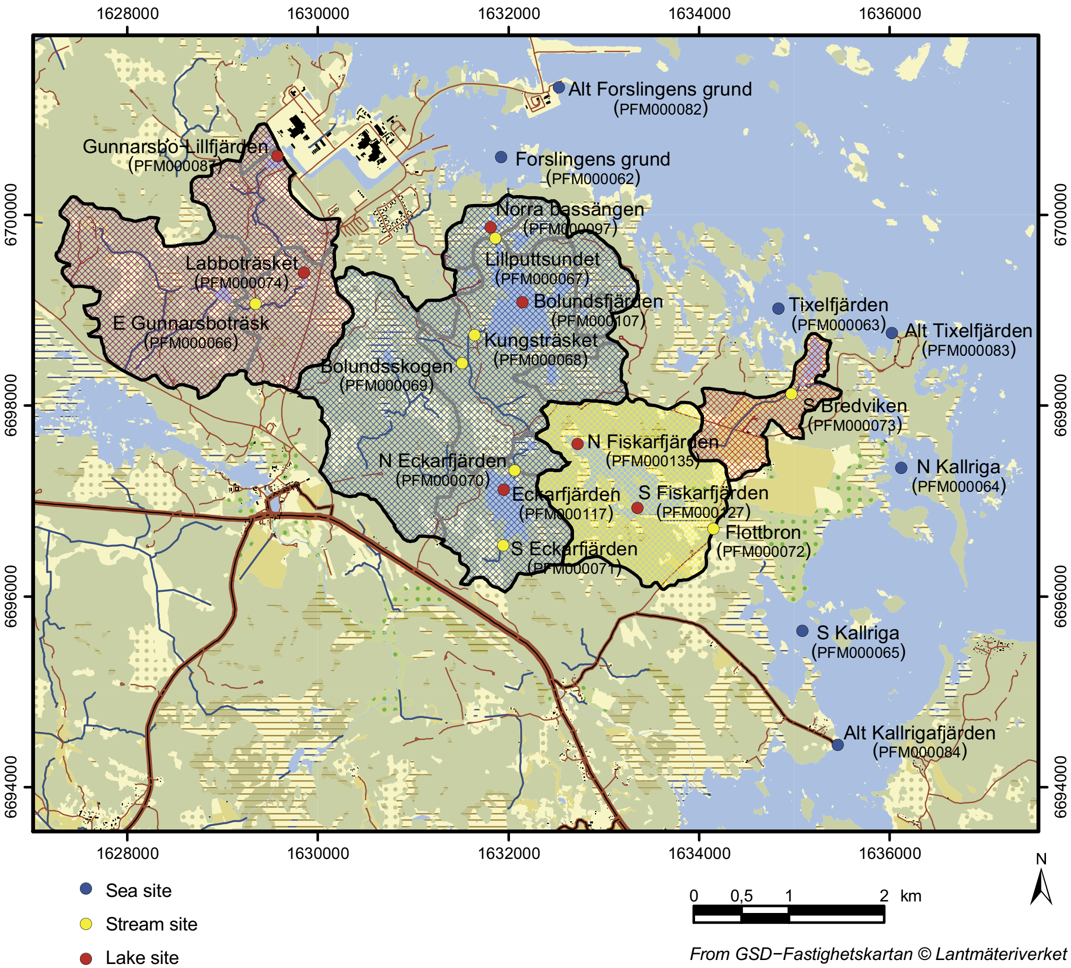

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Figure 3-85. *Location of sampling sites for surface water chemistry in lakes (red), streams (yellow), and the sea (blue) in the Forsmark area. Water divides between the different catchment areas are shown and the SKB id-code for each sampling site is given within brackets.*

Table 3-20. Parameters analysed in the site investigation programme for chemical properties in surface waters and near-surface groundwater.

Main cations and anions	**Na, K, Ca, Mg, Si, Cl HCO_3^-, SO_4^{2-} and S^{2-}**
Nutrients and organic compounds	NO_2-N, NO_3-N, NH_4-N, N-tot, P-tot, PO_4, POP (Particulate Organic P), PON (Part. Org. N), POC (Part. Org. C), DIC (Dissolved Inorganic C), DOC (Dissolved Org. C), TOC (Total Org. C), Chlorophyll-*a*, Chlorophyll-*c* and Pheopigment
Trace elements	U, Th, Al, As, Sc, Cd, Cr, Cu, Co, Hg, Ni, Zn, Pb, V, Rb, Y, Zr, Mo, In, Cs, Ba, La, Hf, Tl, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu
Stable isotopes	^{18}O, ^{2}H, ^{13}C, ^{37}Cl, ^{10}B, ^{34}S
Radiogenic isotopes	^{226}Ra, ^{222}Rn, ^{238}U, ^{235}U, ^{234}U, ^{232}Th, ^{230}Th,^{14}C, ^{3}H and ^{87}Sr
Other data	Temperature, pH, conductivity, salinity, turbidity and O_2

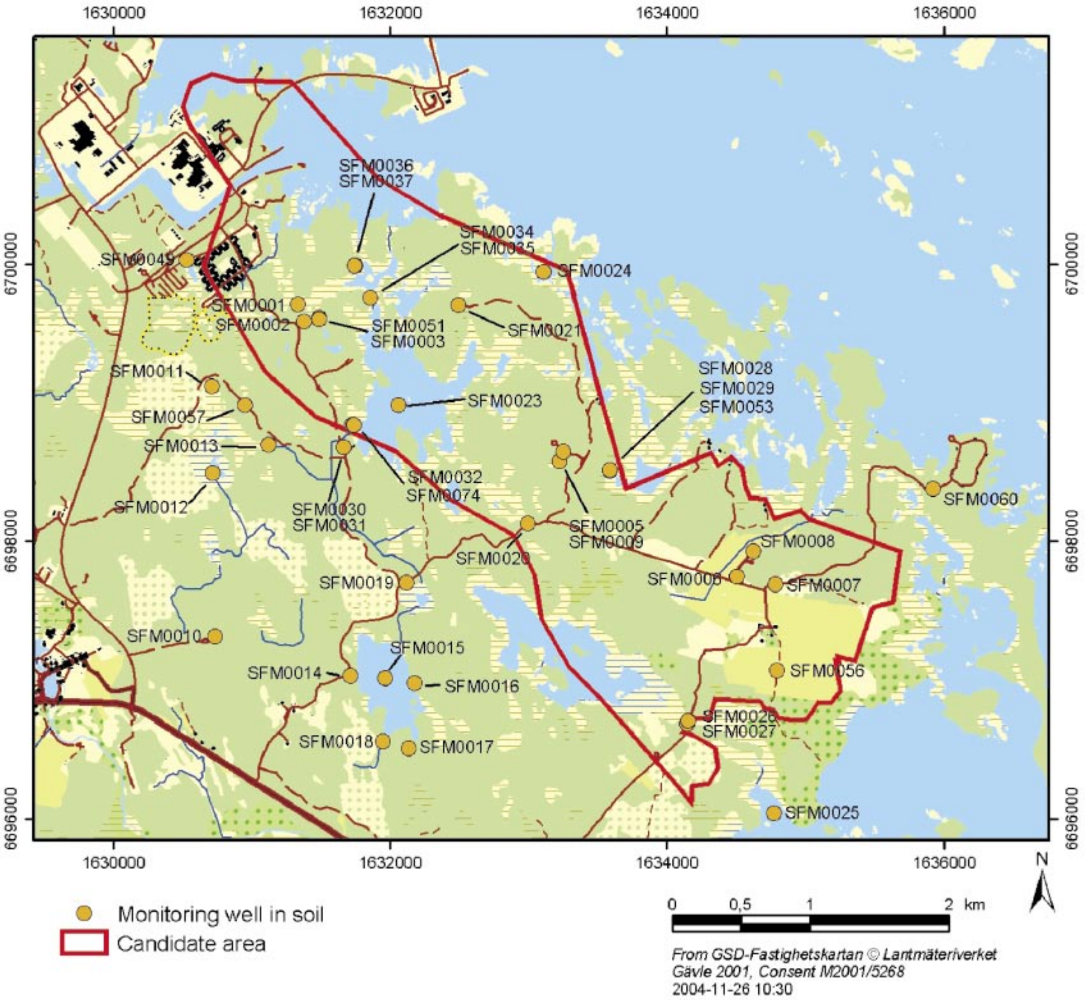

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Figure 3-86. *Location of groundwater monitoring wells in the Forsmark area, sampled for water chemistry.*

Analysed parameters include, for most samples, major cations and anions, nutrients, organic compounds and O_2 (Table 3-20). Water temperature, pH, conductivity, salinity and turbidity were determined in the field. Moreover, trace elements and stable and radiogenic isotopes were analysed at 1–4 sampling occasions per year. The average concentrations of different elements in the analysed water samples have been calculated for each of the wells. These average values are used in most of the forthcoming discussion. For a more detailed description over the chemical parameters analysed in the site investigation programme, see /Nilsson, 2003a,b/.The results for Mg, Ca, HCO3, Cl, SO4, Mn and pH was compared with the median values for groundwater from open aquifers in till or wave washed sediments situated in northern Uppland /Naturvårdsverket, 1999/. The results from Forsmark were also compared with values for the whole of Sweden /Aastrup et al. 1995/. The correlation coefficients between some of the analysed elements are shown in Table 3-22. The concentrations of Mg, Na, Cl and ^{18}O in groundwater from Quaternary deposits were compared with that in lake and seawater.

Data on the water chemistry of precipitation have regularly been collected from one sampling location; however, no evaluation of the chemical composition of the precipitation has been performed yet. No data on the chemistry in biota has so far been collected in the site investigations.

3.6.3 Description of chemical properties

Surface waters

Lakes and streams

Similar to most surface waters in the north-eastern parts of Uppland, the lakes and streams in the Forsmark model area are characterised by high pH, high concentrations of major ions and high electrical conductivity. As mentioned previously, this is a combined effect of the calcium-rich deposits in the area, and of the recent emergence of the area from the Baltic Sea. Due to both chemically and biologically induced processes in the lake water, the amounts of nutrients (e.g. phosphorus) transported to the lakes may be effectively reduced by precipitation of calcium-rich particulate matter. Because of this, the phosphorous concentration in lakes and streams is generally low (Figure 3-87). The nitrogen concentration, on the other hand, tends to be high, or even very high (Figure 3-88), due to a combination of high input and low biotic utilisation /Brunberg and Blomqvist, 1999, 2000/. Generally, the chemical conditions in both the fresh and marine surface waters in the Forsmark area are relatively unaffected by anthropogenic influence. Taken together, these conditions give rise to a unique type of lake in the Forsmark area, the oligotrophic hardwater lake.

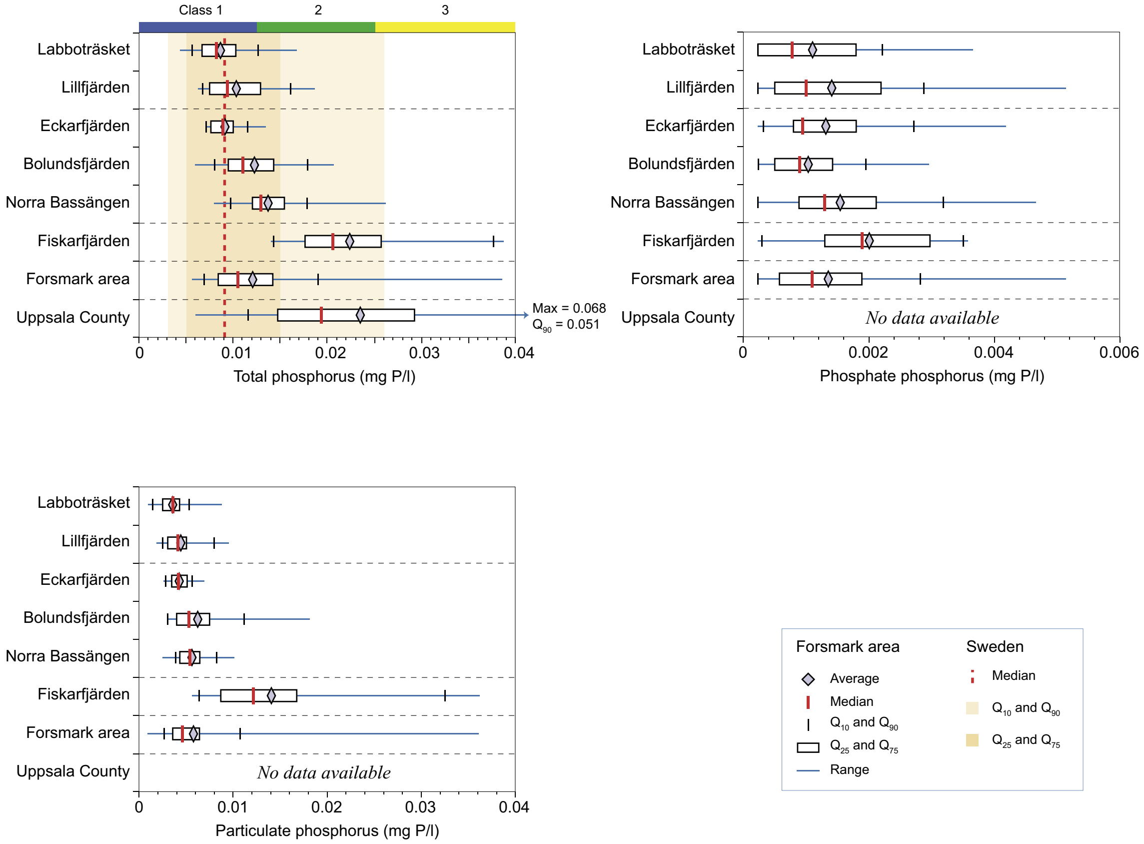

Figure 3-87. *Total phosphorous, phosphate phosphorous, and particulate organic phosphorous (POC) in lakes in the Forsmark area, Uppsala county, and Sweden. Environmental quality criteria for total phosphorous according to /SEPA, 1999/ is shown in the top of the figure, and the corresponding distribution for the national reference data is given as shaded areas (10, 25, 75, and 90 percentiles) and a broken line (median) (from /Sonesten, 2005/).*

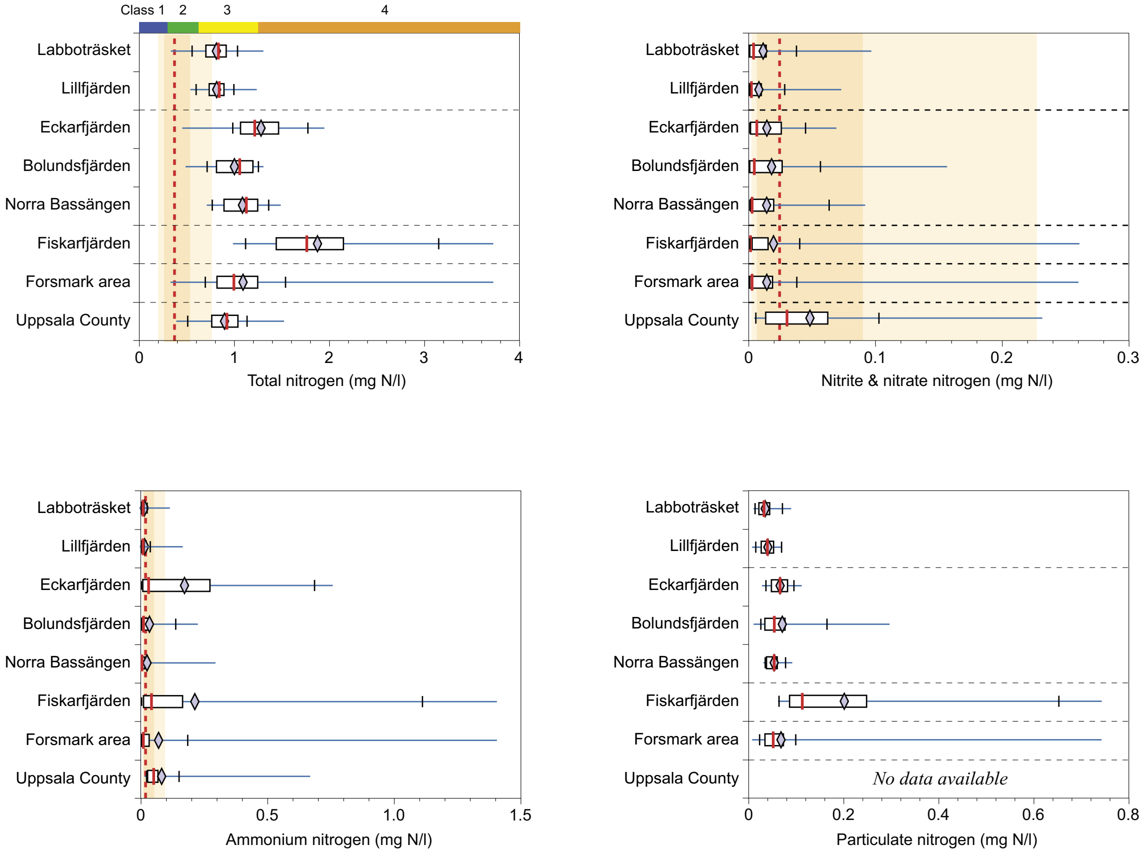

Figure 3-88. *Total nitrogen, nitrite and nitrate nitrogen, ammonium nitrogen, and particulate organic nitrogen (PON) in lakes in the Forsmark area, Uppsala county, and Sweden. Environmental quality criteria according to /SEPA, 1999/. Explanations are given in Figure 3-87 (from /Sonesten, 2005/).*

The catchment areas in the model area are generally small, which means that some of the streams periodically show very low discharge or even get dry. The four different catchment areas investigated in the programme for surface water chemistry are to a large degree similar in the chemical composition, but there are also numerous differences both between the catchment areas and within them:

1. The alkalinity is very high in the whole Forsmark area, but the level in the Gunnarsbo-Lillfjärden catchment is among the highest of all investigated freshwaters. Beside the elevated calcium level, most other dissolved ions are found at lower levels, comparable to other freshwaters in the area. However, the levels are generally markedly higher than in other Swedish lakes.

2. The chemical composition in the Norra Bassängen catchment varies considerably, both at single sampling sites and between the sites. The large variation could partly be an effect of the comparatively large catchment area. The catchment area can be divided into three different sub-catchments, which partly possess different chemical composition.

   The Eckarfjärden sub-catchment is situated in the upper part of the Norra Bassängen catchment. The water in the outlet of Eckarfjärden has lower levels of many dissolved ions compared to the other parts of the catchment area. The main exceptions are Ca, K, I, Li, Fe, and Mn. Occasionally, the outlet possess high ammonium concentrations due to nitrogen released from the lake sediments during episodes with low oxygen levels.

There is also a considerable variation within the Eckarfjärden sub-catchment. In general, the composition in the outlet and in the lake is roughly the same, whereas the inflow deviates markedly. Many dissolved ions and nutrients are found at comparatively higher concentrations in the inlet, whereas the sodium and chloride concentrations are higher in the lake and in the outlet. Two possible explanations to the differences may be proposed. First, the inlet does not cover the whole drainage area of Eckarfjärden and the differences may be a result of inflowing water with very different origin. Secondly, the lake may act as a sink for certain substances due to biogenic precipitation of $CaCO_3$. Substances like phosphate and iron may co-precipitate together with the $CaCO_3$. However, this is not an irreversible process, and the nutrients and the calcium may to some extent be released when dissimilative processes are dominating.

Besides the calcium concentration, the water from the sub-catchment Bolundsskogen generally contains more dissolved ions than the water from the Eckarfjärden area. However, in comparison to the lower parts of the Norra Bassängen catchment, i.e. the subarea around Norra Bassängen and Bolundsfjärden, the ion levels are markedly lower, at least during episodes with brackish water intrusions that heavily affect the chemical composition in these lower stretches of the water system. Actually, there seems to have been a severe brackish water intrusion in this area, all the way up to Bolundsfjärden, before the investigations started in March 2002, as the level of many dissolved ions decrease considerably during the whole first year of investigation.

3. The water in the Fiskarfjärden catchment area is generally, together with the inlet to Bredviken, the most nutrient rich of the freshwaters in the Forsmark area. Like in Eckarfjärden, do the water in both Fiskarfjärden and in its outlet, Flottbron, possess high levels of ammonium during episodes with low amounts of dissolved oxygen.
4. The Bredviken catchment is only monitored at the inlet to the lake, and its chemical composition is the most deviating of all the freshwaters in the area. It possesses among the highest levels of nutrients and many dissolved ions, whereas the levels of organic carbon and the marine ions Na, Cl, Br, and I are low. The alkalinity is considerably higher than in the other areas. The reason why this chemical composition deviates is unclear, but it may be caused by the agricultural activities in the drainage area and, probably most important, the soil composition in the area, which is dominated by clayey moraines.

Many of the investigated chemical parameters show pronounced seasonal variations, coupled either to the production and degradation of organic matter, or to seasonal changes in the amount or composition of inflowing water. The production of organic matter is directly affecting the availability of substances needed for primary production, e.g. phosphate, nitrate, ammonium and silica. An indirect effect of primary production in the Forsmark lakes is the biogenic precipitation of calcite, caused by increased pH during periods of high primary production, which give rise to predictable variations of Ca and P concentration in lake water.

Several of the Forsmark lakes are still not completely isolated from the Baltic Sea because of the small altitude differences in the area. The lakes Norra Bassängen and Bolundsfjärden are both strongly affected by episodic intrusions of brackish water, and there are also indications on intruding brackish water in Lake Fiskarfjärden during the site investigations (see Figure 3-89).

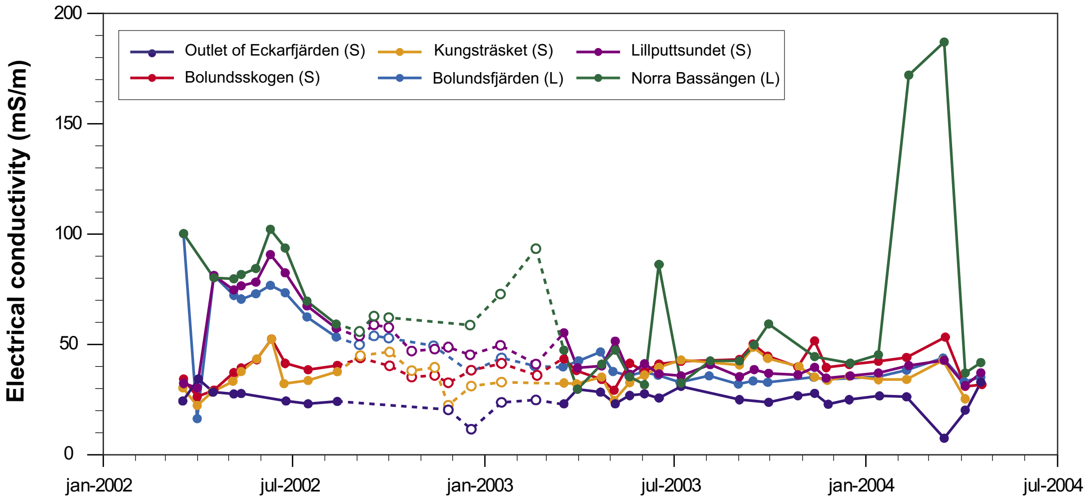

Figure 3-89. The amount of dissolved ions, measured as the electrical conductivity, in some lakes (L) and streams (S) in the Norra Bassängen catchment area. Open symbols denote results from in situ measurements, whereas all other observations are from laboratory measurements.

Sea

Much of the surface water from the regional model area drains into a relatively confined coastal basin, Asphällsfjärden, where the sampling site Forslingens grund (PFM000062) is situated. One would expect that the water chemistry at this site should be affected by the discharge of freshwater and therefore deviate from the chemistry in the open sea. However, since the water turnover in the basin Asphällsfjärden is strongly increased by the intake of cooling water to the Forsmark power plant, the chemical conditions of this site remains more of the open sea. This means that two of the sampling sites in the sea are situated close to the open sea, and show similar and relatively constant chemical conditions. The third site is situated in the shallow bay Kallrigafjärden, which is strongly influenced by the outflow of two rivers entering the bay. The chemical conditions at this site are therefore much more variable, depending on the actual mixing between the ion-rich brackish water and the ion-poor and nutrient-rich freshwater from the two rivers.

Near surface groundwater

The chemical composition of the groundwater is a result of both present and past processes. The Forsmark area has been completely covered with brackish water, and the sea covered large parts of the model area only a few hundred years ago. Relict saline groundwater may consequently remain, especially in areas where the Quaternary deposits have a low hydraulic conductivity /cf Aastrup et al. 1995/. The chemical composition of the groundwater may also be affected by chemical weathering, which leaches metals and other elements to the water. Chemical weathering is especially evident in areas where the overburden and/or bedrock contains calcite, which often causes high alkalinity and high concentrations of Ca in the groundwater /Aastrup et al. 1995/. Most Quaternary deposits in the Forsmark area contain calcite, which has been transported from a limestone area situated north of Forsmark (see Section 3.3). Antrophogenic emissions may also cause high groundwater concentrations of some elements, both on a local and regional scale. Forsmark is, however, not situated close to any large sources of such emissions.

Some of the results from the investigation of groundwater chemistry in the Forsmark area are summarised in Table 3-21. The chemical composition of the groundwater in the Forsmark area differs from the rest of Sweden with regard to several elements /Aastrup et al. 1995/, and to some extent the Forsmark area differs also from other parts of northern Uppland. The groundwater in northern Uppland is characterised by relatively high pH and Ca concentrations /Naturvårdsverket, 1999/. This is an effect of the high calcite content in many Quaternary deposits in the area.

The median concentrations of Ca, Mg and especially Cl and HCO_3 in the Forsmark area are, however, also above the median values for Uppland /Naturvårdsverket, 1999/. The median value for Cl is more than twice as high in Forsmark (50.9 mg/l) compared to the median value for groundwater in till in northern Uppland. Some of the wells in the Forsmark area have Cl concentration far above the median value for the region (Figure 3-90), which also explains the high average Cl value (Table 3-21). The high Cl concentration is caused by the fact that the Forsmark area until recently has been covered by the sea. The occurrence of relict saline water is also reflected by the correlation between Cl and several elements associated with saline water (Na, Mg, Li, Sr, K and Br; see Table 3-22). The high salinity is further reflected by the high electric conductivity in water from some of the wells (Figure 3-90).

The most saline water was recorded in groundwater sampled from Quaternary deposits below lakes, wetlands and bays (Figure 3-90). The highest average Cl concentration (3,894 mg/l), which was recorded in water from SFM0023 in Lake Bolundsfjärden, is in fact higher than the present Cl concentration in the Baltic Sea (2,600 mg/l) /cf Laaksoharju et al. 2004/. This may indicate that water at that site has remained from earlier, more saline, postglacial phases of the Baltic Sea. It is also possible that the high Cl concentration in groundwater from this well is an effect of discharge from the bedrock, where the groundwater has a high salinity /Laaksoharju et al. 2004/. It is at present not possible to make any conclusions regarding the high salinity in water from SSM0023.

Table 3-21. Chemical composition of groundwater from monitoring wells in the Forsmark area. Median values for some elements in groundwater in till and wave washed sediments > 4 m from northern Uppland, are shown on the right column.

	Average	Median	Max	Min	N	Median Uppl
Na (mg/l)	230	32.3	1,596	5.76	37	
Ca (mg/l)	131	110	541	29.0	37	89 (Ca+Mg)
Mg (mg/l)	29.7	11.7	177	4.40	37	
K (mg/l)	12.8	8.22	64.9	1.82	37	
HCO_3 (mg/l)	376	378	721	150	37	180
Cl (mg/l)	437	50.9	3,894	5.1	36	21
SO_4 (mg/l)	86.4	48.7	359	1.04	36	40
Si (mg/l)	5.73	5.43	9.89	3.30	37	
Mn (mg/l)	0.261	0.20	0.990	0.023	21	0.03
Li (mg/l)	0.016	0.011	0.116	0 (below detection limit)	33	
Sr (mg/l)	0.590	0.233	3.90	0.080	37	
Cond. (mS/m)	305	90.0	2,250	51.6	24	
pH	7.31	7.26	7.83	6.65	24	7.4

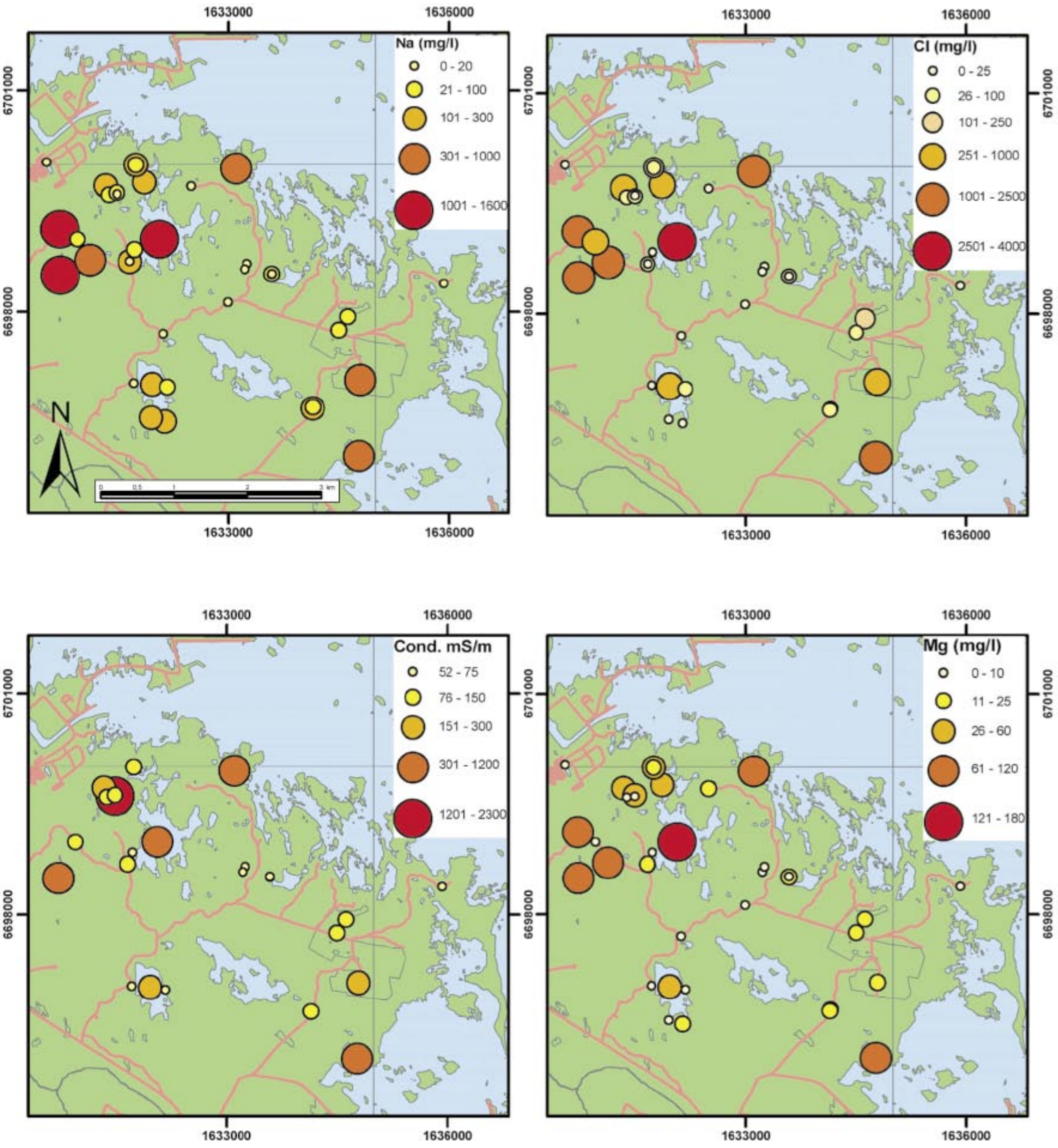

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Figure 3-90. *Median values for Na, Cl, conductivity and Mg in groundwater monitoring wells in the Forsmark area.*

The present bays still constitute brackish water and the groundwater from the two wells situated in bays (SFM0024 and SFM0025) is therefore brackish. The lakes and wetlands are situated in the lowest topographical areas, which most recently has been covered by saline water. Furthermore, these areas are often covered by clay /e.g. Sohlenius et al. 2004/, which has a low hydraulic conductivity and consequently obstruct the water circulation.

The glaciofluvial esker (Börstilsåsen) is situated close to the coast and the groundwater may therefore be affected by saline water. The Cl concentration is, however, low (7 mg/l) at the only site which is situated at the esker (SFM0060), indicating that the groundwater in that part of the esker is not affected by saline water.

The pH is above 7 in water from all wells, except in water from SFM0023 (Figure 3-91). The high pH is an effect of $CaCO_3$ buffering the water. The $CaCO_3$ content was not analysed in the till from SFM0023, but the relatively low pH (6.65) at that site may indicate that the till lacks calcite.

Both Na and Mg are well correlated with Cl (Table 3-22; Figure 3-92 and Figure 3-93). Sodium and especially Mg are, however, depleted when compared with the dilution line for seawater, i.e. the concentrations of these elements are lower than in seawater at a given Cl concentration. Sodium and Mg must therefore be removed from the water by processes taking place within the Quaternary deposits, e.g. cation exchange. Manganese may also be removed by reactions with clay minerals. /Laaksoharju et al. 2004/. It is likely that other elements occurring in saline water, e.g. K, are partly removed from the water in a similar way /cf Laaksoharju et al. 2004/.

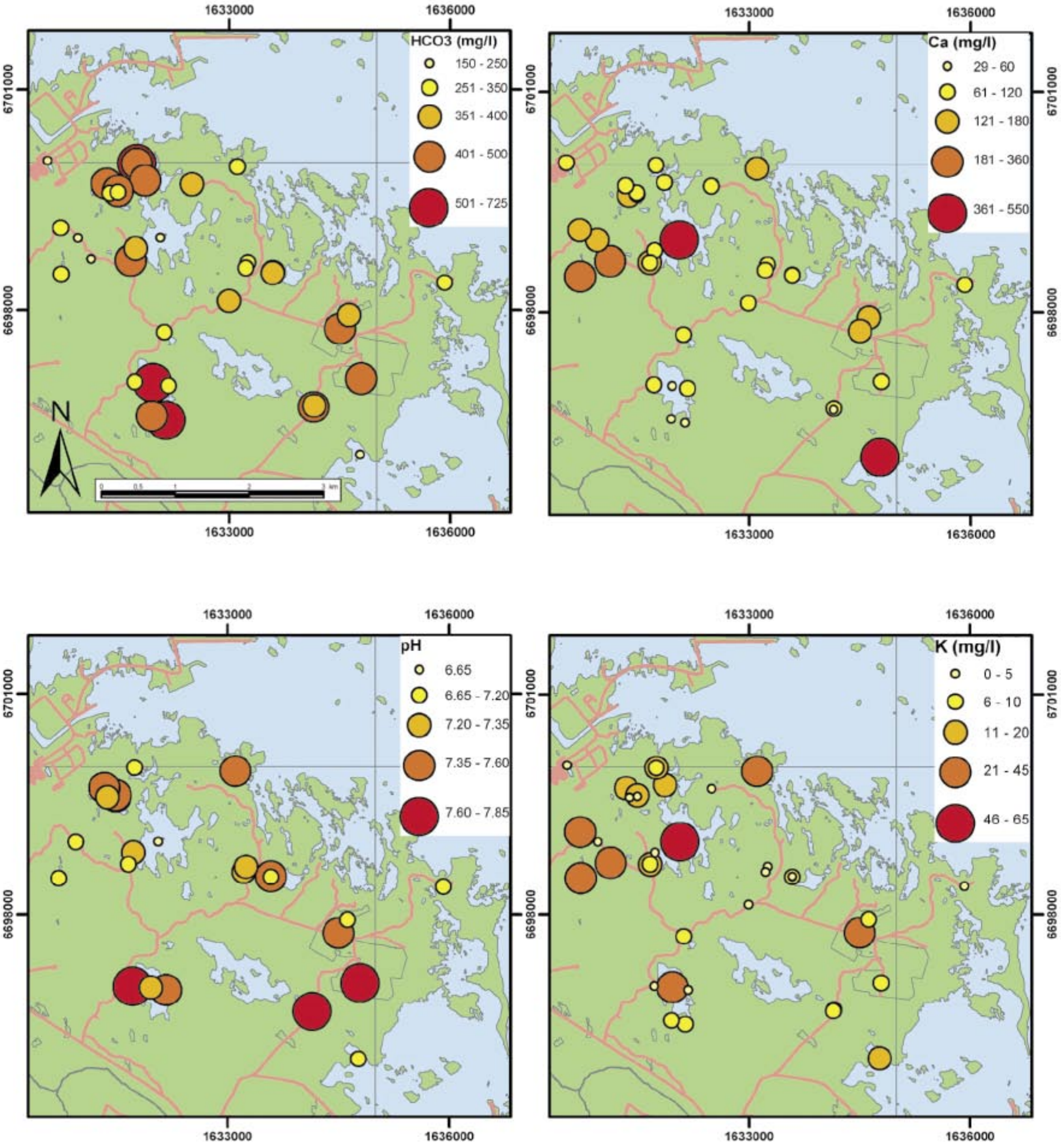

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Figure 3-91. *Median values for HCO_3, Ca, pH and K in groundwater monitoring wells in the Forsmark area.*

Table 3-22. Correlation coefficients between some of the analysed elements in water from monitoring wells in the Forsmark area. N indicates the number of samples. Several elements correlated with sea water salinity are well correlated also in the groundwater. Correlation coefficients higher than 0.8 are marked in bold and coefficients between 0.6 and 0.8 are marked in bold grey (N varies between 53 and 107).

	Li	Cond	Fe	Br	Cl	Na	Sr	Mg	K	SO_4	Mn	Ca	HCO_3	pH
Li	1	**0.75**	0.57	**0.68**	**0.70**	**0.79**	**0.88**	**0.91**	**0.87**	**0.71**	0.45	0.32	0.08	–0.16
Cond	**0.74**	1	0.39	**0.76**	**0.87**	**0.87**	**0.83**	**0.81**	**0.81**	**0.64**	0.49	0.42	–0.04	–0.23
Fe	0.57	0.39	1	0.34	0.44	0.50	0.54	**0.60**	0.45	0.23	**0.74**	0.24	–0.01	–0.20
Br	**0.68**	**0.78**	0.34	1	**0.90**	**0.86**	**0.76**	**0.77**	**0.74**	0.59	0.36	0.32	–0.15	–0.23
Cl	**0.70**	**0.87**	0.44	**0.90**	1	**0.92**	**0.74**	**0.75**	**0.72**	0.57	0.42	0.41	–0.20	–0.26
Na	**0.80**	**0.87**	0.50	**0.86**	**0.92**	1	**0.81**	**0.83**	**0.82**	**0.62**	0.49	0.25	–0.04	–0.20
Sr	**0.88**	**0.83**	0.54	**0.76**	**0.74**	**0.81**	1	**0.95**	**0.89**	**0.71**	**0.62**	0.43	0.03	–0.22
Mg	**0.91**	**0.81**	**0.60**	**0.77**	**0.75**	**0.83**	**0.95**	1	**0.92**	**0.74**	0.57	0.37	0.10	–0.19
K	**0.87**	**0.81**	0.45	**0.74**	**0.72**	**0.82**	**0.89**	**0.92**	1	**0.68**	0.54	0.30	0.16	–0.08
SO_4	**0.71**	**0.64**	0.23	0.59	0.57	**0.62**	**0.71**	**0.74**	**0.68**	1	0.33	0.56	–0.09	–0.29
Mn	0.45	0.49	**0.74**	0.36	0.42	0.49	**0.62**	0.57	0.54	0.33	1	0.36	0.06	–0.16
Ca	0.32	0.42	0.24	0.32	0.41	0.25	0.43	0.37	0.30	0.56	0.36	1	–0.48	–0.57
HCO_3	0.084	–0.04	–0.01	–0.15	–0.20	–0.04	0.03	0.10	0.16	–0.09	0.06	–0.48	1	0.34
pH	–0.16	–0.23	–0.20	–0.23	–0.26	–0.20	–0.22	–0.19	–0.08	–0.29	–0.16	–0.57	0.34	1

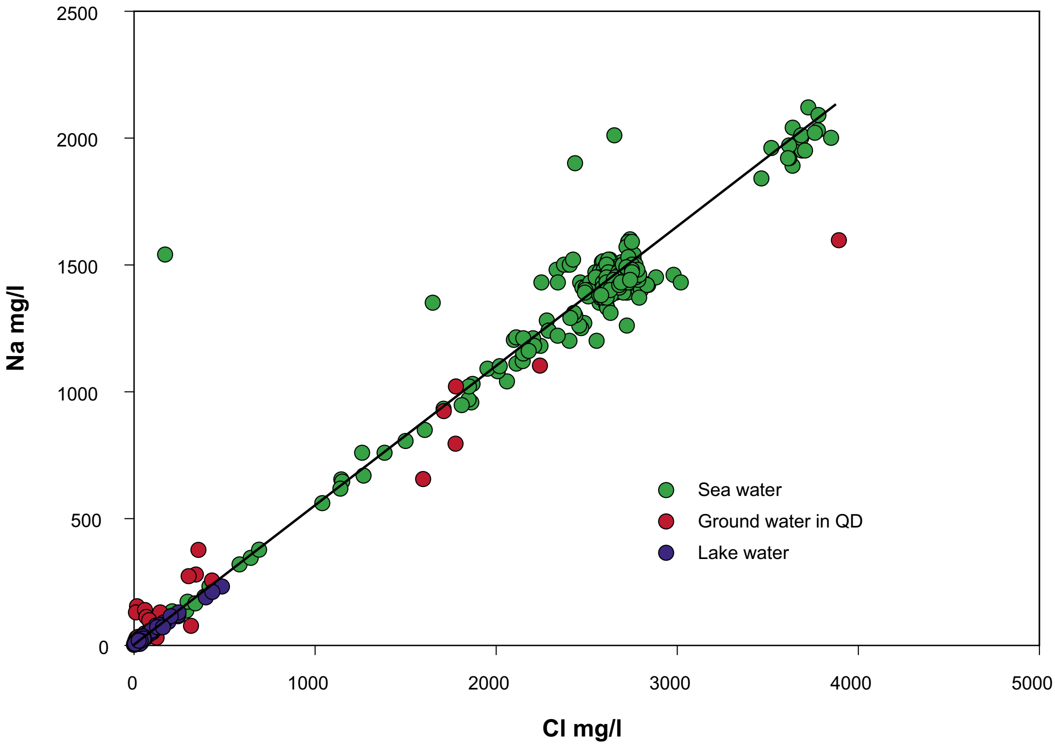

__Figure 3-92.__ Correlation between Cl and Na in near-surface groundwater, lake water and sea water in the Forsmark area.

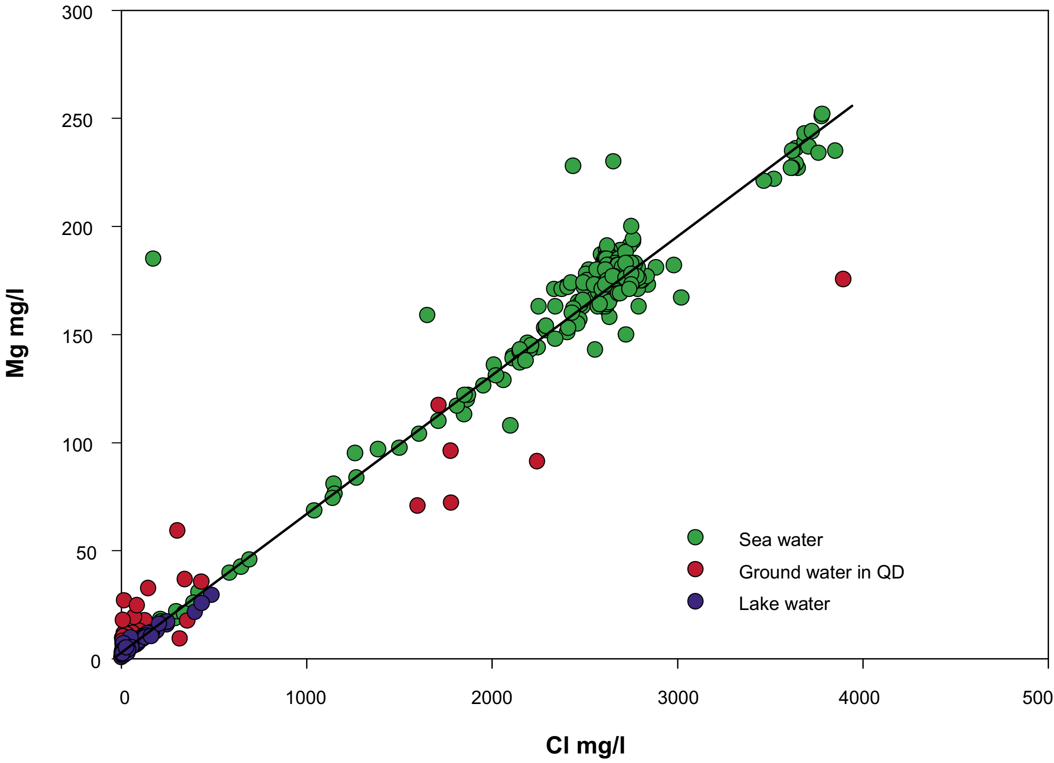

Figure 3-93. *Correlation between Cl and Mg in near-surface groundwater, lake water and sea water in the Forsmark area.*

Calcium and Cl are not as well correlated with Cl as e.g. Na and Mg. The relatively high Ca concentration in groundwater from the Forsmark area (Figure 3-91) is probably both an effect of the high contents of $CaCO_3$ in the Quaternary deposits and the occurrence of relict saline water. The $CaCO_3$ is also responsibly for the high alkalinity (HCO_3 concentration) in water from most of the sampled wells (Figure 3-91). The lowest HCO_3 concentration (150 mg/l) was recorded in water from SFM0023, which further indicates the absence of calcite in the till at that site (see above).

The Si concentrations are only half in groundwater from Forsmark compared with the Simpevarp model area /Lindborg, 2005/. Weathering of silicate minerals is an important source for dissolved Si. The pH is generally high in soils from the Forsmark area /Lundin et al. 2004/, and the weathering of silicate minerals is therefore probably of low significance, which may explain the low Si concentrations in the groundwater.

The annual mean precipitation has $\delta^{18}O$ values of –11 to –12 (SMOW), while the $\delta^{18}O$ value in Baltic Sea water outside Forsmark is around –8 (SMOW) /Laaksoharju et al. 2004/. The groundwater in several of the wells has $\delta^{18}O$ values higher than –11 to –12 (rainwater), but lower than –8 (seawater) (Figure 3-94 and 3-95). This implies that the water in these wells is probably a mixture of brackish water from the sea and meteoric water. Some wells contain S^{2-} (Figure 3-94), which shows that the groundwater at these sites at least occasionally lacks oxygen.

Another striking result is that the Mn concentration in groundwater samples from Forsmark is generally almost ten times higher than the average concentration for northern Uppland /cf Naturvårdsverket, 1999/. The reason for these high Mn concentrations is not known.

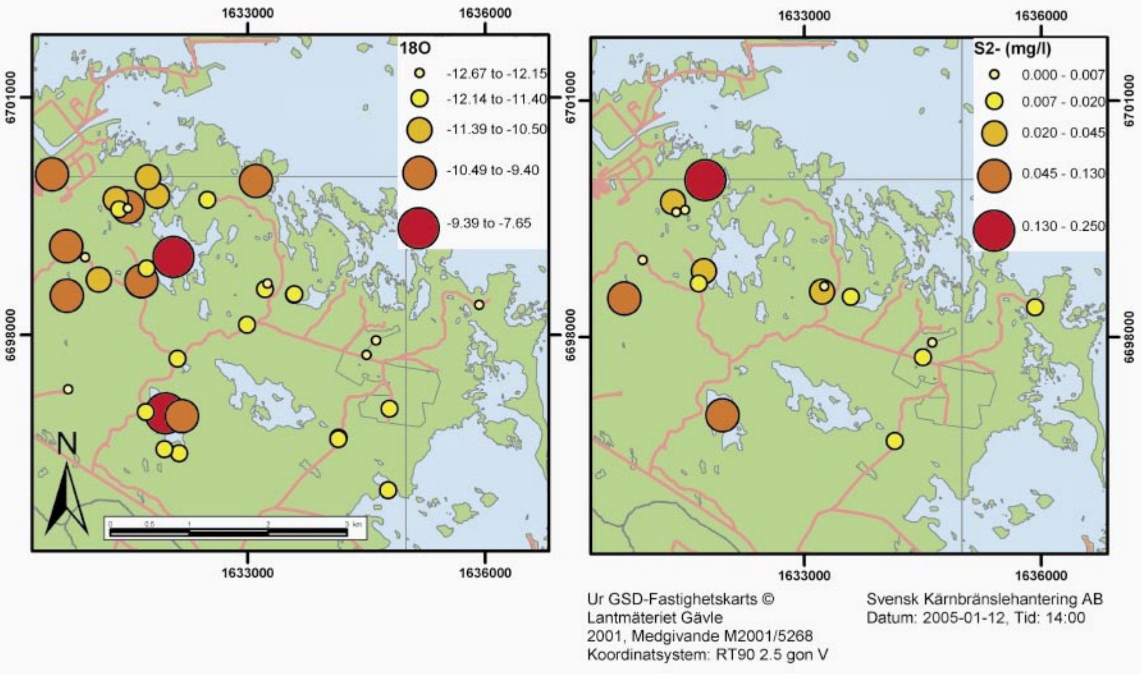

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Figure 3-94. *Median values for ^{18}O and S^{2-} in groundwater monitoring wells in the Forsmark area.*

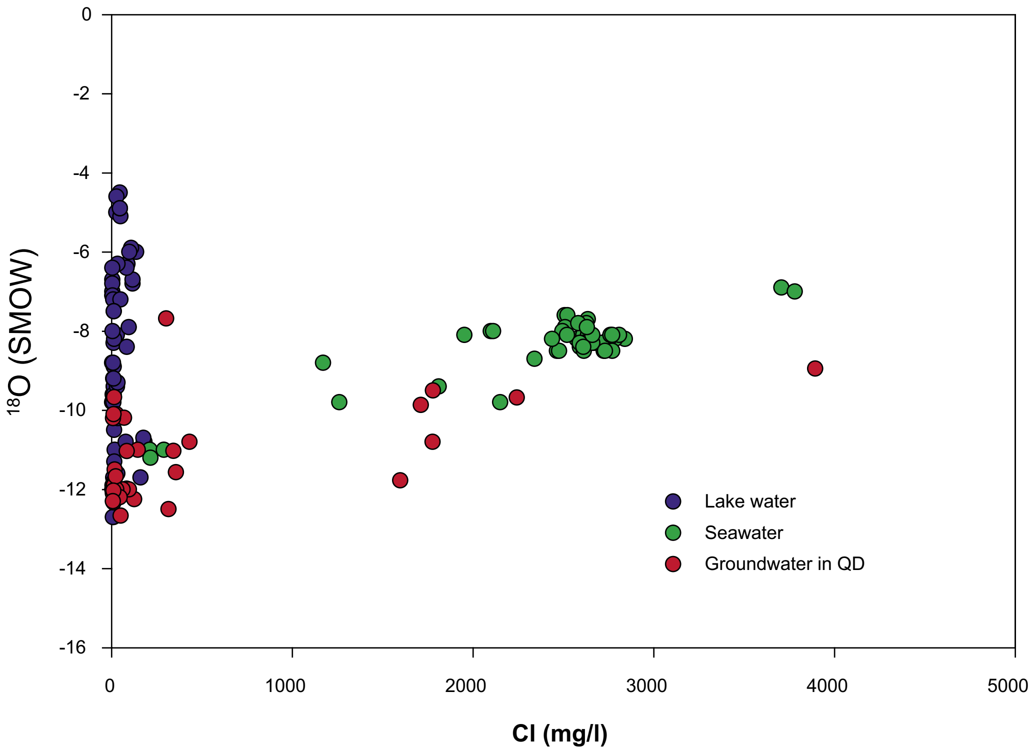

Figure 3-95. *Correlation between Cl and ^{18}O in near-surface groundwater, lake water and sea water in the Forsmark area.*

In summary, there are two main factors causing the characteristic chemical composition of the groundwater in the Forsmark region. The first factor is the occurrence of relict saline water, which remains since the sea covered the area. The lowest topographical areas was covered by the sea only a few hundred years ago, which explains the high concentrations of e.g. Cl in some of the wells. The salinity of the groundwater will probably decrease with time as the area is further uplifted. The second factor is the occurrence of $CaCO_3$ in most of the Quaternary deposits, which causes a high pH and high concentrations of Ca and HCO_3. Weathering processes is slowly dissolving the calcite, but these processes have not been active for a long period of time since the area recently was covered by water. Studies from higher altitudes west of Forsmark have shown that the $CaCO_3$ has been dissolved in the uppermost metres of the till /Ingemar and Moreborg, 1976/. The chemistry of the groundwater will probably change (e.g. lower pH and alkalinity) as the calcite content in the Quaternary deposits decreases.

3.7 Terrestrial biota

This section describes the terrestrial biota divided into producers and consumers at the Forsmark site.

3.7.1 Primary producers

This section, covering the primary producers, is divided into two parts. The first part is a general description of the vegetation in the regional model area, which includes a description of dominating vegetation, species composition, description of taxa, such as species lists for various organism groups belonging to the plant kingdom, e.g. vascular plants, bryophytes, algae and lichens, and fungi that are found in the area. The purpose of this first part is to characterise the vegetation, but also to assist in the classification of functional groups, such as tree, bush, field and ground layer species, and the identification of dominant taxa, but not to provide a complete list of all species in the area. The second part constructs descriptive models of parameters that are used in the terrestrial ecosystem model, such as describing the distribution of biomass and net primary production in the terrestrial environments.

General description

Vegetation

The vegetation is affected by the bedrock, the Quaternary deposits and human land use. The bedrock in Forsmark mainly consists of granites. Outcrop is not a prevalent substrate, making pine forest on acid rocks quite scarce. The Quaternary deposits are mainly wave washed till, where conifer forests are common. In depressions, a deeper regolith layer is found, with a fairly high lime content. The calcareous influence is typical for the north-east part of the county Uppland and is manifested in the flora. The Forsmark area has a long history of forestry which is seen today as a fairly high percentage of younger and older clear-cuts in the landscape (Table 3-23). The spatial distribution of different vegetation types is presented in the vegetation map (Figure 3-96) /Boresjö Bronge and Wester, 2002/.

Table 3-23. The spatial coverage of different vegetation types in relation to the total land area, following the vegetation map by /Boresjö Bronge and Wester, 2002/. The columns describe the number of objects, their total area, min and max size of the objects, and their relative cover of the total area.

Vegetation types	N	Area (m^2)	Min	Max	%
Old spruce forest, mesic-wet types	893	8,609,354	16	687,750	10.5
Young spruce forest, mesic-wet types	1,173	4,252,616	25	184,719	5.2
Old pine forest, mesic-wet types	1,498	8,899,111	16	350,329	10.8
Young pine forest, mesic-wet types	1,735	6,575,338	25	97,067	8
Dry pine forest on acid rocks	493	2,547,290	25	112,864	3.1
Birch-dominated forest	358	1,877,312	25	240,358	2.3
Aspen-dominated forest	1	23,690	23,690	23,690	0
Ash-dominated forest	475	1,542,845	25	141,627	1.9
Mixed forest (conifers/deciduous)	1,350	5,003,416	16	86,946	6.1
Mixed forest/shrub on bedrock islands	6	88,237	5,618	33,403	0.1
Young spruce	149	398,503	50	62,735	0.5
Young pine	276	784,440	25	29,000	1
Unspecified young conifer	538	5,789,438	16	713,450	7
Birch thicket	1,163	7,108,049	17	256,339	8.6
Birch thicket/meadow type	208	1,146,971	150	90,448	1.4
Poor regrowth, meagre ground, boulders	306	1,884,474	25	97,284	2.3
New clear-cut	80	3,759,952	25	377,294	4.6
Forested wetland, spruce-dominated	73	158,411	25	18,189	0.2
Forested wetland, pine-dominated	216	896,447	25	39,886	1.1
Forested wetland, deciduous-dominated	150	1,374,734	25	302,487	1.7
Forested wetland, clear-cut	33	80,956	25	11,110	0.1
Open wetland, lush carpet mire/mud-bottom mire	7	64,113	1,005	36,350	0.1
Open wetland, lush lawn mire	71	417,976	16	67,041	0.5
Open wetland, lush lawn mire, with willow	306	1,347,717	16	248,215	1.6
Open wetland, lush lawn mire, with willow, birch	207	803,063	25	38,130	1
Open wetland, reed-dominated, less wet	388	3,373,350	16	193,329	4.1
Open wetland, reed-dominated/more lush	149	551,085	25	91,876	0.7
Open wetland, reed-dominated, wet	11	413,921	1,680	137,071	0.5
Arable land	103	4,069,638	972	779,490	4.9
Other open land (pastures and meadows)	282	4,341,653	25	358,671	5.3
Coastal bare rocks	230	1,189,429	25	120,069	1.4
Holiday house	10	775,459	7,486	249,742	0.9
Industry	4	770,332	5,441	673,444	0.9
Lowrise house	1	142,154	142,154	142,154	0.2
Other hard surfaces	55	1,312,902	25	371,052	1.6

The forests are dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) forests situated on till. The spruce becomes more abundant where a deeper soil cover is found along with more mesic-moist conditions. The field layer is here heavily influence by the calcareous content and is characterised by herbs and broad-leaved grasses along with a number of orchid species. The deciduous tree species are dominated by *Betula pendula*, *Alnus glutinosa* and *Sorbus acuparia*, but also *Acer platanoides* and *Fraxinus excelsior* is fairly common. Especially *Fraxinus excelsior* may be abundant along sheltered seashores. *Quercus robur* and *Ulmus glabra* are close to their northern limit and are very scarce.

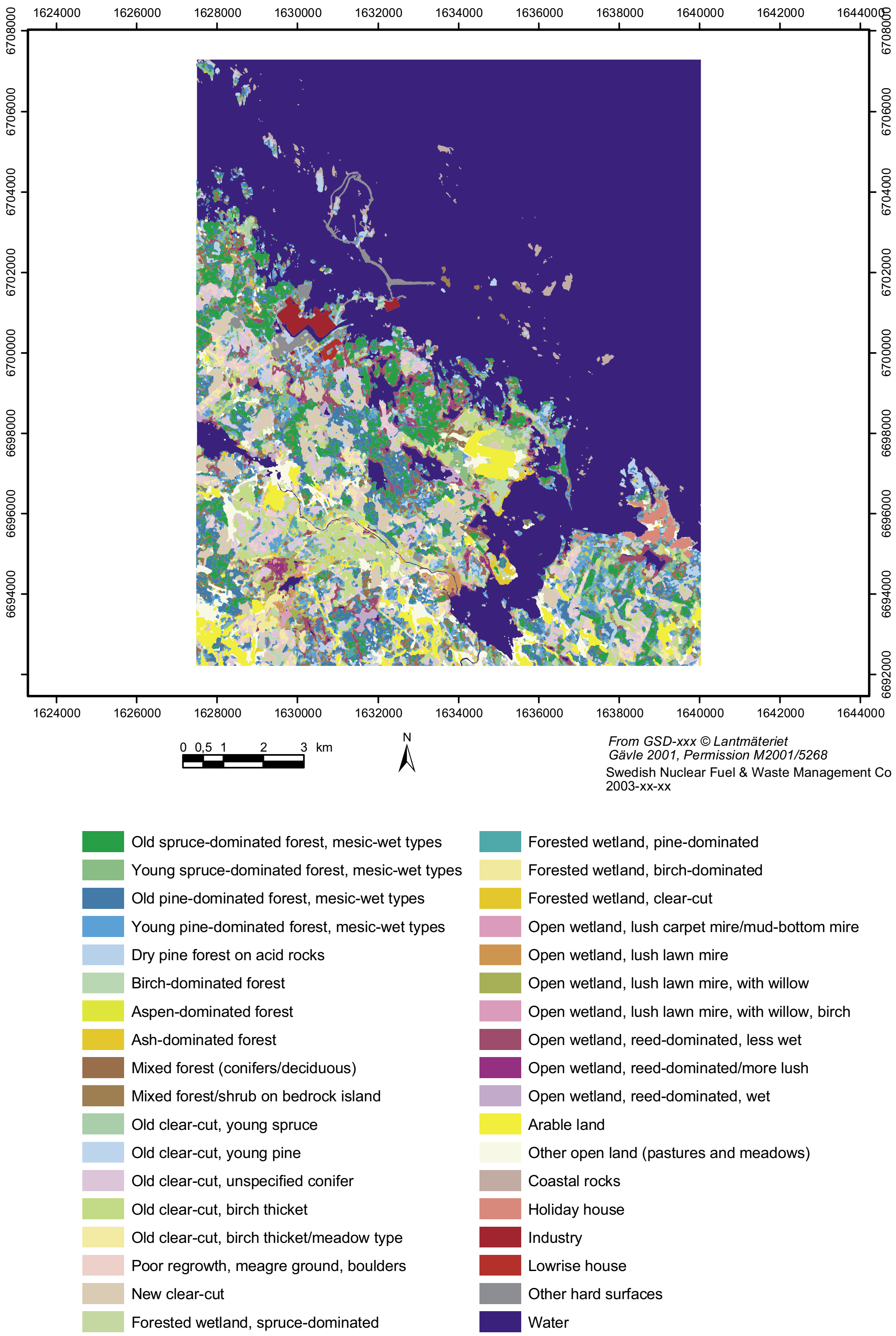

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Figure 3-96. *Vegetation map covering the Forsmark area, from /Boresjö Bronge and Wester, 2002/.*

Arable land, pastures and clear cuts dominate the open land. Arable land and pastures are found close to settlements. The pastures were earlier intensively used but are today a part of the abandoned farmland following the nation wide general regression of agriculture activities.

As a consequence of the forestry activities, there are a lot of clear-cuts in different successional stages in the area (Table 3-23). *Betula pendula* is the dominating species in many of the earlier successional stages until it is replaced by young *Picea abies* or *Pinus sylvestris* depending on soil type and/or management.

The wetlands are characterised by a strong calcareous influence, making the extremely to moderate rich fen types common in this area. These fen types lack the dominance of *Sphagnum species* in the ground layer and are instead dominated by brown mosses, e.g. *Scorpidium scorpioides*. However, the bog is also present in the more elevated parts of the area, but is rare, partly depending on their young age. Roughly, wetlands may be classified in two types: those accumulating peat and those where decomposition is fairly high, thereby minimising peat formation. This is illustrated by over layering the wetlands over the Quaternary deposit map /Boresjö Bronge and Wester, 2002/.

Species composition

The flora in this region has been investigated within the project "Upplands Flora" /Aronsson, 1993/, which is describing the distribution of vascular plants found within the whole county of Uppland. The Hållnäs parish north of Forsmark, which is similar to the Forsmark region, has been thoroughly investigated by /Jonsell and Jonsell, 1995/.

The flora has also been investigated within the "National survey of forest soil and vegetation" that has located 76 sample plots in the area. Their methods include abundance data for 230 species of vascular plants, lichens and mosses. Moreover, within the site investigations, an additional 38 sample plots are located within the area, using the same methodology for taxa as "National survey of forest soil and vegetation" /Abrahamsson, 2003/.

Redlisted species

All information concerning redlisted plants from the site has been obtained from the Swedish Species Information Centre (Artdatabanken) and is presented in Table 3-24. Further information concerning the actual species is presented in /Berggren and Kyläkorpi, 2002/.

Table 3-24. Summarized information of observations of redlisted species within the regional model area of Forsmark from the register at Swedish Species Information Centre /Kyläkorpi, 2005/.

Taxa	No of observations	No of species
Vascular plants	16	10
Lichens	0	0
Fungi	0	0
Mosses	2	1

Protected areas

A number of sensitive areas of conservation interest are located within the site. Some of these areas have an extensive protection while others lack protection so far. The sensitive areas are extensively listed in /Kyläkorpi, 2005/. There are today two areas that are legally protected as nature reserves (Figure 3-97, Table 3-25).

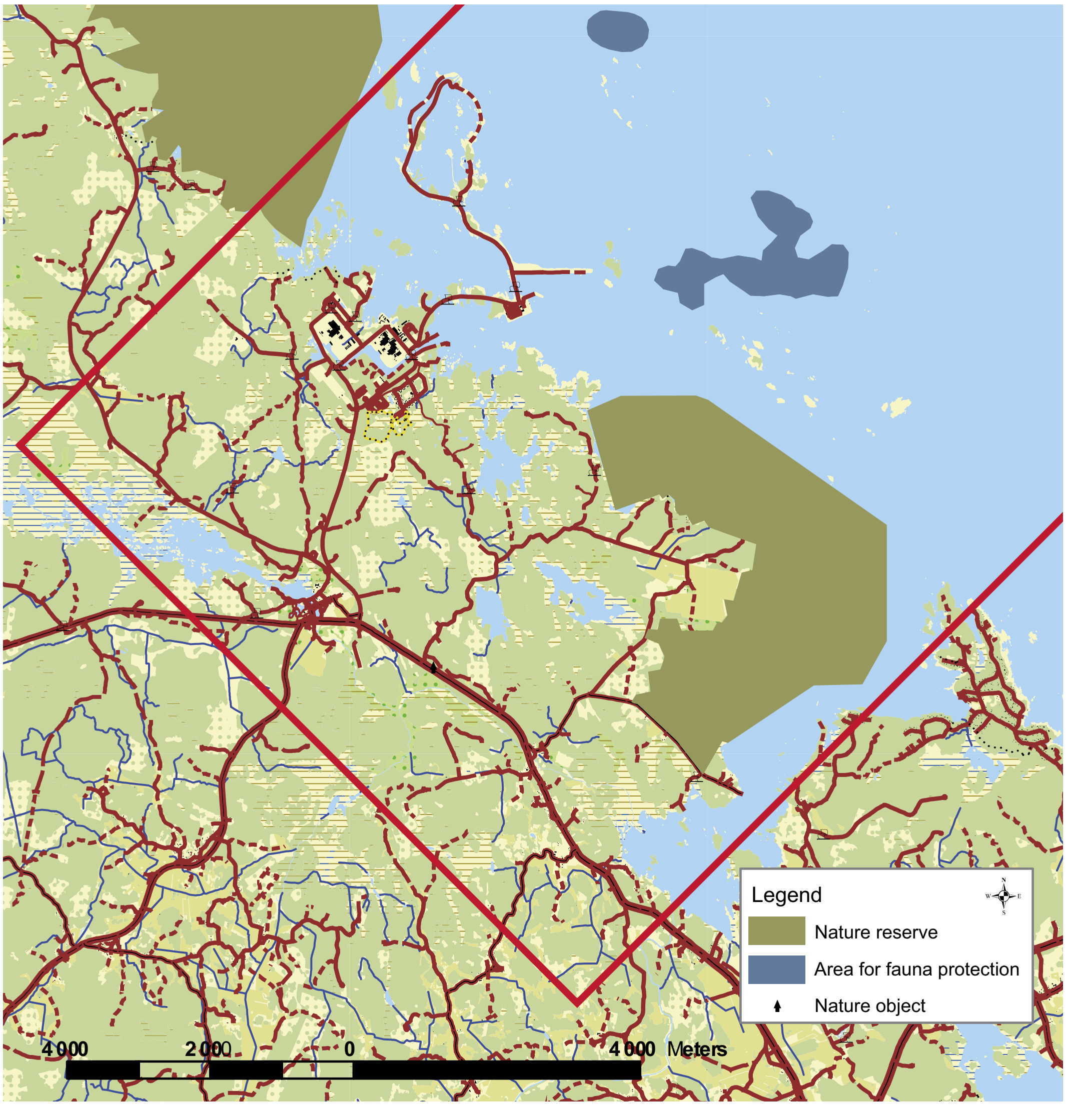

Figure 3-97. Map illustrating areas of conservational interest in Forsmark, from /Kyläkorpi, 2005/.

Table 3-25. Legally protected areas of conservational interest at the site from /Kyläkorpi, 2005/.

Value	Name	No of objects	Area (ha)
Nature reserve (Naturreservat)	Kallrigafjärden	1	1,145.58
	Skaten-Rångsen (part of)	1	78.03
Faunal protection area (Djurskyddsområde)	Länsman	1	39.89
	Öregrundsgrepen	1	184.94
Nature object (Naturminne)	Old pine tree south of Forsmark	1	N/A

Woodland Key Habitats

Woodland key habitats are areas where red listed animals and plants exist or could be expected to exist /Nitare and Norén, 1992/. A nation-wide survey of these habitats has been conducted in Sweden administrated by the Swedish Board of Forestry /SBF, 1999/. As a complement to this survey SKB initiated a deepened survey at the site. 31 habitats were identified with the total area of 100 ha within the total area of 1,810 ha /Eklund, 2004/. The dominating key habitat type, both in number of objects and total area, at the site is conifer forests representing approximately 70% of the different woodland key habitat types (Table 3-26). Their age may be fairly high sometimes reaching above 130 years. Their relatively high age with some amount of woody debris gives a number of polypores the opportunity to persist in this area (species lists in /Eklund 2004/). Effects of calcareous-influenced till is easily distinguished on the flora giving the conifer forests a rich herb and grass layer. Deciduous trees become more common near the coastline and so does the woodland key habitats containing deciduous trees.

Table 3-26. The woodland key habitats found in the Forsmark area after /Eklund 2004/. Swedish names within brackets.

Habitat	Number	Area (ha)
Conifer forest on ground influenced by limestone (Kalkbarrskog)	7	25.7
Old conifer forests (Barrnaturskog)	7	24.6
Seminatural grasslands (Betad hagmark)	2	13
Decidous forest (Lövskogslund)	4	8
Decidous swamp forest (Lövsumpskog)	1	6.5
Conifer forest with a high content of deciduous trees (Lövrika barrnaturskog)	2	5.5
Pine swamp forest (Tallsumpskog)	1	4.7
Mixed swamp forest (Blandsumpskog)	1	3.3
Conifer forest (Barrskog)	1	3.1
Deciduous trees on semi-natural grasslands (Löväng)	1	2.1
Well-influenced ground (Källpåverkad mark)	2	1.8
Forest on thin soil layer (Hällmarkskog)	1	1
Aspen forest (Aspskog)	1	0.8

Wetlands

The wetlands in this area are characterised by moderately to extreme rich fens /Jonsell and Jonsell, 1995/. However, bogs are also present at higher locations. Their location and the number is showed and listed in Figure 3-98 and Table 3-27.

Table 3-27. Summarized information of wetlands within the regional model area of Forsmark after /Kyläkorpi, 2005/. TTC is the Swedish terrain type classification.

Value	Characteristics	No of objects	Area (ha)
Wetlands (Våtmark)	Derived from the vegetation map	1,146	615.91
Wetlands TTC (Våtmark_TTC)	Derived from TTC	50	7.81

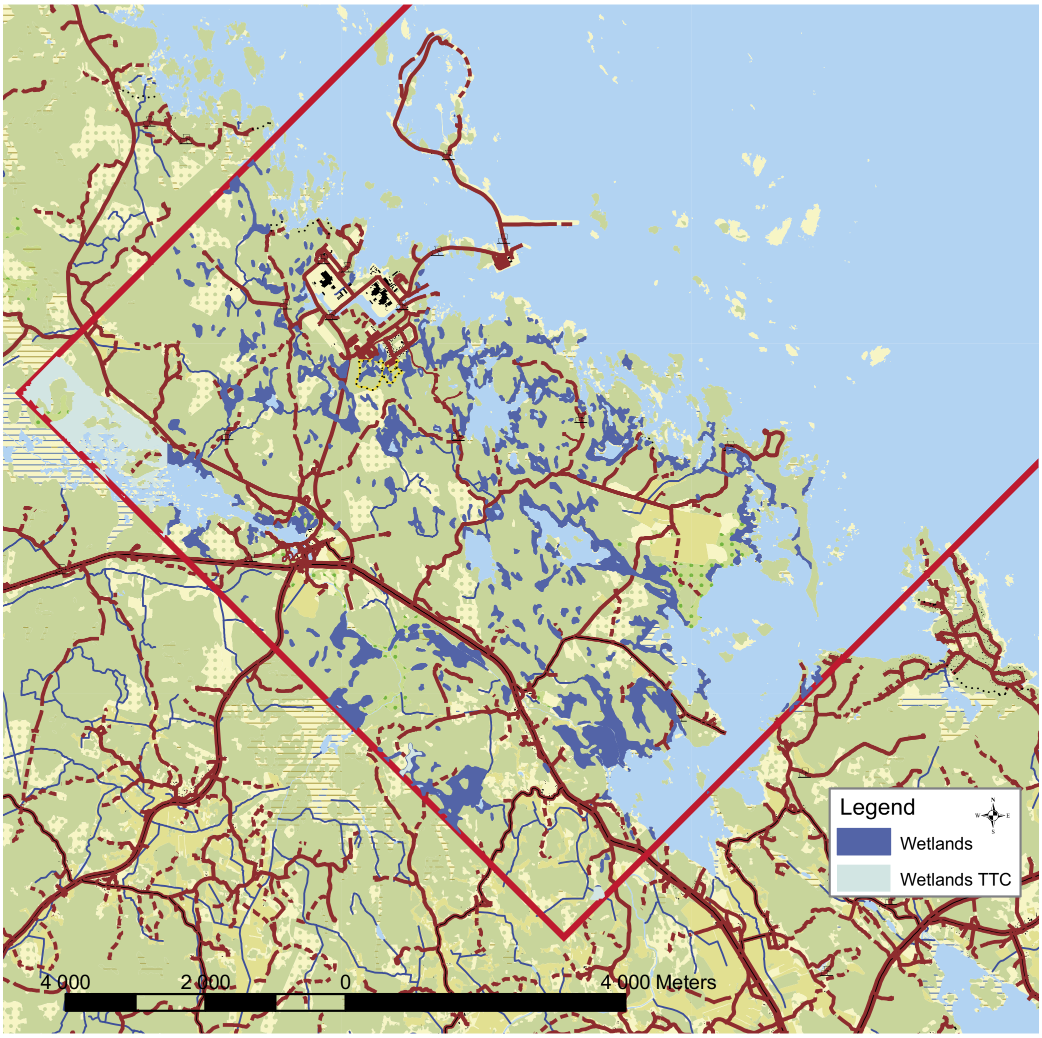

***Figure 3-98.** Wetland areas within the regional model area, after /Kyläkorpi, 2005/.*

Descriptive biomass and NPP models – introduction

The vegetation constitutes the major part of living biomass and comprises the main primary producers in terrestrial ecosystems. The biomass and necromass will therefore be an important measure of how much carbon that may be accumulated in a specific ecosystem. Similarly, the net primary production (NPP) will be an estimate of how much carbon (and other elements) that is incorporated in living tissue. Thus, combining net primary production and decomposition rates will give a rough estimate of the carbon turnover in the ecosystem. The primary producers covering the terrestrial landscape are described by their biomass, NPP and turnover, in order to feed a conceptual ecosystem model with data (see 4.1). This section describes the components, the data, the resolution and the methodology that is used to build the quantitative descriptive models of biomass and NPP that are further treated in 4.1.

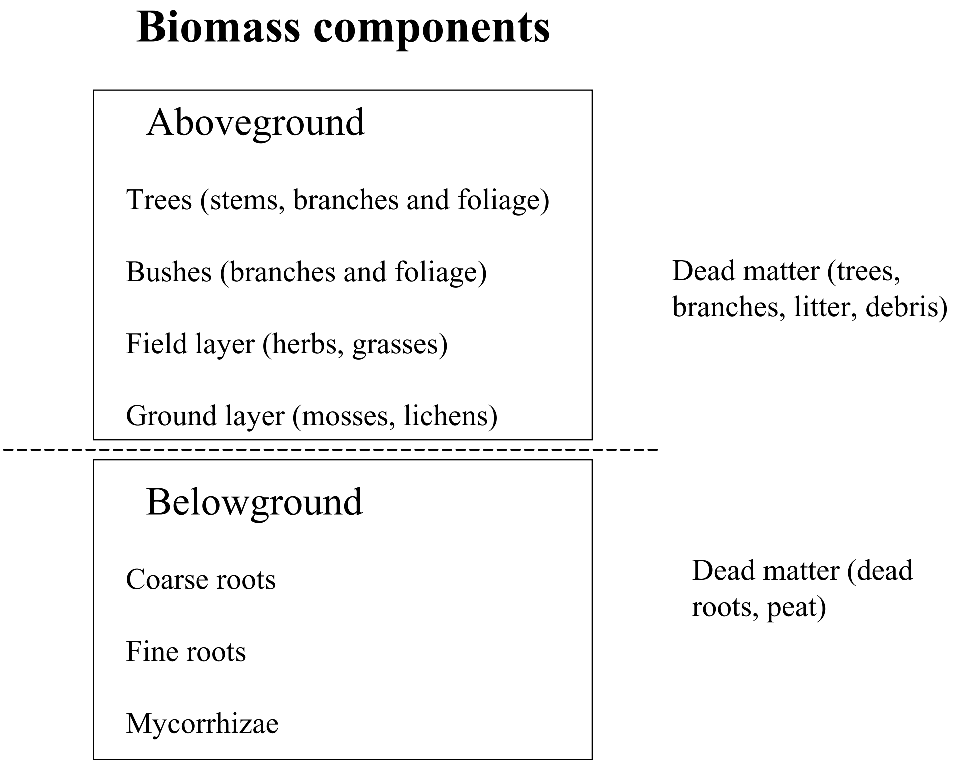

Figure 3-99. *The different components of biomass in a forest.*

Biomass

The plant biomass in an area consists of a number of different components that all have to be measured or estimated to correctly estimate the total biomass (Figure 3-99). Some of these components are well studied while others are poorly investigated which make total biomass difficult to estimate. There are several reasons for the differences in knowledge. Some of the components are extremely labour intensive to study, e.g. root turnover. In the case of mycorrhizae there are few investigations available and have therefore not been included in biomass calculations until quite recently.

NPP

Photosynthesis provides the carbon and the energy that is essential for many important processes in ecosystems. Photosynthesis directly supports plant growth and produces organic matter that is consumed by animals and soil microbes. The photosynthesis at an ecosystem level is termed gross primary production (GPP). Approximately half of the GPP is respired by plants to provide the energy that supports the growth and maintenance of biomass /Chapin et al. 2002/. The net carbon gain is termed net primary production (NPP) and is the difference between GPP and plant respiration. However, GPP can not be measured directly and total respiration is difficult to measure, especially in multi-species forests /Gower et al. 1999/.

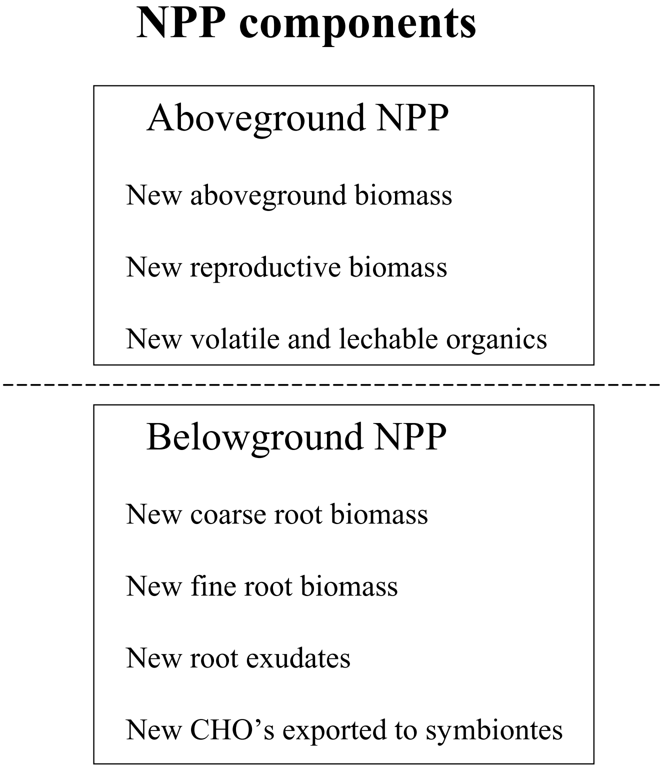

Figure 3-100. *The changes in biomass components that together constitutes the NPP during a specific time interval after /Clark et al. 2001/.*

The different components constituting the NPP for a certain ecosystem may be measured separately /Clark et al. 2001/ (Figure 3-100). NPP is here the sum of all materials that have been produced and are retained by live plants at the end of the interval and the amount of organic matter that was both produced and lost by the plants during the same interval /Clark et al. 2001/. NPP can then be calculated directly using equation:

$$NPP = \sum P_i + H \qquad \text{(Equation 3-2)}$$

where P is the net production of dry biomass for each of the plant tissues (i), including wood, foliage, reproductive tissue, roots (including mycorrhizae) and H is the consumption of organic matter by herbivory. Herbivory is partly treated below, but is also treated in 3.7.2.

A number of components that so far are considered to be less important have been omitted. Studies concerning volatile and lechable components above ground suggest that these components constitute an insignificant loss of the forest NPP /Clark et al. 2001; Persson and Nilsson, 2001/. Root exudates and transport to symbionts are poorly studied fields, but some studies have shown that the loss may be significant at the individual level with up to 30% of the NPP. No estimates of root exudates and transport to symbionts are known at the forest stand level, and this flux is therefore left for further investigations. A general review of herbivory showed that herbivores generally consume less than 10% of NPP in forests, except during insects outbreaks when it can be up to 50% of NPP /Schowalter et al. 1986/.

Herbivory on Scots Pine (*Pinus sylvestris*) was estimated to be 0.7% of the total needle biomass and 2.5% of the total needle production during one year /Larsson and Tenow, 1980/, while root consumption by phytophagous nematodes was estimated to 0.3% of the annual production of fine roots /Magnusson and Sohlenius, 1980/. Herbivory is, due to the low documented impact on total NPP in boreal systems, excluded from the calculations of NPP in equation (3-2).

The stock of dead plant tissue and the yearly flux of dead organic matter is important for both the input of organic matter to the soil organic matter pool and for the calculation of NPP. So far we have no data of losses of larger branches, coarse roots or mortality of living trees. No data are available of the ingrowth, which describes the continuous recruitment of new trees. However, the ingrowth is expected to have a low impact on the biomass and NPP estimations in managed forests.

The components

The tree is divided into stem, branches and foliage. The green tissue is of particular importance as it continuously is replaced, while the dead tissue will remain until the death of the entire tree. If trees are present, they comprise the major component of the total biomass. This biomass component has a long history of interest because of its value to the forest industry. For example, /Marklund, 1988/ developed allometric functions describing the distribution of biomass (dry weight) among the different parts of a tree for Scots pine, Norway spruce and Birch. These functions are based on 1,286 sampled trees of various dimensions covering the whole of Sweden from a wide variety of stand and site conditions. The National Forest Inventory (NFI) calculates the volume of trees for Norway spruce, Scotch pine, Contorta, Birch, and other deciduous trees in the forest. This volume can be partitioned into dead, green and non-green biomass /Marklund, 1988/. These figures can be used to estimate the total biomass and the biomass partitioned into dead, green and non-green biomass for each habitat type in the area.

Plants in the shrub layer lack per definition a stem but may nevertheless gather a considerable biomass over time and may in some habitats be a major constituent e.g. *Salix sp* on mires or *Betula pendula* on clear-cuts.

The field layer constitutes of herbs, grasses and dwarf shrubs (e.g. *Vacccinium vitas-idaea*). The significance of this layer in relation to the total plant biomass varies between habitats, from being the major constituent in some grasslands to being of low importance in some types of mires and forests.

The ground layer includes all plants that are directly attached to the ground or litter without penetrating roots e.g. lichens and mosses. Lichens may be the dominating plant in dry pine forests while the mosses may be of significance in moist Norway spruce forests and is the dominating plant in mires.

Roots are often defined after their function, where fine roots has the major function of absorbing water and nutrients from the surrounding soil, while the coarse roots may have multiple functions where the size often decides the function /Persson, 2002/. There is no conventional definition of fine roots, but many forest biomass studies have defined fine roots as having a diameter less than 5 mm /Vogt and Persson, 1991/ and correspondingly are coarse roots having a diameter more than 5 cm in diameter. However, it is important to notice that this distinction is more or less arbitrarily and is crudely related to their function.

The fine roots of forest trees are almost always infected by mycorrhizal fungi /Persson, 2002/. Their total contribution to the total biomass is low (≈ 1%, /Vogt et al. 1982/). However, few studies have incorporated this component into biomass calculations.

Descriptive biomass and NPP models – methodology

Input data

The descriptive model (Figured 3-101) contains a large number of components that describe biomass (Table 3-28), NPP (Table 3-29) and turnover of plant tissue (Table 3-30). These tables also present information concerning site specificity of the data, where it is published and some information about the method used to estimate/calculate results. NPP is sometimes (e.g. for trees) the same as the net accumulation of biomass during one year. In those cases are the NPP and the turnover different. Sometimes are the NPP and turnover set to equal, e.g. for mycelia, as a simplification, meaning that there is no net accumulation of biomass between years.

All the results are presented in dry weight carbon per square metre (dw gCm^{-2}) for biomass components and in dry weight carbon per square metre and year (dw gCm^{-2}year^{-1}) for NPP and turnover components.

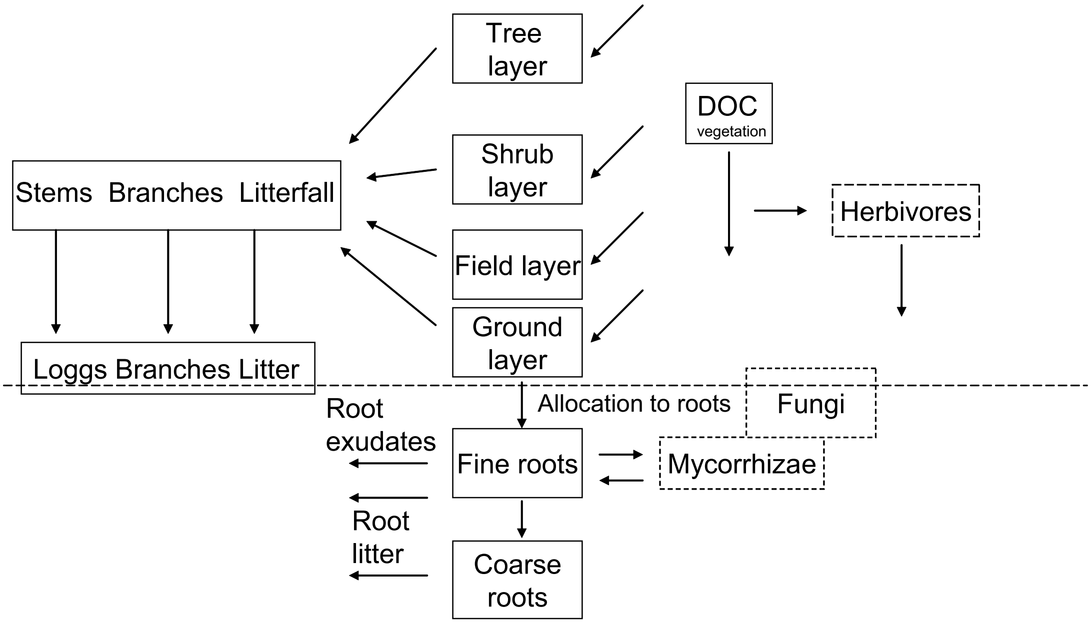

Figure 3-101. *An illustration of the different pools and fluxes of matter in a terrestrial ecosystem with the focus on the producers. Boxes with broken line are consumers. Herbivores are also described in 3.7.2.*

Table 3-28. The different descriptive units and their components that describe the biomass of the vegetation. All components are presented in dw gCm^{-2}. Data is taken from the three categories L/R/G, which is Local/Regional/Generic. Source shows from where the data is taken, e.g. the National swedish Forest Inventory (NFI). Method describes how the result in this report was calculated, e.g. a biomass expansion factor (BEF) is a factor describing a relationship between two biomass components, such as foliage and root biomass.

Descriptive unit	Component	Data L/R/G	Source	Method ref
Tree layer	Woody parts (above ground)	L/R	NFI	Measured, Allometric eq
	Needles/Foliage	L/R	NFI	Allometric eq
	Coarse roots	L/R	NFI	BEF
	Fine roots	L/R	NFI	BEF
Shrub layer	Woody parts	G	Gower et al. 2001	Measured, allometric eq
	Green parts	G	Gower et al. 2001	Measured
	Coarse roots	G	Gower et al. 2001	Allometric eq
	Fine roots	G	Gower et al. 2001	Allometric eq
Field layer	Green parts	L	Fridriksson and Öhr, 2003	Measured
	Non-green parts	L	Fridriksson and Öhr, 2003	Measured
	Below ground	L	Fridriksson and Öhr, 2003	BEF
Ground layer	Mosses	L	Fridriksson and Öhr, 2003	Measured
	Lichens	L	Fridriksson and Öhr, 2003	Measured
Fungi	Mycorrhizae/mycelia	G	Vogt et al. 1982	Measured
Dead organic material	Loggs	L	Andersson, 2004	Measured
	Branches	No data	–	–
	Litter layer	L	Fridriksson and Öhr, 2003	Measured
Rotzon	Depth	L	Lundin et al. 2005	Measured

Table 3-29. The different descriptive units and their components that describe the NPP of the vegetation. All components are presented in dw gCm^{-2}year^{-1}. Data is taken from the three categories L/R/G, which is Local/Regional/Generic. Source shows from where the data is taken, e.g. the National swedish Forest Inventory (NFI). Method describes how the result in this report was calculated, e.g. a biomass expansion factor (BEF) is a factor describing a relationship between two biomass components, such as foliage and root biomass.

Vegetational unit	Component	Data L/R/G	Source	Method ref
Tree layer	Woody parts (AG)	L/R	NFI	Measured, equations
	Needles/Foliage	L/R	NFI	BEF
	Coarse/fine roots	L/R	NFI	BEF
	Ingrowth	No data	–	–
Shrub layer	Woody parts	G	Gower et al. 2001	Measured, allometric eq.
	Green parts	G	Gower et al. 2001	Measured
	Coarse roots	G	Gower et al. 2001	Allometric eq
	Fine roots	G	Gower et al. 2001	Allometric eq
Field layer	Green parts	L	Fridriksson and Öhr, 2003	Measured
	Below ground	L	Fridriksson and Öhr, 2003	BEF
Ground layer	Mosses	G	Bisbee et al. 2001	Measured
	Lichens	No data	–	–
Fungi	Mycorrhizae /mycelia	G	Vogt et al. 1982	Measured

Table 3-30. The different descriptive units and their components that describe the turnover of a number of vegetational units. All components are presented in dw gCm^{-2}year^{-1}. Data is taken from the three categories L/R/G, which is Local/Regional/Generic sources. Source shows from where the data is taken. Method describes how the result in this report was calculated, e.g. a biomass expansion factor (BEF) is a factor describing a relationship between two biomass components, such as foliage and root biomass.

Vegetational unit	Component	Data L/R/G	Source	Method ref
Tree layer	Needles/Foliage (litter fall)	L/R	Berggren et al. 2004	Measured
	Fine roots	G	Majdi, 2001	BEF
Shrub layer	Green parts	G	Gower et al. 2001	BEF
	Fine roots	G	Gower et al. 2001	BEF
Field layer	Green parts	G	Fridriksson and Öhr, 2003	BEF
	Below ground	G	Fridriksson and Öhr, 2003	BEF
Fungi	Mycorrhizae/mycelia	G	Vogt et al. 1982	BEF
Dead organic material	Branch fall	R	Berggren et al. 2004	Measured

Conversion factors

Net accumulation per year was presented for the stem volume in the data from The National Forest Inventory (NFI). It was converted into biomass using Table 3-31. When carbon content was not presented as a part of each study, it was calculated using the factors presented in Table 3-32 if not stated otherwise.

Table 3-31. Biomass expansion factors for conversion from volume (m^3) to biomass (Ton dry matter) after /Fink et al. 2003/. Stem refers to stem and bark above stump height. One m^3 stem wood corresponds to the value in column 2 as ton dry matter.

Ton DM	Stem biomass including tops
Pinus sylvestris	0.407
Picea abies	0.404
Broad-leaved	0.501
All trees	0.402

Table 3-32. Carbon content in some common tree species in procent of the dry weight /Skogsstyrelsen, 2000/. Carbon content in roots is from /Alriksson and Eriksson, 1998/.

Tree species	Stem	Branch	Neddles	Root
Picea abies	48.0	58.8	48.6	48.0
Pinus sylvestris	48.8	51.2	51.2	48.0
Betula sp	48.0	58.8	48.6	48.0
Other decidous trees	49.0	49.0	49.0	48.0*

*Same value as *Betula pendula*.

Quantitative descriptive models

The quantitative descriptive model is the quantification of the components listed above and further transferred into GIS giving the data a spatial distribution.

Tree layer

This layer was created using information from the vegetation map /Boresjö Bronge and Wester, 2002/. The Swedish Terrain Type Classification /Lantmäteriet, 1999/ was used to cover the lower left and right corners of the model area, not covered by the vegetation map, to make the regional model area map spatially complete. The classification is presented in Table 3-33.

The biomass for the tree layer was described using the four fractions; woody parts (above ground), green parts, coarse roots and fine roots (≤ 1 cm) (Table 3-34). Data for the above ground (AG) biomass was extracted from The National Forest Inventory (NFI). Deciduous forest is defined as a forest where the broad-leaved component is above 70% otherwise it is classified as a conifer forest. Below ground (BG) biomass for conifers were calculated using figures from /Berggren et al. 2004/ from a nearby locality Knottåsen (61º00’N 16º13’E). /Berggren et al. 2004/ used /Marklund, 1988/’s equations to calculate the BG biomass (0.16 of the AG biomass was found BG). They also found that 0.11 of AG biomass was found as fine root biomass using a soil corer. Marklunds equations for fine roots (< 5 cm) are considered less accurate in describing the fine root biomass, due to the methodology used to estimate it /Marklund, 1988/. Therefore is the fine root biomass from /Berggren et al. 2004/ (≤ 1 cm) used for fine roots, while Marklunds fraction is used as an estimate for coarse roots. This resulted in a value of 11% for fine roots as a function of the AG biomass (corrected for field layer rot biomass representing 38% of the fine roots, but not corrected for stone and boulder frequency /Berggren et al. 2004/).

The data for deciduous forests was extracted from NFI. The green part is 0.02 of the total AG biomass (/Li et al. 2003/, using data from *Fagus sylvatica* in Sweden). BG biomass for deciduous trees was calculated using figures (0.15 of the above ground biomass is equal to the below ground biomass) from /Nihlgard, 1972; Nihlgard et al. 1981/ that presented figures from four *Fagus sylvatica* stands in southern Sweden. The fraction fine roots of the total root biomass was taken from a study by /DeAngelis et al. 1981/ in a *Fagus sylvatica* stand in southern Sweden (0.12 of the root biomass is fine root biomass).

Table 3-33. The classes used to describe the tree layer and the GIS sources from where the information is obtained to construct the classes. TTC is the Swedish Terrain Type Classification map.

Class	Gridcode in vegetation /Boresjö Bronge and Wester, 2002/	Gridcode in TTC
Young coniferous forest (< 30 y) mesic-moist	12, 14, 41, 42, 43	76
Dry coniferous forest	15, 31	–
Old coniferous forest (> 30 y) mesic-moist	11, 13, 30, 61, 62	71, 72
Deciduous forests	21, 23 26, 63	73
Water	100	–

Table 3-34. Mean biomass of different fractions in dw gC m^{-2} of the trees in Forsmark.

Class	Number of NFI plots	Woody parts	Green parts	Coarse roots	Fine roots
Young coniferous forest (< 30 y) fresh-moist	92	1,072	93	186	128
Dry coniferous forest	29	2,750	219	474	326
Old coniferous forest (> 30 y) fresh-moist	368	565	399	967	665
Deciduous forests	13	3,005	61	460	55

Data for annual biomass increment in stems was extracted from NFI as a volume and was then converted to dry matter per unit area using Table 3-31. Annual biomass increment allocated to needles was calculated using a BEF of 48% of stem increment (Table 3-35). /Gower et al. 2001/. Total root increment was estimated from total AG biomass increment using a BEF of 67% /Gower et al. 2001/.

The above NPP for the green fraction is set equal to the leaf mass in deciduous trees. The above ground net annual biomass increment is related to the below biomass increment using a 4.37:1 relationship in deciduous forests (N = 18 studies, /Gower et al. 2001/).

The total amount of dead wood in the Forsmark area /Andersson, 2004/ is divided by the total area inventoried for each class. Transformation factor from volume to dry weight is taken from /Fink et al. 2003/, which makes a difference between *Pinus sylvestris*, *Picea abies* and broadleaved trees (Table 3-36). For classes that make no difference between tree species we have used a mean value of the trees comprised in the class. Transformation from dry weight to carbon for decaying wood is difficult and is very much dependent on the decay stage of the wood. Here is a general conversion factor of 0.5 used for the carbon content in the dead wood.

Table 3-35. Annual biomass increment in dw gC m^{-2} year^{-1} for different fractions of the tree.

Class	Number of NFI plots	Stem	Green parts	Coarse and fine roots
Young coniferous forest (< 30 y) mesic-moist	92	52	25	128
Dry coniferous forest	29	66	32	326
Old coniferous forest (> 30 y) mesic-moist	368	121	58	665
Deciduous forests	13	110	61	55

Table 3-36. Dead organic material as logs in the Forsmark area in dw gCm^{-2}. Figures are means calculated from /Andersson, 2004/.

Class	Gridcode in vegetation map /Boresjö Bronge and Wester, 2002/	Total area (ha) inventoried in /Andersson, 2004/	Conversion of m^3 to g dw	Standing dead wood dw gCm^{-2}	Laying dead wood dw gCm^{-2}	Total dw gCm^{-2}
No tree layer (< 30% crown coverage) within forest area	1	6.28	570,000	17.1	28.4	45.5
No tree layer (< 30% crown coverage) outside forest area	2	86.74	570,000	2.2	6.7	9.0
Old spruce	11	145.53	600,000	20.3	82.2	102.5
Old pine	13	55.44	510,000	13.5	59.0	72.5
Young pine	14	30.96	510,000	0.6	3.1	3.6
Unspecified young conifer	17	16.20	560,000	2.2	3.1	5.4
Birch	21	7.68	640,000	8.2	2.0	36.1
Young birch (thicket on clear-cut)	22	12.93	640,000	2.5	5.0	7.6
Ash	26	4.14	640,000	8.7	30.5	39.2
Mixed forest	30	14.43	570,000	30.6	61.5	92.1

Data for litter fall and larger components such as cones and branches were taken from /Berggren et al. 2004/ (Table 3-37). However, these figures were used without recalculation, using a BEF. Fine root turnover was approximated setting it equal to the Biomass of fine roots /e.g. Majdi, 2001/.

Table 3-37. Annual amount of litterfall and other falling components, such as cones and branches. These values are taken from /Berggren et al. 2004, where three 40 years old Picea abies forests with different moisture regimes were investigated in Kottåsen.

Class	Class in /Berggren et al. 2004/	Other comp. $gCm^{-2}year^{-1}$	Litterfall $gCm^{-2}year^{-1}$	Root litter from trees $gCm^{-2}year^{-1}$
Young coniferous forest (< 30 y) mesic-moist	Moist	23	105	52
Dry coniferous forest	Dry	11	63	66
Old coniferous forest (> 30 y) mesic-moist	Moist	23	105	120
Deciduous forests	–	–	61*	39

* Is set equal to foliage biomass taken from Table 3-34.

Shrub layer

This layer was created using information from the bush layer and the vegetation map /Boresjö Bronge and Wester, 2002/. The Swedish Terrain Type Classification /Lantmäteriet, 1999/ was used to cover the lower left and right corners of the model area, not covered by the vegetation map, to make the regional model area map spatially complete. However, TTC does only cover the class birch (*Betula sp* gridcode 74) and this class was non-significant in this area. A comparison of the field layer type that is associated with willow (*Salix sp*) suggested that the willow cover in the corners not covered by /Boresjö Bronge and Wester, 2002/ also were non-significant. The classification is presented in Table 3-38.

A significant shrub layer is associated with certain habitats such as *Juniperus communis* in certain pastures, *Salix sp* on certain types of mires or *Rubus idaeus* on clear-cuts. The shrub layer can also be important in certain successional forests. However, field inventories /Abrahamsson, 2003/ indicated that the shrub layer most often is insignificant when a tree layer is present in this area. A habitat that had a very significant shrub layer was clear cuts of varying age where *Betula pendula* is very dominant. *Salix sp* can be abundant on mires and was identified by /Boresjö Bronge and Wester, 2002/ in their shrub layer. Therefore is the focus in the shrub layer on *Betula* and *Salix*. However, due to lack of biomass and NPP data for *Salix sp* the values for Birch are used. Values representing *Betula pendula* was taken from a Finnish study on *Betula pubescens* presented in /Gower et al. 2001/ (Table 3-39, 3-40). These were however from a 50 year old stand, but are here used to represent much younger stand in lack of better data so far. The fine root fraction was set to 0.12 in accordance with values used for deciduous trees (above). Turnover of fine roots per year were set to 1 (Table 3-40).

Table 3-38. The classes used to describe the bush layer and the GIS sources from where the information is obtained to construct the classes. TTC is the Swedish Terrain Type Classification map /Lantmäteriet, 1999/.

Class	Gridcode in vegetation map /Boresjö Bronge and Wester, 2002/	Gridcode in bush layer /Boresjö Bronge and Wester, 2002/
Willow	–	12
Birch	44, 45	–
Water	100	–

Table 3-39. The values of biomass in dw gC m^{-2} after /Gower et al. 2001/.

Class	Wood	Foliage	Coarse roots	Fine roots	Total biomass
Willow	1,262	94	359	49	1,767
Birch	1,262	94	359	49	1,767

Table 3-40. The values of NPP in dw gC m^{-2}year^{-1} after /Gower et al. 2001/.

Class	Wood	Foliage	Coarse roots	Fine roots	Total NPP	Litter fall	Root litter
Willow	76	93	10	35	214	93	35
Birch	76	93	10	35	214	93	35

Field and ground layer

This layer was created using information from the soil map constructed by /Lundin et al. 2004/ and the ground layer map /Boresjö Bronge and Wester, 2002/. No information has been gathered to cover the corners to make the regional model area map spatially complete. This may be done using information from the Quaternary deposit map (Svensk Geologisk Undersökning) and the Swedish Terrain Type Classification /Lantmäteriet, 1999/. The classification is presented in Table 3-41.

Table 3-41. The classes used to describe the field layer in Forsmark. The classes is constructed using information from /Lundin et al. 2004/ describing the soil in Forsmark and the ground layer map /Boresjö Bronge and Wester, 2002/.

Class	Code in soil map /Lundin et al. 2004/	Gridcode in ground layer /Boresjö Bronge and Wester, 2002/
Mires	HI	–
Forested wetlands	GL	–
Herb dominated moist soils on fine texture parent material	GL/CM	–
Pasture and seminatural grasslands	RG/GL-a (agriculture land excluded)	–
Woodland, well drained, herbs, grasses and dwarf shrubs	RG/GL + RG	–
Thin soils with lichen rich heath vegetation	LP	–
Shore line (bedrock excluded)	AR/GL	–
Agriculture land	RG/GL-a	0

The classes mires and forested wetlands were compared with the habitat classification in lakes by /Brunberg et al. 2004/ were their class "Littoral 1" was used as theme to exclude overlapping parts between the lake and the two "terrestrial" wetland classes. In some cases a part was left in the open lake after this enclosure. This part was excluded.

Data for biomass AG for the different field layer types in Table 3-42 was taken from a study done in Forsmark /Fridriksson and Öhr, 2003/. However, this study had fewer classes (lower resolution) than the one presented in Table 3-41. It was therefore necessary to use the same values for some of the classes (Table 3-42, column 2). Below ground biomass for mires and wetlands was taken from an investigation of an ombrotrophic bog in Canada /Moore et al. 2002/. They found an average ratio of above- to belowground biomass of 0.16:1. However, they had a somewhat lower aboveground biomass than /Fridriksson and Öhr, 2003/ ranging from approximately 175 to 225 gCm^{-2}.

Below ground biomass for Grasslands, Seashore and Herb dominated moist soils are calculated using values from /Saugier et al. 2001/. They found that the root biomass was 67% of the total biomass in temperate grasslands and 13% among crops. The biomass of the arable land was calculated based on the standard yield figures of oat, which is the main crop cultivated in the area /Berggren and Kyläkorpi, 2002/. To the standard yield of 312.5 g barley m^{-2} /Berggren and Kyläkorpi, 2002/ was added generic values of treshing loss (x 1.05) and straw yield (x 1.4). Root biomass was calculated as 0.43 of AG biomass /Jerling et al. 2001/. The total figure was then translated to carbon content using the factor 0.453 in accordance with /Fridriksson and Öhr, 2003/.

Production for the ground layer in mires and forested wetlands was set to equal the biomass. These figures are in the lower part in comparison with other investigations in the northern hemisphere /Rochefort et al. 1990/ (Table 3-43).

Production for the ground layer in forests was taken from /Bisbee et al. 2001/. They found that the dominating moss species in the ground layer, *Hylocomium splendens*, covering in mean 70% of the ground layer was 24 $gCm^{-2}y^{-1}$. Consequently, *Hylocomium splendens*, represents the ground layer and was recalculated due to the large cover in the sample plots (100%, /Fridriksson and Öhr, 2003/) to represent 100% cover. The ground layer production for grasslands was calculated using the same production estimate but recalculated using coverage of 13% /Fridriksson and Öhr, 2003/.

Table 3-42. Biomass values in dw gCm^{-2} for the different field, ground and litter layer classes in the Forsmark area. Figures are medians (N = 6) recalculated from /Fridriksson and Öhr, 2003/.

Class	Class in /Fridriksson and Öhr, 2003/	Litter gCm^{-2}	Ground layer gCm^{-2}	Field layer green gCm^{-2}	Field layer total AG gCm^{-2}	Below ground gCm^{-2}
Mires	Wetlands	322	62	202	202	1,261
Forested wetlands	Wetlands	322	62	202	202	1,261
Herb dominated moist soils on fine texture parent material	Seashore area	153	0	61	61	41
Pasture and seminatural grasslands	Grazing area	48	17	108	112	75
Woodland, well drained, herbs, grasses and dwarf shrubs	Picea area	154	401	0	0	0
Thin soils with lichen rich heath vegetation	Pinus area	259	181	25	31	40*
Shore line (bedrock excluded)	Seashore area	153	0	61	61	41
Agriculture land	–	0	0	210	0	90

*From /Berggren et al. 2004/ were mean total root biomass was taken from the dry plots in Knottåsen and then substracting tree roots (62% from /Majdi and Andersson, 2004/). That figure was used to create a fraction (1.29) describing the BG biomass as a function of AG.

Table 3-43. NPP values in dw gC $m^{-2}year^{-1}$ for the different field, ground and litter layer classes in the Forsmark area. The values are medians (N = 6) recalculated from /Fridriksson and Öhr, 2003/.

Class	Class in /Fridriksson and Öhr, 2003/	Ground layer gCm^{-2} $year^{-1}$	Field layer green gCm^{-2} $year^{-1}$	BG gCm^{-2} $year^{-1}$	AG litter fall	BG root litter gCm^{-2} $year^{-1}$
Mires	Wetlands	62	202	403	202	403
Forested wetlands	Wetlands	62	202	403	202	403
Herb dominated moist soils on fine texture parent material	Seashore area	–	61	123	61	123
Pasture and seminatural grasslands	Grazing area	5	108	217	108	217
Woodland, well drained, herbs, grasses and dwarf shrubs	Picea area	34	0	0	0	0
Thin soils with lichen rich heath vegetation	Pinus area	34*	25	49	25	49
Shore line (bedrock excluded)	Seashore area	–	61	123	61	123
Agriculture land	–	–	210	90	210	90

*In lack of other data the ground layer NPP for the “Woodland” category was used. This is most certainly an underestimation of the actual NPP.

Fungi/mycorrhizae

Carbon transfer from vegetation through roots to fungi that are symbiotically associated with the roots is of significant importance when describing the flow of carbon. There are two dominating types of plant – mycorrhizal associations, the arbuscular mycorrhiza (AM) and the ectomycorrhiza. A third type the ericoid mycorrhiza is exclusively formed by plants in the Ericales. These are an important component of high altitude boreal forests. Except in boreal and some temperate forests in heatlands are the AM symbiosis the normal state of the root system of most plant species /Fitter et al. 2000/. We have no data covering biomass and NPP for the arbuscular and ericoid mycorrhiza.

Data for ectomycorrhiza was extracted from an investigation made in USA, Washington State, estimating mycorrhizal fungal biomass and production from two *Abies amabilis* stands of different age (23 and 180 years old), /Vogt et al. 1982/. Conifer fine roots (including mycorrhizal roots) and *Cenococcum graniforme* (Sow.) Fred. and Winge sclerotia were hand sorted from soil cores. Epigeous and hypogeous sporocarps were collected from permanent sub plots during one year. However, the tree root biomass calculations from NFI includes ectomycorrhizal sheath so that amount was here subtracted (16% of total fungal component) from the total, to avoid accounting for that biomass twice. Similarly is that part excluded from the NPP calculations. Here we use data from the plot covered with 23-year-old trees, which seems to better approximate the age classes of the forests in focus. A conversion factor of 0.5 was used to convert dry weight to carbon weight. The deciduous forest gets the same values as coniferous forest in lack of other data (Table 3-44). Turnover of mycelia was calculated using an assumption of steady state in between years, which gives a turnover equal to NPP/biomass.

Table 3-44. Biomass and NPP for fungi in forest habitats.

Class	Biomass gCm^{-2}	NPP gCm^{-2} $year^{-1}$	Litter $gCm^{-2}year^{-1}$
Young coniferous forest (< 30 y) mesic-moist	117	137	137
Dry coniferous forest	117	137	137
Old coniferous forest (> 30 y) mesic-moist	117	137	137
Deciduous forests	117	137	137

Root zone depth

Describes the depth of the root zone. The estimation of the root depth was done by /Lundin et al. 2005/ at two localities for each class in Oskarshamn but is here directly transferred to the Forsmark vegetation types (Table 3-45). The statistics presented in the Table 3-45 are taken from the locality that had the deepest mean root zone value.

Table 3-45. Statistics describing the depth of the root zone for a number of classes.

Class	Code in soil map /Lundin et al. 2004/	Mean (sd) (m)	Min–Max (m)	N
Mires	HI	0.34 (0.07)	0.30–0.47	7
Forested wetlands	GL	0.31 (0.05)	0.25–0.43	8
Herb dominated moist soils on fine texture parent material	GL/CM	0.42 (0.09)	0.26–0.58	8
Pasture and seminatural grasslands	RG/GL-a (agriculture land excluded)	0.26 (0.13)	0.17–0.54	8
Woodland, well drained, herbs, grasses and dwarf shrubs	RG/GL + RG	0.26 (0.04)	0.18–0.32	8
Thin soils with lichen rich heath vegetation	LP	0.28 (0.07)	0.16–0.37	8
Shore line (bedrock excluded)	AR/GL	0.25 (0.06)	0.17–0.35	7
Agriculture land	RG/GL-a	0.19 (0.07)	0.09–0.027	8

Confidence and uncertainties

The largest stocks and flows are associated with trees (except the SOC). This means that a low confidence in these would have a large effect on the overall confidence of the descriptive models. The estimates of tree properties are, however, the best estimates we have (compared with all the data used) in the sense of number of replicates, coverage of the region and the allometric functions used within the NFI to calculate biomass for the fractions above ground. There is a large variation depending on a number of factors such as nutrient status and wetness. Nutrient status is known to have a large effect on the biomass of roots /Persson, 2002/. However these variations depending on local factors are supposed to be evened out when viewing a larger area /Svensson, 1984, see also Banfield et al. 2002/. The average error for the estimate of the tree biomass in NFI (for the area 217 km^2 forest) should be approximately 6% /Svensson, 1984/. We have introduced errors by joining continuous data into a number of categories, but these are on the other hand averages of a large sample covering most forest types. The use of biomass expansion factors to distribute biomass and NPP properties among tree fractions (where such has not been found in the NFI data) also introduces errors. BEF's are known to be sensitive to tree age /e.g. Lehtonen et al. 2004/.

An assumption of a steady state has repeatedly been used when quantifying turnover of plant tissue. This assumption is in some cases an overestimation of the actual turnover because there some net accumulation perennial taxa, but there is a lack of data describing these processes on the community level. In other cases the assumption is more justified e.g. root turnover /Majdi, 2001/.

Interestingly, few or no single studies have been able, or chosen, to estimate all the properties that have been treated above. Partly, because of the laborious work but also because many of the pools and fluxes are small in comparison and therefore expected to have a small influence on the overall carbon budget.

3.7.2 Consumers

Input data

A compilation of site-specific data and generic data obtained from different reports are presented in Table 3-46. Other data that have been used, such as weighed values for specific species and consumption data, are obtained from internet sites, e.g. The Swedish association for Hunting and Wildlife Management (*Sw: Svenska Jägareförbundet*), The National Association of Huntsmen (*Sw: Jägarnas Riksförbund*), BBC- Nature wildfacts and The Mammal Society.

A mammal report with more detailed information about weights, feeding- and migration habits, reproduction, carbon content etc is in preparation by *Svensk Naturförvaltning* (former *Svensk Viltförvaltning*).

Table 3-46. List of sources for input data for terrestrial consumers in Forsmark region.

Fauna family	Species	Data	Source
Mammals	Moose (*Sw: älg*)	Density (site specific)	/Cederlund et al. 2004/
		Carcass weights (site specific)	/Svensk Viltförvaltning, 2003/
	Roe deer (*Sw: rådjur*)	Density (site specific)	/Cederlund et al. 2004/
		Carcass weights (generic)	/Cederlund, 1995/
	Red deer (*Sw:kronhjort*)	Density (site specific)	/Cederlund et al. 2004/
	European hare (*Sw: fälthare*) and Mountain hare (*Sw: skogshare*)	Density (site specific)	/Cederlund et al. 2004/
	Small mammals in field (mainly water vole, field vole) and in forest (mainly yellow necked mouse, wood mouse and bank vole)	Density (site specific)	(Kjell Wallin and Göran Cederlund, pers comm, 2004)
	Marten (*Sw: mård*)	Density (site specific)	/Cederlund et al. 2004/
	Fox (*Sw: räv*)	Density (generic)	/Jägareförbundet, 2004, website/
	Wild boar (*Sw: vildsvin*)	Density (site specific)	/Cederlund et al. 2004/
		Population structure (age-distribution -generic)	(Jonas Lemel, pers comm, 2004)
Birds	–	No site-specific density figures expressed as birds×km^{-1}	/Green, 2004/

Fauna family	Species	Data	Source
Amphibians and reptiles	–	Species that occur in the Forsmark area	/Andrén, 2004a/
	Snakes (Adder/*huggorm*, Grass snake/*vanlig snok* and Smooth snake/*hasselsnok*)	Density, weight, consumption (generic)	/Andrén, 2004b/
	Newts (Smooth newt/*mindre vattensalamander* and Great creasted newt/*stor vattensalamander*)	Density around a water pond, weight, consumption (generic)	Andrén, 2004b/
	Common toad (S*w: vanlig padda*)	Density, weight, consumption (generic)	/Andrén, 2004b/
	Moor frog (*Sw: åkergroda*)	Density around a water pond, weight, consumption (generic)	/Andrén, 2004b/
	Lizards (Sand lizard/*sand ödla*, Common lizard/*skogsödla* and Slow-worm/*kopparödla*)	Density, weight, consumption (generic)	/Andrén, 2004b/
Soil fauna	–	Density in a deciduous forest, a moor pine and a grass land.	/Lohm and Persson, 1979/

Metodology

General

The major aim in this section is to calculate the carbon flow among the terrestrial consumers, expressed as $gC \times m^{-2} \times y^{-1}$ and total $gC \times y^{-1}$, in Forsmark 2 within Forsmark area. This has not been possible for all species, as the input data is incomplete. When calculating the consumption of carbon for herbivores, the carbon content in the vegetation is assumed to be 46.1% (mean value) of the dry weight as for the green field layer in /Fridriksson and Öhr, 2003/. The carbon content of the fresh weight is assumed to be half of that, 23.05%.

The carbon content in mammals is proposed to be 10% of the fresh weight /Lindborg and Kautsky, 2004/. The carbon content in reptiles and amphibians are assumed to be equal to the carbon content in mammals. The herbivore faeces (vertebrate) is set to 50% of the energy input (consumption), and the carnivore faeces (vertebrate) to 20%, according to /Jerling et al. 2001/.

Moose

The moose density was investigated in the Forsmark area in 2003 through pellet (fecal) counts. The methodology is described in /Cederlund et al. 2004/. A control area for the mammal investigations was placed in Hållnäs. The carcass weights from Saxmarken, close to Forsmark /Svensk Viltförvaltning AB, 2003/, has been divided with 0.55 in order to get the live weight, which is normal according to (Cederlund, 2004, pers comm). A sex ratio of 0.5/0.5 has been assumed when calculating the average weight. The production is proposed to be 30% of the biomass (Cederlund, 2004, pers comm). Consumption figures for moose were found at /Jägareförbundet, 2004a, website/. A mean value of the winter- and summer consumption was calculated.

Roe deer

The roe deer density was investigated in the Forsmark area (and Hållnäs) in 2003 through pellet (fecal) counts. The methodology is described in /Cederlund et al. 2004/. An average weight was calculated based on the distribution of fawns (*Sw: kid*), goats (*Sw: get*) and bucks (*Sw: bock*) presented at /Jägareförbundet, 2004b/, and the live weights for fawns, goats and bucks given in /Cederlund and Liberg, 1995/. The production is proposed to be 50% of the biomass (Cederlund, 2004, pers comm). A mean value of the winter- and summer consumption was calculated based on consumption values for roe deers in enclosure were found on /Jägareförbundet, 2004c, website/.

Red deer and Fallow deer

The red deer (*Sw: kronhjort*) density was investigated in the Forsmark area (and Hållnäs) in 2003 through pellet (fecal) counts. The methodology is described in /Cederlund et al. 2004/. An average weight has been calculated based on the weight values for stags (male) and hinds (female) found at /Jägareförbundet, 2004d, website/, and an assumption of a sex ratio of 0.5/0.5. No consumption values have been found, and the red deer is thus assumed to consume 5% of the average live weight, which is the case for moose in Forsmark. The production is assumed to be equal with the moose production, i.e. 30% of biomass.

The fallow deer (*Sw: dovhjort*) density was investigated in the Forsmark area (and Hållnäs) in 2003 through pellet (fecal) counts. The methodology is described in /Cederlund et al. 2004/. No fallow deer was found in either Forsmark or Hållnäs.

Hare

The hare density was investigated in the Forsmark area (and Hållnäs) in 2003 through pellet (fecal) counts. The methodology is described in /Cederlund et al. 2004/. Data sets from the fields and from the forests were separated. Normally, the mountain hare (*Sw: skogshare*) is associated with forest and European hare (*Sw: fälthare*) with fields, but there is no absolute border in habitat use between the species. Since it is hard to discriminate pellets from the two species, calculations refer to the two main habitat types, which are the density in the forests is applied to the mountain hare and the density in the fields to the European hare.

When calculating the total number of individuals in Forsmark 2, the density values have been multiplied with the forest area and field area (grassland, arable land and wetlands), respectively. The live weight for an adult mountain hare and an adult European hare have been obtained from /Jägareförbundet, 2004e,f, website/. The production is estimated to be 30% of the biomass (Cederlund, 2004, pers comm). The consumption figure for mountain hare was found at /Jägareförbundet, 2004g, website/.

Small mammals

The density have been modified since /Cederlund et al. 2004/, and new density values for small mammals in the field and the forest have been obtained from (Cederlund, 2004, pers comm). When calculating the total number of individuals in Forsmark 2, the density has been multiplied with the forest area and the field area (grassland, arable land and wetlands), respectively.

Average weights for small mammals in the field and in the forest were estimated by (Wallin, 2004, pers comm). According to /Anticimex, 2004, website/ a house mouse consumes 2–3 g food per day. That is 13% of its biomass. The production is assumed to be 10 times the biomass for all rodents (10 generations per year) (Cederlund, 2004, pers comm).

Cattle

There is no active agriculture in Forsmark 2, but the amount of grasslands and arable fields in the area may theoretically support five dairy cows (age 1–5 years) in Forsmark 2. This assumption is based on the fact that a cow need 1.8–3.0 hectares (mean 2.4 ha) for fodder production and grazing /Arnesson, 2001/. A dairy cow is inseminated by the age of 15–18 months and then gives birth to her first calf at the age of two years. Thereafter she has a calf a year and gives milk during ten months a year. An average dairy cow is slaughtered at the age of five years after she has given birth to three calves /Miliander et al. 2004/. Accordingly, the five cows in Forsmark 2 can produce three calves per year of which two are slaughtered each year as well as the oldest cow. The production is thus calculated as the biomass of two calves and one cow.

A dairy cow consumes yearly approximately 3,500 kg grass, 2,000 kg crops and 1,000 kg concentrated fodder, in total 6,500 kg food (17 kg per day) /Livsmedelssverige, 2004, website/. The carbon content in food is estimated to 25% of the total weight (wet weight). The living weights of a cow and a calf have been calculated from the utilized carcass weights in /Miliander et al. 2004/. The utilized carcass weight is assumed to be 80% of the carcass weight and the carcass weight, in its turn, is assumed to be 55% of the living weight, as for the game meat /Miliander et al. 2004/.

Marten

The marten density was investigated in the Forsmark area (and Hållnäs) in 2002 by using line transects in the snow according to the Buffon method. The number of tracks per transect length can be converted into number of animals per km^2. The methodology is described in /Cederlund et al. 2003/.

The live weight has been obtained from /Jägarnas Riksförbund, 2004a, website/. No consumption data has been found for marten. Its consumption is therefore assumed to be in proportion to the consumption for lynx that is also a carnivore. The consumption for lynx is 5.3% of its biomass (1 kg per day /Järvzoo, 2004, website/ and an average weight of 19 kg /Jägarnas Riksförbund, 2004b, website/). The production is estimated to be 30% of the biomass (Cederlund, 2004, pers comm).

Fox

There are no site-specific density data for fox. A generic density value as well as a weight value have been found at /Jägareförbundet, 2004h, website/. No consumption data have been found for fox. Its consumption is therefore assumed to be in proportion to the consumption for lynx that is also a carnivore (5.3% of its biomass). The production is assumed to be 30% of the biomass, as proposed for marten (Cederlund, 2004, pers comm).

Lynx

The lynx population was investigated in the Forsmark area (and Hållnäs) in 2003 by counting tracks along line transects in the snow. There were no attempts to estimate density that year. The lynx density was calculated in 2002 though, by using line transects in the snow according to the Buffon method /Cederlund et al. 2003/.

The live weight has been obtained from /Jägarnas Riksförbund, 2004b, website/. A daily consumption value has been found at /Järvzoo, 2004, website/. The production is estimated to be 30% of the biomass (Cederlund, 2004, pers comm).

Wild boar

The wild boar population was investigated in the Forsmark area (and Hållnäs) in 2003 by using line transects in the snow according to the Buffon method and through pellet counting. The methodology is described in /Cederlund et al. 2004/.

The live weight has been obtained from /Jägareförbundet, 2004i,j, website/. The mean weight has been calculated based on the fact that 55% of the population are six months (0–1 year), 25% are 1.5 years old (1–2 years) and 20% are full sized, according to the population structure given by (Lemel, 2004, pers comm). Consumption values during the summer for an adult wild boar and a piglet was found at /Jägareförbundet, 2004k, website/. An average consumption was calculated based on the fact that approximately 50% of the population are piglets (0–1 year). The carbon consumption has been calculated based on a 100% vegetarian diet. Normally a wild boar consumes animalia to 15% /Lemel, 1999/.

The production is assumed to represent 1% of the energy input (consumption) according to /Jerling et al. 2001/. This gives a production equal to almost 50% of the biomass.

Birds

A bird survey has been performed in Forsmark, mainly to evaluate the possible effects of the site investigation on the numbers of breeding birds, and in some cases also on their breeding success /Green, 2004/. The number of birds registered per kilometre during the line transects, as well as numbers of territories per km^2, are presented in /Green, 2004/, but there are no density values. Since no density data are available, bird biomass has not been calculated.

Amphibians and reptiles

A field study was performed in 2003 mainly to verify the presence of suitable habitats for the species that are likely to occur in Forsmark /Andrén, 2004a/.

Densities for the species that occur in the Forsmark area have been estimated from generic data by /Andrén, 2004b/. Average weight values as well as feeding habits and the number of eggs/youngsters per individual are also included in /Andrén, 2004b/. No attempt has been made to calculate the production from the number of eggs/youngsters per female. Instead the production of the amphibians and the reptiles has been calculated based on /Jerling et al. 2001/, showing that the production of vertebrates (ectothermal, *Sw: växelvarma*) represent 8% of the energy input (consumption). Amphibians and reptiles are carnivores and their diet (small mammals, other amphibians and reptiles, insects and invertebrates) is, as the mammals, assumed to contain 10% carbon.

Soil fauna

Three examples of soil fauna densities and biomass values have been obtained. The three examples come from a pine moor in Gästrikland, a deciduous forest in Uppland (Andersby-Ängsbacka in Dannemora) and a grassland in Uppland /Lohm and Persson,1979/. The carbon content in soil fauna is 50% of the dry weight according to (Persson, 2004, pers comm). There are no data concerning the consumption and production.

Description

Moose

The pellet counts in 2003 gave a mean density of approximately 1.23 moose×km^{-2} in Forsmark and 0.67 in Hållnäs. The density increased with 50% in Forsmark between 2002 and 2003. This might be due to random movements among moose and the relatively small area in relation to moose home ranges /Cederlund et al. 2004/.

The average carcass weights from Saxmarken, close to Forsmark, are 161 for a bull and 146 kg for a cow /Svensk Viltförvaltning AB, 2003/. These values are lower than the carcass weights suggested at /Jägareförbundet, 2004l, website/, 180–230 kg for a bull and 170–200 kg for a cow. The carcass weights in Forsmark correspond to live weights of 293 kg and 265 kg, respectively. An adult moose consumes 6–10 kg food per day during winter and 2–3 times more during summer /Jägareförbundet, 2004a, website/. That is a yearly consumption of, in average, 14 kg fresh weight per day (3.5 kgC per moose and day).

During the summer the moose eats leafs from deciduous trees, such as birch (*Sw:björk*), aspen (*Sw:asp*), willow (*Sw:vide*) and sallow (*Sw:sälg*). They also eat herbs like meadow-sweet (*Sw:älgört*), rose bay willowherb (*Sw:mjölkört*), clover and some water plants. During the autumn the diet changes to berry shrubs, heather (*Sw:ljung*), oat and wheat. Twigs and sprouts of pine, common juniper (*Sw:en*) as well as of deciduous trees and scrubs are the winter diet, together with bark from primarily aspen, rowan (*Sw:rönn*) and pine /Jägareförbundet, 2004l, website/.

The moose cow becomes fertile at the age of two and she gives birth to her first calf at the age of three. The cow gives birth to one or two calves in May–June, after a gestation period of eight months /Jägareförbundet, 2004m, website/. A moose has a so called "home range", which is a specific area that the moose chooses to live in during a temporary time period (a winter, a summer or a whole year). The size of the home range varies. Generally, the bulls have larger ranges than the cows. At Grimsö research station in Bergslagen, the home ranges are in average 1,400 ha for cows and 2,600 ha for bulls /Jägareförbundet, 2004n, website/.

Roe deer

Pellet counts indicated that there were at least two times more deer in Forsmark than in Hållnäs. 9.36 moose×km^{-2} in Forsmark compared with 4.8 in Hållnäs. It is well known that roe deer density varies considerably between adjacent, local areas. There is now reason to believe that the densities found in this study are exceptional /Cederlund et al. 2004/.

The live weights for roe deer are 22–28 kg for a buck, 21–27 kg for a goat and 12–16 kg for a fawn /Cederlund and Liberg, 1995/. According to /Jägareförbundet, 2004b,website/ the population is composed by 30% fawns and 70% adults, of which 60% are goats. This gives an average weight of 21.3 kg.

The roe deer diet during the summer consists of berry scrubs, heather (*Sw: ljung*), three leafs, grass and herbs; primary rose bay willowherb (*Sw: mjölkört*), wood anemone (*Sw: vitsippa*) and cow-wheat (*Sw: kovall*). Mushrooms are also an important part of the diet and sometimes also crops. Berry scrubs and heather are also an important part of the winter diet as long as they are not completely covered by snow. If so, the roe deer change over to twigs of coniferous and deciduous trees. An adult roe deer in enclosure consumes in average 3 kg food per day during summertime and in average 1 kg per day in wintertime /Jägareförbundet, 2004c, website/. This means an average consumption of approximately 2 kg fresh weight per roe deer and day, i.e. 0.5 kgC per roe deer and day.

The roe deer goat becomes fertile at the age of one and she gives birth to her first fawn at the age of two. The goat gives birth to one to three fawns in May–June. A roe deer lives at the most in 10–12 years /Jägareförbundet, 2004o, website/. A roe deer has, like the moose, a "home range". The size of the home range varies. Generally, the bucks have larger ranges than the goats. Goats can also have overlapping ranges and share ranges with other goats and a buck. The roe deer migrate in dusk and dawn /Jägareförbundet, 2004p, website/.

Red deer and fallow deer

There were no signs of fallow deer in either Forsmark or Hållnäs.

Red deer was found at low density in Forsmark (0.01 deer×km^{-2}). Red deer are living patchily in small groups along the coastal area. Their patchy distribution might lead to too low estimates. According to local managers the population is increasing, as is the entire population in Sweden /Cederlund et al. 2004/.

Red deer prefer an open deciduous woodland and they feed on grasses, herbs, leaves, buds, shoots and bark. At the age of two, the female gives birth to her first calf in May–June. The females do only get one calf per year and some years they don't reproduce at all. This is the reason why the population growth is slow. A red deer lives probably in 15–20 years /Jägareförbundet, 2004d, website/.

Hare

Hare density in the fields during 2003 varied considerably, from 0.32 hares×km^{-2} in Forsmark to 2.28 hares×km^{-2} in Hållnäs. The high values in Hållnäs might be accidental as the figure was 0.25 hares×km^{-2} in 2002. In the forest, density was generally low in both years, 0.23 hares×km^{-2} in Forsmark (0.44 in 2002) and 0.15 hares×km^{-2} in Hållnäs (0.23 in 2002). /Cederlund et al. 2004/ declare the density of hare to be fairly low in Forsmark and Hållnäs. Hares in the area might be under strong pressure from several predators like fox, marten and lynx.

The live weight is 3–5 kg (mean 4 kg) for an adult mountain hare and 4–6 kg (mean 5 kg) for an adult European hare according to /Jägareförbundet, 2004e,f, website/.

Mountain hares graze on heather, blueberry scrubs, twigs of deciduous trees, grasses, herbs, small coniferous plants and occasionally, farm crops /Jägareförbundet, 2004e, website/. The European hare eats almost the same, but is more bound to farm crops. The smallest amount of food that a mountain hare need to survive during the winter is 500 gram per day /Jägareförbundet, 2004g, website/. This means 125 gC per hare and day.

The female mountain hare gives birth to a litter of 1–7 leverets after a gestation period of 50 days. Two litters per breeding season is most normal, but three can occur /Jägareförbundet, 2004f, website/. The European hare has a somewhat shorter gestation period (45 days) and get 1–5 leverets in three litters /Jägareförbundet, 2004e, website/. The hares are mainly solitary, but they don't avoid each other. The home-range of the mountain hare is approximately 200 ha on a year basis /Jägareförbundet, 2004q/. Their greatest danger is from predation by red foxes.

Small mammals –forest

The small mammals in forest are mainly bank vole (*Sw: skogssork*), yellow-necked mouse (*Sw: större skogsmus*) and wood mouse (*Sw: mindre skogsmus*). According to (Cederlund, 2004, pers comm), there are 1,200 small mammals per km^2 forest in Forsmark.

A yellow-necked mouse weights 22–44 g and a wood mouse (and house mouse) weights 10–28 g according to /Svenskt Naturlexikon, 2000/. The bank vole weights 12–35 g according to /ARKive, 2004a, website/.

The bank vole inhabits broadleaved woodlands, scrub, parks, hedgerows and banks where there is plenty of herbaceous cover. They have a broad diet, which is mainly herbivorous, including fruit, soft seeds, leaves, fungi, roots, grass, buds and moss. They may also occasionally take invertebrate food such as snails, worms and insects. 4 to 5 litters are produced in a year, each one consisting of 3–5 young. Gestation takes around 21 days. Predators such as owls, kestrels, foxes and weasels take their toll on vole populations; the maximum life span for the bank vole is 18 months /ARKive, 2004a, website/.

The wood mouse is a highly adaptable species that exploits a wide range of habitats, providing that they are not overly wet. They feed on seeds, invertebrates, fruits, nuts, seedlings, moss and fungi. Females give birth to 2–9 young, after a gestation of 25–26 days. They tend to have 4–7 litters a year. This species has many predators, including foxes, weasels, cats, owls and kestrels. The maximum life span is up to 20 months /ARKive, 2004b, website/.

The yellow-necked mouse usually occurs close to arable farmland. It may also inhabit orchards, field margins, wooded gardens, hedgerows and buildings in rural areas. They feed on fruit, seedlings, buds and invertebrate. Females give birth to 2–11 young, but usually 5, after a gestation of 25 or 26 days. Around three litters are produced each year. Yellow-necked mice are adept climbers, and as a result they feed in trees and bushes and enter houses more often than wood mice /ARKive, 2004c, website/. The life span is up to one year /BBC, 2004a, website/.

Small mammals –field

The small mammals in field are mainly field vole (*Sw: åkersork*), water vole (*Sw: vattensork*) and common shrew (*Sw: vanlig näbbmus*). According to (Cederlund, 2004, pers comm), there are 1,500 small mammals per km^2 field in Forsmark.

A common shrew weights 5–12 g, according to /BBC, 2004b, website/. The field vole weights 20–40 g and the water vole 150–300 g according to /the Mammal society, 2004a,b, website/. (Wallin, 2004, pers comm) proposed a mean weight of 30 g for small mammals in the field, as the field vole is dominating.

The field vole occurs typically in abandoned grassland or in the early stages of forestry plantations but may also live in woodland or moorland, wherever grass is available. Grass is the field voles’ only food source. The females produce 5–6 litters a year of 4–6 young. The average life span of a field vole is less than a year /The Mammal society, 2004b, website/.

The water voles inhabit the banks of ditches, dykes, slow-moving rivers and streams, and grassland. The water vole feed mainly on grasses and other plant material. The water vole produce up to five litters a year of in average six young. The life span of a water vole is up to 2 years /BBC, 2004c, website/

Common shrews are insectivorous and carnivorous, feeding on insects, slugs, spiders, worms and carrion. They need to eat 80–90 per cent of their own body weight in food daily. The shrew females rear 2–4 litters a year of typically 6 young. The life span of a common shrew is up to 23 months /BBC, 2004b, website/.

Cattle

See Section 3.10.

Marten

The track indexes indicate that marten is a common predator in both Forsmark and Hållnäs. By using the Buffon method the density was estimated to 0.24 marten×km^{-2} in Forsmark in 2002. This density estimate is relatively uncertain (large confidence intervals) and is probably too high /Cederlund et al. 2003/.

The live weight is 0.8 –1.5 kg according to the website of /Jägarnas Riksförbund, 2004a, website/. The marten prefer well wooded areas with plenty of cover. They feed on squirrels, birds, small mammals, rabbits/hares, eggs, insects and berries. They also eat carrion of cervids /Jägareförbundet, 2004r, website/. No consumption data has been found for marten.

The population growth is low. The first litter normally comes when the female is 2–3 years old. Females give birth to 1–4 young, which become fully independent after six months. Their greatest danger is from predation, especially by red foxes /Jägareförbundet, 2004r, website/.

Fox

There are in general 0.8 foxes×km^{-2} in southern Sweden, but the density depends on the amount of food /Jägareförbundet, 2004h, website/.

The male weights approximately 7.5 kg and the female 6.5 kg. Rodents is the main diet, but they do eat hares, roe deer fawns, birds, frogs, berries, insects and scraps left by humans. The female fox becomes fertile at 9–10 months of age and she gives birth to five to six cubs, after a gestation period of approximately 52 days. The fox lives normally in 10 years /Jägareförbundet, 2004s,t,u, website/. Foxes forage alone in different parts of their territory, which may extend from 20 to 2,000 ha depending on the food supply /Jägareförbundet, 2004v, website/.

Lynx

Lynx is present in Forsmark and in Hållnäs, but in low number. There were no attempts to estimate lynx density in 2003. An estimate in 2002 from a small data set revealed a density of 0.02 lynx/km^2 /Cederlund et al. 2004/.

The weight is 14–24 kg (mean 19 kg) according to the website of /Jägarnas Riksförbund, 2004a, website/. An adult lynx eats about 1 kg meat per day according to /Järvzoo, 2004, website/.

The lynx lives solitary in forests and migrates within a home-region of 200–600 km^2, sometimes larger. They prey mainly on roe deer, rein deer and hare, but do also take fox, small rodents and birds. The females give birth to one to three kittens in May–June. /Jägareförbundet, 2004y,z, website/.

Wild boar

The wild boar population has still a low mean density in the region, but is expected to increase in the near future like in many other areas in Sweden. The population growth is estimated to be 13% in central Sweden, on a year basis /Lemel, 1999/. The animals live in groups and use the landscape variably. That might be the reason why they did not find more than just occasional tracks on the line transects. The pellet counting in Hållnäs gave a density of 0.01 boar×km^{-2}, which is probably too low /Cederlund et al. 2004/.

The sows weight normally 80–90 kg, while the boars are heavier and can weight 150 kg /Jägareförbundet, 2004i, website/. A piglet weights 20 kg after six months and 60–65 kg after one year /Jägareförbundet, 2004j, website/. According to /Lemel, 2004, pers comm/, the population structure is as follow: 50–55% of the population is 0–1 years old, 25% is 1–2 year, 10% is 2–3 year, 5% is 3–4 year and 2.5% is 4–5 year. The mean weight has been calculated to be approximately 57 kg.

An adult wild boar consumes 4 kg per day during the summer, while a piglet consumes half of that amount, according to /Jägareförbundet, 2004k, website/. The mean consumption is assumed to be approximately 0.75 kgC per wild boar and day, as 50% of the wild boars are 0–1 year. A wild boar is to 85% herbivorous (vegetation and mushrooms) and to 15% carnivorous /Lemel, 1999/. The animal diet consists mainly of invertebrates like earthworms, insects and larvae. Small mammals are sometimes a part of the diet /Jägareförbundet, 2004k, website/.

A young sow gives birth to one litter of 3–4 piglets. A sow of three years or older can get a larger litter of 5–6 piglets (sometimes more) /Jägareförbundet, 2004j, website/. The size of a wild boar home ranges varies. An adult wild boar uses in night time in average a region of approximately 100 ha. The total area that a wild boar uses is at least tree times that size. A group of sows with piglets can use a home range of 2,000 ha /Jägareförbundet, 2004x, website/.

Birds

In total, 96 species were found in the regional model area in 2003, compared to 96 in 2002. The most common species on land were Chaffinch and Willow warbler (Table 3-47). For detailed information on each species found in the Forsmark area, see /Green, 2004/.

Table 3-47. The ten most common nesting species in the Forsmark regional area, presented as the total number of birds registered and the number of birds per km during transect surveys /Green, 2004/.

Species English (Swedish)	Latin	Total number (2003)	Abundance (n/km) 2003	Abundance (n/km) 2002
Chaffinch (Bofink)	*Fringilla coelebs*	617	13.27	11.36
Willow Warbler (Lövsångare)	*Phylloscopus trochilus*	401	8.62	11.31
Common gull (Fiskmås)	*Larus canus*	190	4.09	1.36
Robin (Rödhake)	*Erithacus rubecula*	188	4.04	3.54
Song Thrush (Taltrast)	*Turdus philomelos*	178	3.83	1.81
Jackdaw (Kaja)	*Corvus monedula*	153	3.29	1.29
Greylag goose (grågås)	*Anser anser*	137	2.95	2.65
Blackbird (Koltrast)	*Turdus merula*	105	2.26	2.46
Goldcrest (Kungsfågel)	*Regulus regulus*	97	2.09	0.54
Goldeneye (Knipa)	*Bucephala clangula*	90	1.94	0.85

Reptiles and Amphibians

The information that was given in /Andrén, 2004b/ is compiled in Table 3-48.

Table 3-48. Ecological data concerning amphibians and reptiles /Andrén, 2004b/.

Species	Weight (g)	Density (ind/km^2)	Diet	Energy needs	Reproduction
Adder (huggorm)	150	100	Primarily mice and voles	330 g dry weight per year (900 mg/day)	In average 5 young per year
Grass snake (vanlig snok)	175	100 (200 in wetlands)	Frogs and toads, fish, newts	350 g dry weight per year (960 mg per day)	Approx 13 eggs per year
Smooth snake (hasselsnok)	70	20	Other reptiles such as slowworm	140 g dry weight per year (380 mg per day)	In average 6 young per year
Slow-worm (kopparödla)	15	1,000	Earthworms and snails	60 g dry weight per year (165 mg per day)	8 young per year
Common lizard (skogsödla)	5	500	Spiders and insects	21 g dry weight per year (58 mg per day)	7 young per year
Sand lizard (sandödla)	8	15 (in Forsmark)	Spiders and insects	27.2 g dry weight per year (75 mg per day)	10 eggs per year
Moor frog (åkergroda)	20	3,000 (0– 100 m from pond) 1,000 (100–300 m from pond) 100–500 (300–500 m from pond)	Insects, spiders and worms	20 g dry weight per year (55 mg per day)	1,500 eggs per year
Common toad (vanlig padda)	60	4,000	Insects, spiders and worms	123.2 g dry weight per year (338 mg per day)	4,000 eggs per year
Smooth newt (mindre vattensalamander)	3	2 per m^2 water area, the population size can be up to 10,000 individuals. They stay within 300 m from the pond.	Larger zooplankton, waterinsects, waterspiders, earthworms, snails and larvae of insects	3 g dry weight per year (8.2 mg per day)	350 eggs per year
Great creasted newt (stor vattensalamander)	9	1 per m^2 water area, the population is never larger than a few thousand individuals They stay within 500 m from the pond.	Insects, earthworms, snails, waterinsects, waterspiders, larvae of frog and smooth newt.	7.65 g dry weight per year (21 mg per day)	200 eggs per year

Soil fauna

The density and biomass in three different biotopes are listed in Table 3-49. The biomass is approximately six times lower in the pine forest than in the deciduous forest. The highest biomass is found in the grassland.

In general, the deciduous forest has a humus layer of mould (*Sw: mull*) with mineral earth, which indicates that the soil contain larger species that burrow. The coniferous forest has a humus layer without mineral soil (*Sw: mår*), which indicates that there are no burrowing fauna. The total amount of soil fauna is larger in coniferous forest, because the organisms are microscopic, such as nematodes (*Sw: rundmaskar*), mites (*Sw: kvalster*) and springtails (*Sw: hoppstjärtar*), which can be seen in Table 3-49. In coniferous forests the decomposition is mainly carried out by fungi though, not soil fauna, while it is mostly a bacterial decomposition in deciduous forests /SkogsSverige, 2004, website/.

The soil fauna accounts for 10% of the carbon turn over in soil, while the fungi and bacterial flora accounts for approximately 90% (Persson, 2004, pers comm). The soil fauna has instead a larger importance for the soil structure and soil properties. Among the soil organisms, the fungi has most likely the largest storing capacity of radionuclides, according to (Persson, 2004, pers comm). As mammals, such as moose, consume fungus, they should be an important part of the safety assessment.

The main part of the soil fauna is microbivores (they consumes microorganisms), while some species are primary decomposers (Persson, 2004, pers comm). According to /Jerling et al. 2001/ the production for microbivores accounts for 12% of the energy input (consumption), while the respiration accounts for 18%. The rest goes out as faeces (70%).

Table 3-49. Biomass and density in the soil fauna in three different biotopes /Lohm and Persson, 1979/.

	Decidious forest (Uppland)			**Pine moor (Gästr.)**			**Grassland (Uppland)**		
	Number per m²	**Dry weight per m² (mg)**	**mgC per m²**	**Number per m²**	**Dry weight per m² (mg)**	**mgC per m²**	**Number per m²**	**Dry weight per m² (mg)**	**mgC per m²**
Earthworm (daggmask)	180	6,100	3,050	< 1	16.9	8.45	130	5,900	2,950
Enchytraeidae (småringmask)	3,800	370	185	17,000	420	210	24,000	850	425
Wood louse (gråsuggor)	2	9	4.5	< 1	2.25	1.125	< 1	4	2
Centipede (tusenfotingar)	1,200	70	35	25	3	1.5	2	30	15
Springtails (hoppstjärtar)	66,000	110	55	65,000	100	50	110,000	140	70
Protura (trevfotingar)	3,800	2	1	1,000	1	0.5	40	0.5	0.25
Thrips (tripsar)	100	0.5	0.25	1,400	6	3	720	3	1.5
Homoptera (växtsugare)	70	2	1	270	11	5.5	70	1	0.5
Hemipteron (skinnbaggar)	10	7	3.5	190	10	5	10	3	1.5
Beetles (skalbaggar)	600	480	240	500	170	85	1,400	2,800	1,400
Steklar, tex myror	50	50	25	40	15	7.5	110	3	1.5
Wiggler (mygglarver)	1,300	50	25	700	20	10	4,400	320	160
Fly-maggot (fluglarver)	30	80	40	70	9	4.5	1,100	330	165
Spiders (spindlar)	220	70	35	340	70	35	200	40	20
Mite (kvalster)	190,000	600	300	620,000	400	200	110,000	130	65
Sum	**267,362**	**8,000.5**	**4,000.25**	**706,535**	**1,254.15**	**627.1**	**252,182**	**10,554.5**	**5,277.3**

Quantitative model

The calculations are compiled in Table 3-50 and the carbon flow is visualised in Figure 3-102 and 3-103.

The density of mice and voles are much lower in Forsmark than in Simpevarp. As the production of the small mammals has been calculated to be 10 times the biomass, the total production of herbivores becomes approximately half as high as in Forsmark. When the amount of production that goes to fox, marten, lynx and man is withdrawn, the amount left is assumed to go to other carnivores (see Figure 3-103). This value, however, is somewhat larger than the amount that goes to marten, fox and lynx.

Approximately half of the herbivorous production within Forsmark 2 goes to humans. The fictitious cattle population represents a considerable part of the carbon flow, which can be seen in Figure 3-103.

Table 3-50. Calculations of biomass, production, consumption and faeces in the drainage area Forsmark 2, expressed as $gC \times m^{-2} \times y^{-1}$ and $gC \times y^{-1}$.

Species		Number		Biomass				Production		Consumption			Feaces	
		Number per km²	Total number in Forsmark 2	Live weight kg/ind	Biomass g/m²/y	Biomass C gC/m²/y	Biomass C Tot gC/y	Prod C gC/m²/y	Prod C Tot gC/y	Consump C gC/ind/day	Consump C gC/m²/y	Consump Tot C gC/y	Faeces C gC/m²/y	Faeces Tot C gC/y
Mammals – herbivores	Moose	1.2	9.6	279	0.34	0.034	268,616	0.010	80,585	3,500	1.6	12,299,529	0.79	6,149,765
	Roe deer	9.4	73	21	0.20	0.020	155,909	0.010	77,954	500	1.7	13,370,917	0.85	6,685,458
	Red deer	0.010	0.078	190	0.0019	0.00019	1,487	0.000057	446	2,375	0.0087	67,855	0.0043	33,927
	European hare (field)	0.32	0.33	5.00	0.0016	0.00016	166	0.000048	50	125	0.015	15,159	0.0073	7,580
	Mountaine hare (forest)	0.23	1.6	4.00	0.00092	0.000092	625	0.000028	187	125	0.010	71,244	0.0052	35,622
	Small mammals -field	1,500	1,557	0.030	0.045	0.0045	4,672	0.045	46,724	0.98	0.53	554,269	0.27	277,134
	Small mammals -forest	1,200	8,147	0.020	0.024	0.0024	16,294	0.024	162,940	0.65	0.28	1,932,876	0.14	966,438
	Cattle[1]	42	5.0	329	14	1.4	164,523	0.55	66,068	4,250	65	7,756,250	32	3,878,125
Mammal – omnivorous	Wild boar	0.010	0.08	57	0.00057	0.000057	449	0.000027	214	750	0.0027	21,428	0.0014	10,714
	Sum herbivores (and wild boar)						**612,740**		**435,169**			**36,089,526**		**18,044,763**
Mammals – carnivores	marten	0.24	1.9	1.2	0.00028	0.000028	216	0.00001	65	6.1	0.00053	4,179	0.00011	836
	Lynx	0.020	0.16	19	0.00038	0.000038	297	0.00001	89	100	0.00073	5,714	0.00015	1,143
	Fox	0.80	6.3	7.0	0.0056	0.00056	4,383	0.00017	1,315	37	0.011	84,797	0.0022	16,959
	Sum carnivores						**4,897**		**1,469**			**94,690**		**18,938**
Reptiles	Adder	100	783	0.15	0.015	0.0015	11,741	0.00131	10,285	0.45	0.016	128,567	0.0033	25,713
	Grass snake	100	783	0.18	0.018	0.0018	13,698	0.00140	10,971	0.48	0.018	137,138	0.0035	27,428
	Smooth snake	20	157	0.070	0.0014	0.00014	1,096	0.00011	869	0.19	0.0014	10,857	0.00028	2,171
	Slow worm	1,000	7,827	0.015	0.015	0.0015	11,741	0.00241	18,856	0.0825	0.030	235,705	0.0060	47,141
	Common lizard	500	3,914	0.0050	0.0025	0.00025	1,957	0.00042	3,314	0.029	0.0053	41,427	0.0011	8,285
	Sum reptiles						**40,233**		**44,295**			**553,693**		**110,739**
Amphibians	Common toad	4,000	31,310	0.060	0.24	0.024	187,860	0.01974	154,508	0.17	0.25	1,931,355	0.049	386,271
Soil fauna[1]					1.3	0.63								

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[1] Fictious numbers since there is no cattle in Forsmark 2. In theory there could be five milkcows in the area as there are some agricultural landarea within Forsmark 2.

[2] Dry weight. The figure demonstrate the results from a pine moor in Gästrikland.

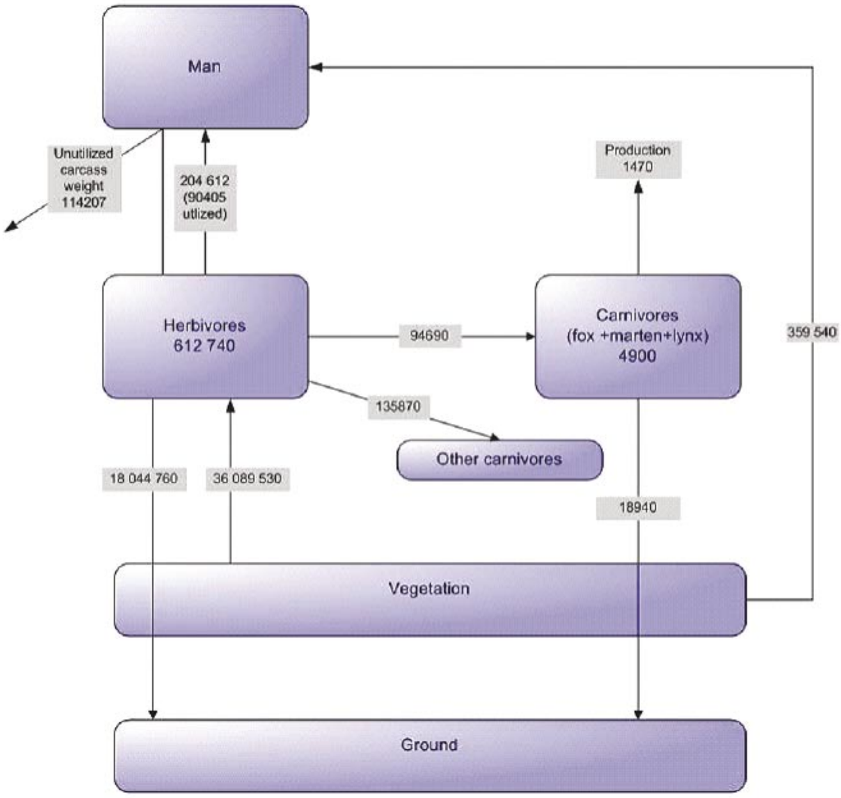
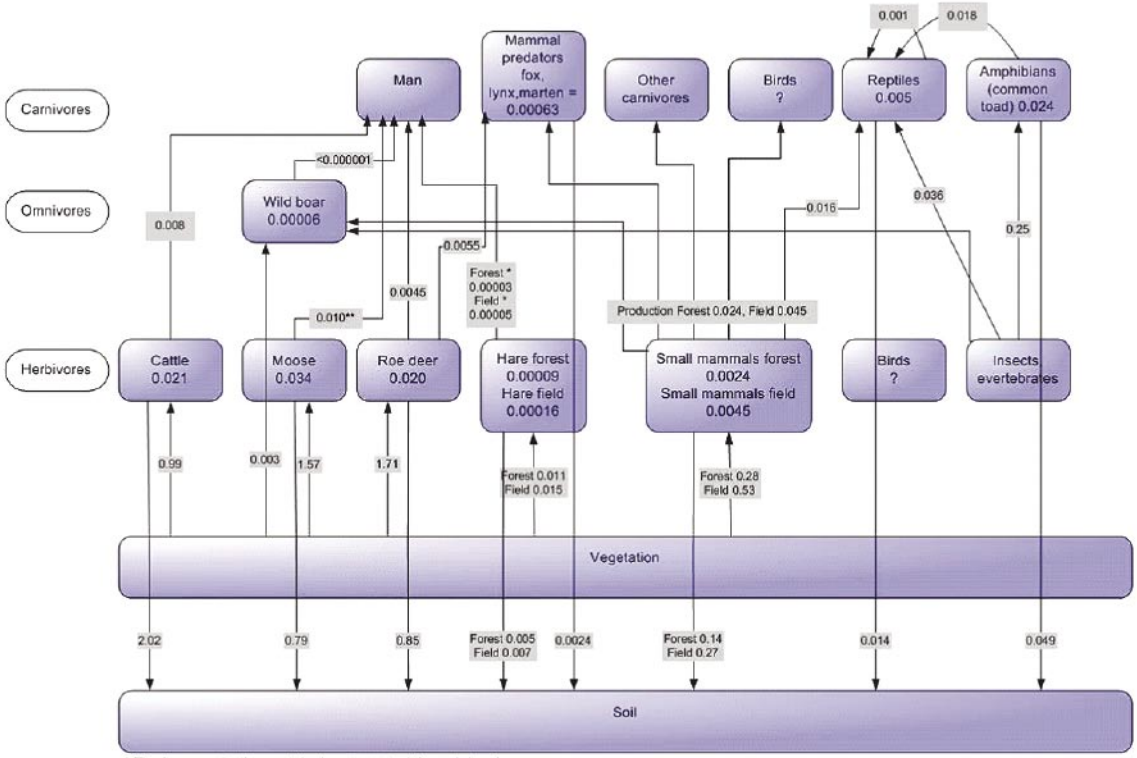


***Figure 3-102.** Carbon budget for the terrestrial fauna in the drainage area Forsmark 2, expressed as total carbon (gC×y^{-1}).*



* The hare production, not the human output through hunting

** The moose production, not the human output through hunting

***Figure 3-103.** Detailed carbon budget for the terrestrial fauna in the drainage area Forsmark 2, expressed as gC×m^{-2}×y^{-1}.*

When comparing the human data (see Table 3-70 in Section 3.10) and the fauna values, it is notable that the moose production is less than the output of moose through hunting. The source of this error is either a miscalculation of the production figure or a result of the fact that the moose migrate within a large home range and are not evenly harvested within the Forsmark parish. The harvest figure comes from the Forsmark parish (94.2 km^2), an area approximately of the same size and the same location as the selected study area (110 km^2). This should make the figures fairly corresponding.

If we instead use the production figure from /Jerling et al. 2001/, which is 1% of the energy input (consumption), the moose production will be larger than the output through hunting

The density values and the hunting figures for hare are not coherent. When it comes to roe deer the calculated production is approximately twice the human output though hunting.

3.8 Limnic biota

3.8.1 Introduction

The characteristics of the limnic system in the Forsmark regional model area is to a large extent determined by the small topographic gradients in combination with the ongoing shore displacement and a short distance to the sea, and by the occurrence of calcium-rich deposits. A total of eight small water systems, which are situated partly or entirely within the SKB site investigation area, have been identified, and the total number of lakes and ponds within these catchments is 25 /Brunberg et al. 2004/. The lakes are generally small (only 3 of the lakes are larger than 0.2 km^2, and most of them are considerably smaller) and shallow (average max depth is 1.2 m, average mean depth is 0.4 m), which means that they have small water volumes and short water renewal times. Some of the lakes have not yet been completely separated from the sea, and in these lakes saline water from the Baltic Sea may occasionally intrude during low pressure weather conditions. Many of the streams in the area get periodically dry due to small catchment areas and low precipitation.

All investigated lakes in the area can be classified as oligotrophic hardwater lakes. This means that they show very unusual chemical conditions, with high alkalinity, conductivity, pH-value and nitrogen concentrations, very high concentrations of slightly coloured DOC, while phosphorus concentrations are very low. Phytoplankton and bacterioplankton biomasses are low, and the microbial community (including both autotrophs and heterotrophs) is mainly confined to the sediments where a 10–15 cm thick microbial mat, mainly consisting of cyanobacteria, is found. Preliminary measurements of primary production in the lake show that while the production in the pelagial always is low, the production in the microbial mat may potentially be very high /Blomqvist et al. 2002/.

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

One of the larger lakes in the area, Lake Eckarfjärden, has been intensively studied during several years by Uppsala University, and the most comprehensive dataset concerning limnic biota in the Forsmark area is therefore from this lake. Because of the similar characteristics of all lakes in the area, most of the biotic data from Lake Eckarfjärden can be assumed to be valid also for the less investigated lakes.

3.8.2 Producers

Input data and data evaluation

Primary producers in Lake Eckarfjärden have been thoroughly investigated for several years. During 2000–2002, biomass of microbiota was investigated each month during winter and every second week during summer /Blomqvist et al. 2002/. Production by microbiota was measured during the summer of 2001. During 2002, biomass of zooplankton, benthic fauna and macrophytes, as well as production of microbiota, were investigated /Andersson et al. 2003/.

The borders between different habitats within the lakes have been determined and dominating species within each habitat identified /Brunberg et al. 2004/.

Table 3-51. Data sources concerning primary producers in the limnic systems of Forsmark.

Parameter	Lake	Year	Reference
Habitat borders (with dominating species)	25 lakes in the Forsmark area	2002–2003	Brunberg et al. 2004
Microbiota:			
– Biomass	Lake Eckarfjärden	2000–2002	Blomqvist et al. 2002 Andersson et al. 2003
– production	Lake Eckarfjärden	2001–2002	Blomqvist et al. 2002
			Andersson et al. 2003
Macrophyte biomass	Lake Eckarfjärden	2002	Andersson et al. 2003
Microbial mat			
– biomass	Lake Eckarfjärden	2000–2002	Blomqvist et al. 2002
			Andersson et al. 2003
– production	Lake Eckarfjärden	2001–2002	Blomqvist et al. 2002
			Andersson et al. 2003

Metodology

The delimitations between different habitats in the lakes were determined in connection with the lake characterisation, which included identification of watershed, data collection and field investigations /Brunberg et al. 2004/. The extension of different lake habitats was identified in the field and the borders were recorded using a DGPS equipment.

Microbiota was sampled monthly or biweekly from January 2000 to March 2003. Samples were taken with a tube sampler at 15 sites and pooled in a bucket from which sub-samples were drawn. The samples were preserved in the field with acidified Lugols solution. Species composition and biomass of planktonic microbiota (phytoplankton and heterotrophic nanoflagellates) and microphytobenthos were determined using an inverted phase-contrast microscope /Andersson et al. 2003/.

Density of *macrophytes* was measured by randomly placing a frame with the side of 25 cm in stands of *Phragmites australis* (28 samples) and *Typha sp* (28 samples), and a frame with the side 50 cm in stands of *Equisetum fluviatile* (10 samples) and *Schoenoplectus lacustris* (10 samples). The number of straws within the frame was counted. All straws of *P. australis* and *Typha sp* and subsamples of 10 and 30 straws of *S. lacustris* and *E. fluviatile*, respectively, were taken to the lab where dry weight was measured.

Primary production was measured in situ with ^{14}C-incorporations at 9 and 14 occasions in the sediment zone and in the pelagial, respectively /Andersson et al 2003/. Primary production in the pelagic zone was measured with duplicates at 5, 25, 50, 100 and 150 cm depth. In the sediment zone, primary production was measured at 150 m water depth, and on three occasions also at 50 and 100 cm depth.

Descriptive models

The Forsmark lakes were divided into five different habitats; the Littoral type I, II and III, the Pelagial and the Profundal, according to /Blomqvist et al. 2002/. The different habitats are defined as follows:

Littoral type I: The littoral habitat with emergent and floating-leaved vegetation. This habitat is developed in wind-sheltered, shallow areas where the substrate is soft and allows emergent and floating-leaved vegetation to colonise.

Littoral type II: The littoral habitat with hard substrate. This habitat develops in wind-exposed areas of larger lakes, but also in smaller lakes, where the lake morphometry includes rocky shores. The photosynthesizing organisms colonizing these areas include species that are able to attach to the hard substrate, e.g. periphytic algae.

Littoral type III: The littoral habitat with submerged vegetation. This habitat is found in deeper areas of the littoral, where light enough to sustain photosynthetic primary production penetrates down to the sediment.

The profundal habitat: This habitat develops at the sediments of the lakes where light penetration is less than needed to sustain a permanent vegetation of primary producers. Non-photosynthesising organisms dominate this habitat. The profundal organisms are dependent on carbon supplies imported from other habitats of the lake or from allochtonous sources.

The pelagic habitat: This habitat includes the open lake water, where a pelagic food-web based on planktic organisms is developed. Depending on the light availability, these plankton are dominated by either photosynthetic production (i.e. by autotrophic phytoplankton) or, if the water is strongly coloured or turbid, by heterotrophic carbon processing (e.g. by heterotrophic or mixotrophic bacterioplankton and phytoplankton). The pelagic habitat covers the same area as the sum of littoral type II, littoral type III and profundal habitats within a lake.

Since the Forsmark lakes are small and shallow, only three of these habitats are found, namely the Littoral types I and II and the pelagial /Brunberg et al. 2004/.

Below, the available data on primary producers from lakes in the Forsmark area is presented. Lake Eckarfjärden is by far the most investigated lake in the area, and in the parameterisation of quantitative models for the other lakes in Forsmark, most of the data used will therefore be data from this lake.

Lake Eckarfjärden

The pelagic habitat and the littoral with submerged vegetation (Littoral type III), which have the same areal distribution, cover 66% of the lake area (Figure 3-104). The submerged vegetation in this area is dominated by stoneworths (*Chara sp*), which covers 75% of Littoral III /Blomqvist et al. 2002/ (Figure 3-105), while the emergent vegetation is strongly dominated by *Phragmites australis* and *Typha sp* (Figure 3-105 and Table 3-52).

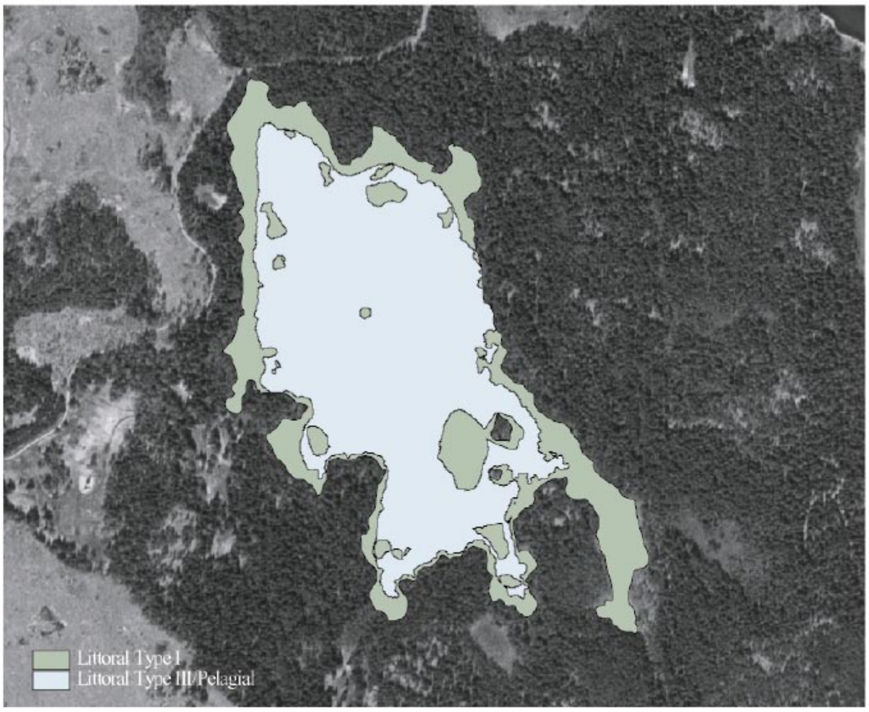


Figure 3-104. Distribution of major habitats in Lake Eckarfjärden /Brunberg et al. 2004/.

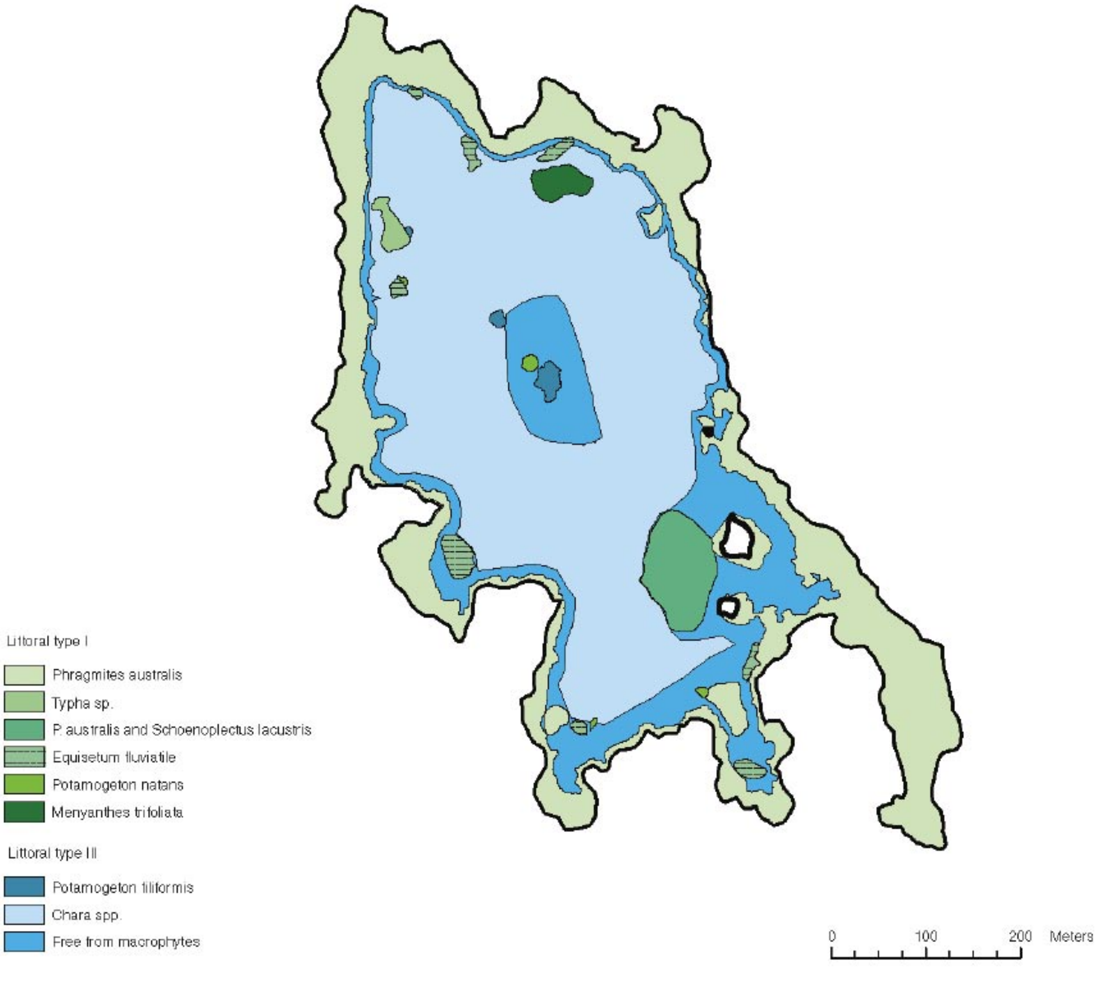


Figure 3-105. Dominating species of vegetation in the littoral of type I and III in Lake Eckarfjärden /Brunberg et al. 2004/.

Table 3-52. Biomass (mean ± SD) and areal coverage of dominating macrophyte species in Lake Eckarfjärden 2002 /Andersson et al. 2003/.

Species	Biomass (g dw/m^2)	Coverage (% of lake area)
Phragmites australis	296 ± 316	31
Typha sp	184 ± 246	29
Schoenoplectus lacustris	54 ± 11	3
Equisetum fluviatile	34 ± 27	1

The biomass of microbiota is clearly concentrated to a 10–15 cm thick microbial mat covering almost the entire bottom of the Littoral type III. The top 5 cm of this mat is dominated by microphytobenthos, mainly cyanobacteria (Table 3-53).

Table 3-53. Average biomass and production values of microbiota in the open water and surface sediments (the upper 0–5 cm) of Lake Eckarfjärden during 2002 /Andersson et al. 2003/.

Parameter	Biomass (mgC m^{-2})	Production (mgC m$^{2-1}$ h^{-1})
Phytoplankton	74 ± 53	11 ± 11
Microphytobenthos	3,056 ± 1,100	12 ± 15

The temporal variation of phytoplankton in Lake Eckarfjärden has been studied during 2000–2002. The results are shown in Figure 3-106 below. An average value has been calculated for each month during these three years. In the carbon budget an annual average value, estimated from these monthly average values, have been used.

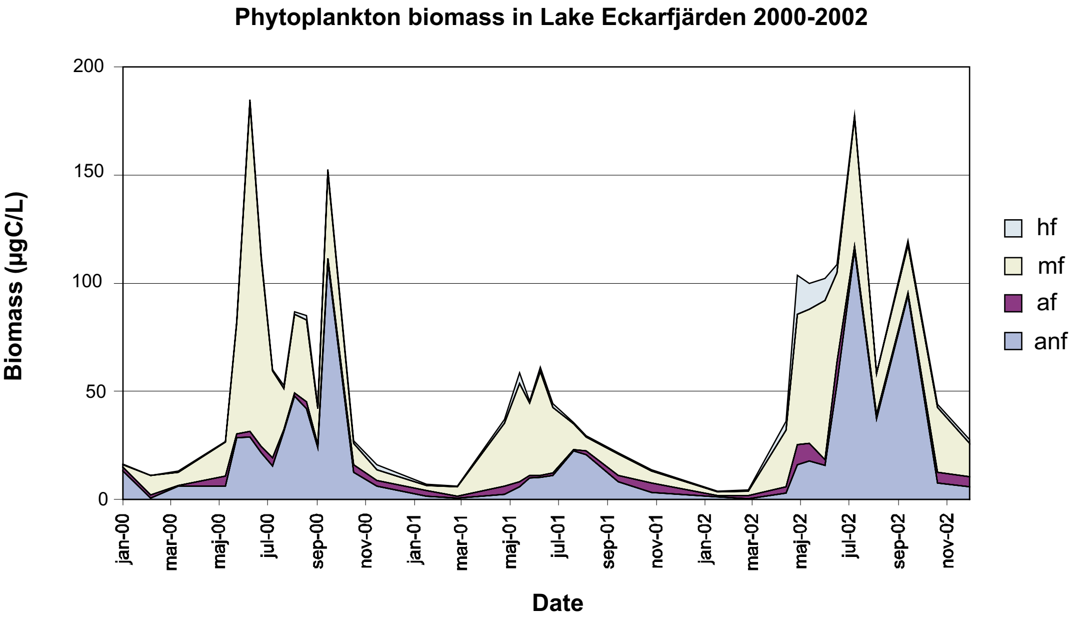


Figure 3-106. Biomass of functional groups of phytoplankton in Lake Eckarfjärden during the period January 2000 to December 2002 /Andersson et al. 2003/. Hf = heterotrophic flagellates, Mf = mixotrophic flagellates, af = autotrophic flagellates and anf = autotrophic non-flagellates.

The biomass of primary producers in the microbial mat varies with depth in the mat. Maximum density is found 2–4 cm down the mat and decreases successively downwards. The density also varies over the year, with the highest biomass in July (Figure 3-107).

The primary production of phytoplankton varies between 0.1 and 24 mgC×m^{-2}×h^{-1} and for microphytobenthos between 0.03 and 144 mgC×m^{-2}×h^{-1} during 2001 and 2002 (Andersson and Brunberg, unpubl). Yearly primary production was 25 gC×m^{-2}×y^{-1} for phytoplankton and 56 gC×m^{-2}×y^{-1} for microphytobenthos. The annual variation in primary production of phytoplankton and microphytobenthos is shown in Figure 3-108. Besides the temporal variation, primary production also varies between different depths. For example, the estimated primary production in August was lowest in the deepest part of the lake (1.5 m depth) with ca 40 mgC×m^{-2}×h^{-1} and highest at intermediate depth (1.0 m depth) with ca 75 mgC×m^{-2}×h^{-1}. At 0.5 m depth the production was ca 60 mgC×m^{-2}×h^{-1} /Andersson et al. 2003/.

Lake Bolundsfjärden

Lake Bolundsfjärden has three major habitats; the littoral with emergent and floating-leaved vegetation (Littoral type I), the littoral with submerged vegetation (Littoral type III), and the pelagic habitat. The open water surface, i.e. the pelagic habitat, covers 66% of the lake area (Figure 3-109). Due to the shallowness and clear water of the lake, light penetrates down to all bottom areas and no profundal areas are present. Hence, the littoral with submerged vegetation has the same distribution as the pelagic habitat.

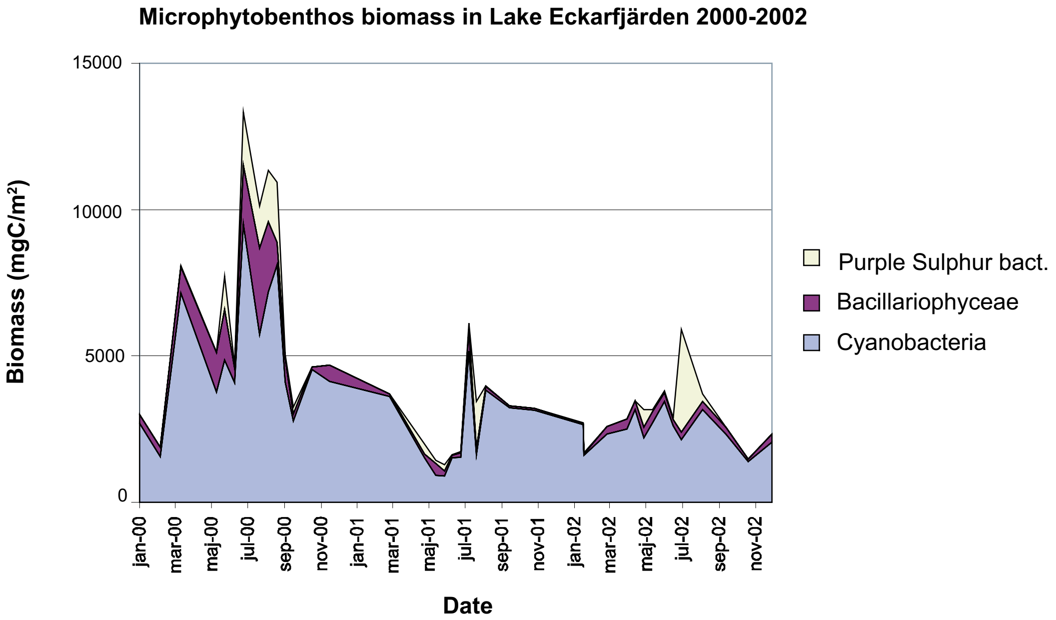


Figure 3-107. *Biomass of microphytobenthos in the top 5 cm of the microbial mat In Lake Eckarfjärden during the period January 2000 to December 2002.*

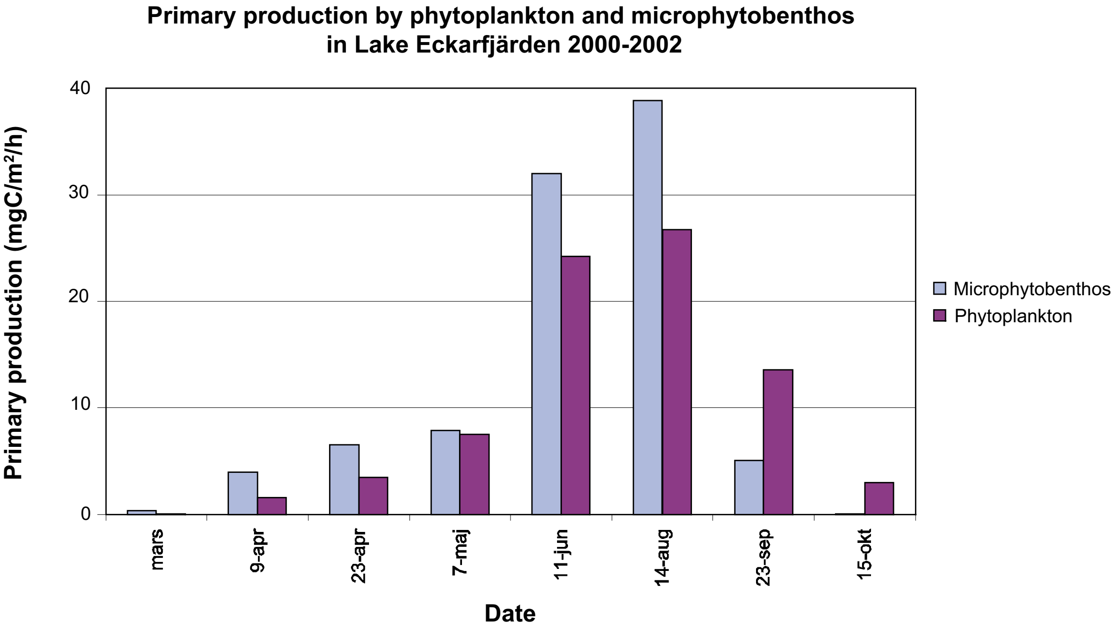


Figure 3-108. *Primary production by phytoplankton and microphytobenthos, estimated on an areal basis in/below a water column of 1.5 m, in Lake Eckarfjärden 2002 /Andersson et al. 2003/.*

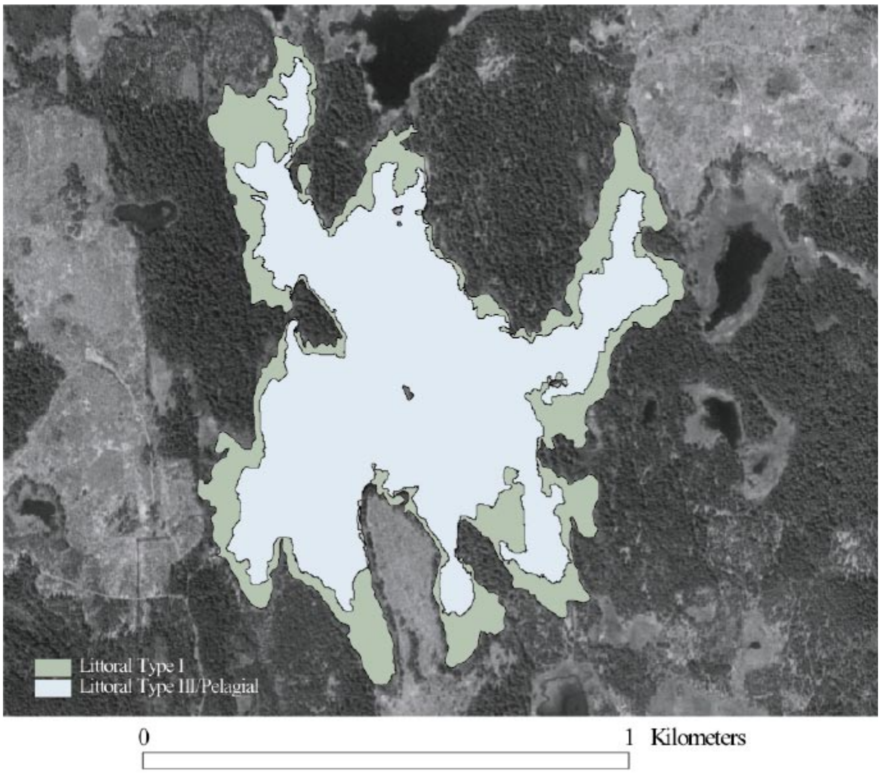


Figure 3-109. *Distribution of major habitats in Lake Bolundsfjärden /Brunberg et al. 2004/.*

Biomass data for phytoplankton and microphytobenthos from Lake Bolundsfjärden are available for the period August–October 2001 /Franzén, 2002/. Phytoplankton biomass was in the same order of magnitude as in Lake Eckarfjärden, whereas no direct comparison was possible for microphytobenthos. However, due to the short time series of this data and the considerable temporal variation in biomasses shown in Lake Eckarfjärden (cf Figure 3-106 and Figure 3-107), phytoplankton and microphytobenthos data from Lake Eckarfjärden was used in the quantitative model. No data on primary production is available from Lake Bolundsfjärden.

Lake Fiskarfjärden

Similar to the other larger lakes in the area, three major habitats are present also in Lake Fiskarfjärden; the littoral habitat with emergent and floating-leaved vegetation (Littoral type I), the littoral habitat with submerged vegetation (Littoral type III), and the pelagic habitat (Figure 3-110). Half of the lake area is covered by littoral of type III with the overlaying pelagic habitat, the other half is covered by littoral of type I.

No data on primary production or biomass of primary producers are available for Lake Bolundsfjärden.

General characteristics for lakes in the Forsmark area

The dominating habitat in the larger lakes in the area is the littoral with submerged vegetation (Littoral type III). In Lake Eckarfjärden, Bolundsfjärden and Fiskarfjärden this habitat makes up at least 50% of the lake area, whereas 20 of the other 22 lakes in the area have a larger share of the littoral with emergent and floating-leaved vegetation (Littoral type I, cf Table 3-54 and /Brunberg et al. 2004/). This is not surprising since these lakes are smaller, shallower and in a later successional stage. The extreme is Lake Labboträsket where 96% of the area consists of littoral with emergent and floating-leaved vegetation.

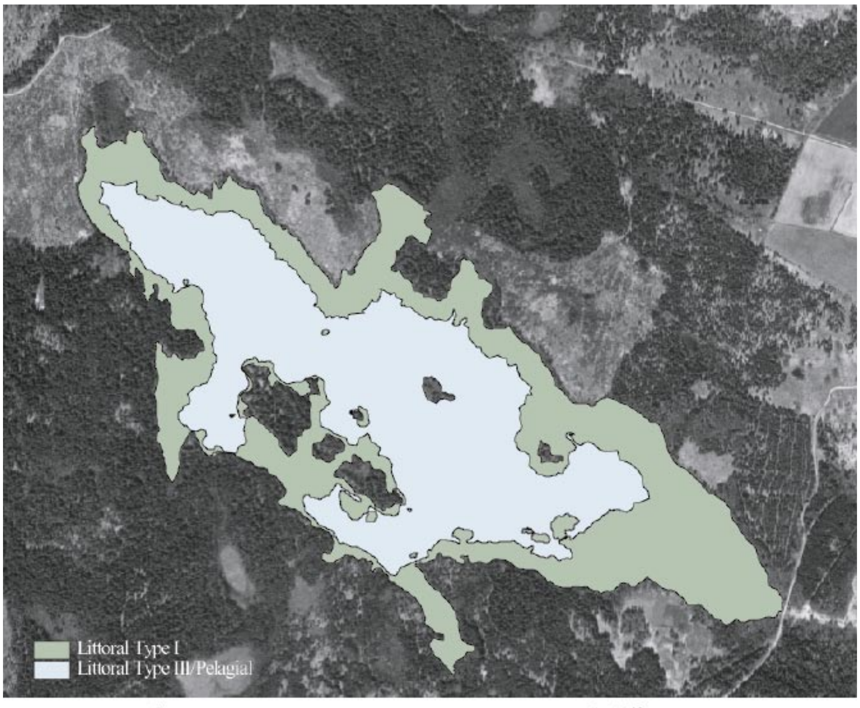


Figure 3-110. *Distribution of major habitats in Lake Fiskarfjärden /Brunberg et al. 2004/.*

Table 3-54. Depth, surface and volume characteristics of importance for primary production in the lakes in the drainage area Forsmark 2 (data from /Brunberg et al. 2004/). The area covered by *Chara* is determined by field investigations only for Lake Eckarfjärden, whereas it is calculated for the other lakes, based on the assumption that the *Chara* coverage of Littoral 3 in all the Forsmark lakes is the same as in Lake Eckarfjärden (75%).

	2:10 Eckar-fjärden	2:3 Bolunds-fjärden	2:1 N. Bassängen	2:2	2:4 Graven	2:5 Fräken-gropen	2:6 Vambörs-fjärden	2:7 Kungs-träsket	2:8 Gällsbo-träsket	2:9 Stock-sjön	2:11 Puttan
Depth info (m)											
Average depth	0.9	0.6	0.3	0.3	0.1	0.2	0.4	0.2	0.2	0.2	0.4
Max depth	2.1	1.8	0.9	0.6	0.4	0.8	1	0.5	1.5	0.8	1.3
Surface info (m²)											
Littoral I	95,318	206,719	44,395	4,954	42,185	16,913	29,781	4,755	178,344	31,012	56,230
Littoral II											
Littoral III	188,532	404,593	31,675	4,975	7,902	2,510	19,796	2,978	8,704	5,468	26,511
Chara area	142,330	305,443	23,913	3,756	5,966	1,895	14,945	2,248	6,571	4,128	20,014
Profundal (aphotic zone)											
Pelagial	188,532	404,593	31,675	4,975	7,902	2,510	19,796	2,978	8,704	5,468	26,511
Total lake area	283,850	611,312	76,070	9,929	50,087	19,423	49,577	7,733	187,048	36,480	82,741
Volume info (m³)											
Volume photic zone	257,000	374,000	24,000	3,000	6,000	4,000	21,000	2,000	32,000	8,000	30,000
Volume aphotic zone											
Total volume	257,000	374,000	24,000	3,000	6,000	4,000	21,000	2,000	32,000	8,000	30,000

3.8.3 Consumers

Input data and data evaluation

During 2002, biomasses of zooplankton and benthic fauna were investigated in Lake Eckarfjärden /Andersson et al. 2003/. Biomasses of bacterioplankton and benthic bacteria were investigated during the time period 2000–2002. Bacterial production in the pelagial as well as in the top 5 cm of the sediments in Lake Eckarfjärden was measured during 2002.

Fish data has been collected from four of the larger lakes in the area (Lake Bolundsfjärden, Lake Eckarfjärden, Lake Fiskarfjärden and Lake Gunnarsbo-Lillfjärden) in August 2003 /Borgiel, 2004/.

Table 3-55. Data sources concerning consumers in the limnic systems of Forsmark.

Parameter	Lake	Year	Reference
Bacteria (bacterioplankton and benthic bacteria):			
– biomass	Lake Eckarfjärden	2000–2002	/Andersson et al. 2003/
– production	Lake Eckarfjärden	2002	/Andersson et al. 2003/
Zooplankton biomass	Lake Eckarfjärden	2002	/Andersson et al. 2003/
Benthic fauna biomass	Lake Eckarfjärden	2002	/Andersson et al. 2003/
Fish biomass	Lake Eckarfjärden	1991, 2003	National board of Fisheries, /Borgiel, 2004/
	Lake Fiskarfjärden	2003	/Borgiel, 2004/
	Lake Bolundsfjärden	2001, 2003	National board of Fisheries, /Borgiel, 2004/
	Lake Gunnarsbo-Lillfjärden	2003	/Borgiel, 2004/

Metodology

Pelagical bacterial biomass was sampled 7 times during 2002. Samples were taken with a tube sampler at 15 sites in the lake and pooled in a bucket from which sub-samples were drawn. Samples for the analysis of bacterioplankton were preserved with formaldehyde. Samples of heterotrophic bacteria in sediments were taken with a tube sampler at a station located in the deepest part of the lake at 11 occasions during 2002. Also these samples were preserved with formaldehyde. Heterotrophic bacterioplankton and sediment bacteria were counted and measured in an epifluorescence microscope.

Bacterial production in the water column as well as in the upper sediment in Lake Eckarfjärden was measured after incubation with (methyl–^{3}H) /Andersson et al. 2003/.

Zooplankton was sampled monthly or biweekly from January 2002 to March 2003. Samples were taken with a tube sampler at 15 sites and pooled in a bucket from which sub-samples were drawn. 5-10 L water was sieved through a 40 µm sieve. The samples were preserved in the field with acidified Lugols solution. Species composition, length and width of zooplankton were analysed in an inverted light microscope after sedimentation of organisms for at least one hour. The biovolumes were transformed to biomass and calculation of carbon content were slightly differently depending on species /Andersson et al. 2003/.

Benthic fauna was sampled in March 2002 at 10 randomly chosen sites in Lake Eckarfjärden /Andersson et al. 2003/. Samples were taken with an Ekman grabber with an area of 2.5 dm^2 and were sieved through a 0.5 mm sieve. The benthic animals were identified to species, counted and weighed.

A fish survey was performed using standardised benthic multi-mesh gillnets of Nordic type /Borgiel, 2004/. The standardised procedure allowed the result to be compared with other studies, and so that the weight values per unit effort could be transferred into biomass per hectare. For this conversion a factor of 33 have been used (1 kg fish in the net represents 33 kg fish/ha in the lake) as proposed by Per Nyberg at Fiskeriverket (Örebro). Here the data set has also been classified into functional groups; zooplanktivore fish (Z-fish), benthivore fish (M-fish) and piscivore fish (F-fish), based on the weight of the individual fishes according to /Holmgren and Appelberg, 2000/ (Table 3-56). For crucian carp smaller than 64 g no information about probable food preference has been found. Here we assume that individuals smaller than 8 g are feeding on zooplankton, whereas larger individuals mainly feed on macroinvertebrates.

Table 3-56. Classification of fish species into functional groups according to /Holmgren and Appelberg, 2000/.

Functional group	Included species
Z-fish – Planktivorous fish	Small perch, roach, rudd and crucian carp (< 8 g)
M-fish – Benthivorous fish	Ruffe, tench, bream, roach, rudd, white bream, Crucian carp and medium-sized perch (8–64 g)
F-fish – Piscivorous fish	Pike, large perch (> 64 g)

Descriptive models

Below, available data concerning consumers from lakes in the Forsmark area is presented. Lake Eckarfjärden is by far the most investigated lake in the area, and in the parameterisation of quantitative models for the other lakes in Forsmark, most of the data used will therefore be from this lake.

Lake Eckarfjärden

Heterotrophic *bacteria* make up a substantial part of the microbial mat in the surface sediments (Table 3-57), and the bacterial biomass is in the same order of magnitude as that of microphytobenthos (cf Table 3-53). In the pelagic habitat, the community is dominated by heterotrophic organisms /Blomqvist et al. 2002/. The (secondary) production of benthic microbiota is as high as or higher than that in the pelagial (Table 3-51). The benthic community therefore has a key role in the production and metabolism of organic matter in the system.

Zooplankton biomass was dominated by copepods and showed an opposite seasonal trend compared to most other Swedish lakes, with a summer minimum and winter maximum (Figure 3-111). One explanation for this seemingly inverse seasonal development could be that the copepods are mainly benthic, but forced to move to higher strata in the winter when oxygen concentrations near the bottom are low. Another possible explanation is a high grazing pressure by fish in the summer.

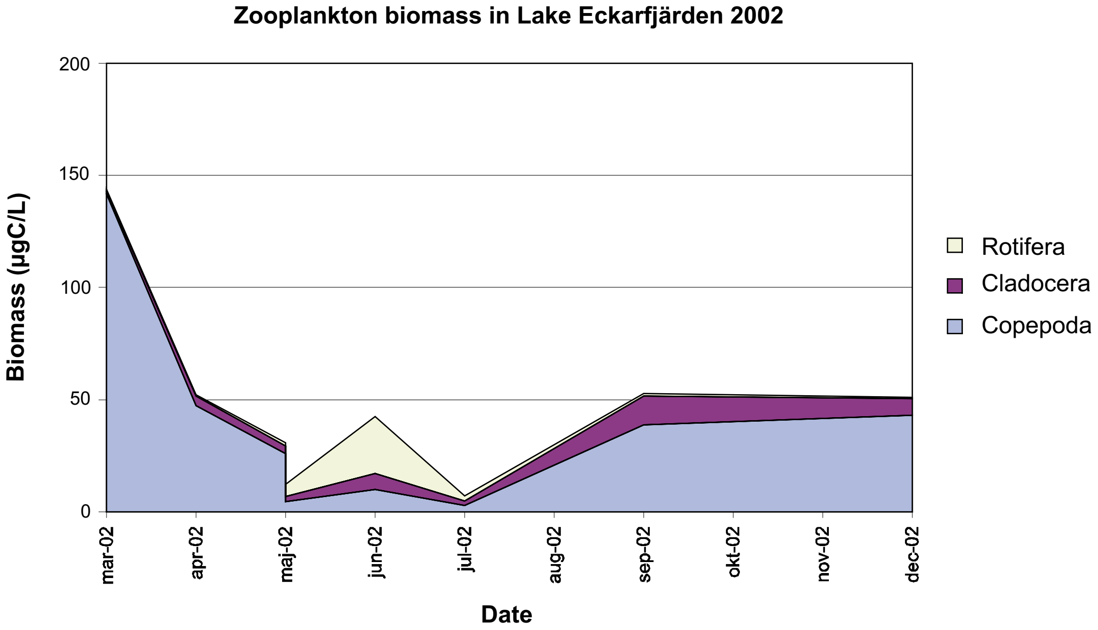


Figure 3-111. *Biomass of zooplankton in Lake Eckarfjärden during the period March 2002 to December 2002 /Andersson et al. 2003/.*

Table 3-57. Average biomass and production values for microbiota in the open water and surface sediments (the upper 0–5 cm) of Lake Eckarfjärden during 2002 /Andersson et al. 2003/.

	Biomass (mgC m⁻²)	**Production (mgC m⁻² h⁻¹)**
Bacterioplankton	36 ± 13	4 ± 4
Benthic bacteria	3,848 ± 605	6 ± 5

The biomass of benthic fauna was low compared to other lakes. The benthic fauna was dominated by herbivores, both in terms of number of individuals and in terms of biomass (Table 3-58).

Table 3-58. Biomass and density of benthic fauna, divided into functional groups, in Lake Eckarfjärden in March 2002 /Andersson et al. 2003/.

Functional group	**Biomass (mg ww m⁻²)**	**Individuals m⁻²**
Herbivores	1,520	1,048
Carnivores	261	7,756
Detritivores	395	452
Filtrators	484	1,216

Five fish species were caught in Lake Eckarfjärden in the fish survey /Borgiel, 2004/. Roach and perch dominated in numbers, while tench made up 40% of the biomass, followed by perch (25%), roach (22%) and pike (12%). Data from the fish survey, divided into functional groups, is presented in Table 3-59.

Table 3-59. Compiled results of fish data from Lake Eckarfjärden (8 gillnets), August 2003 /Borgiel, 2004/.

Functional group	Species	Weight per Unit Effort (WPUE) (kg)	Biomass per hectare (kg ww ha^{-1})	Total biomass in Lake Eckarfjärden (kg ww)	Total biomass in LakeEckarfjärden (kg C)
Z-fish	Perch	0.014			
	Roach	0.081			
	Z-fish total	**0.10**	**3.1**	**59.2**	**5.8**
M-fish	Perch	0.282			
	Ruffe	0.005			
	Roach	0.712			
	Tench	1.470			
	M-fish total	**2.47**	**81.4**	**1,535.6**	**151.4**
F-fish	Perch	0.625			
	Pike	0.451			
	F-fish total	**1.08**	**35.5**	**669.1**	**66.0**
Total		**3.65**	**120.1**	**2,263.9**	**223.2**

A fish survey was performed in Lake Eckarfjärden also in 1991. The results from that inventory are presented in Table 3-60. When comparing the results from 1991 with those from 2003 some large differences are obvious. The total weight is very similar, but when looking at specific species some drastic changes seems to have occurred. The weight of roach and pike has almost doubled, whereas the weight of perch is only half as large as in 1991. In the carbon budget, only data from the sampling 2003 has been used.

Table 3-60. Results from earlier inventory sampling of freshwater fish with multi-mesh gillnets in Lake Eckarfjärden 1991 (Data received from the National board of Fisheries) and from the fish survey in 2003 /Borgiel, 2004/.

Species	Weigth per unit effort (WPUE) (g) 1991 (n = 6)	2003 (n = 8)	$WPUE_{2003}/WPUE_{1991}$
Roach	431.0	790	1.8
Perch	1,920.0	920	0.5
Ruffe	9.8	0	
Tench	1,312.5	1,470	1.1
Pike	199.3	450	2.3
Total	3,872.6	3,630	0.9

Lake Bolundsfjärden

There are no data concerning zooplankton or benthic fauna from Lake Bolundsfjärden.

In the fish survey, eight species were caught in Lake Bolundfjärden. Perch was dominating by number, followed by roach. Tench made up 41% of the biomass, followed by perch (27%), roach (19%), crucian carp (9%) and pike (1.6%) /Borgiel, 2004/. Data from the fish survey, divided into functional groups, is presented in Table 3-61.

Table 3-61. Compiled results of fish data from lake Bolundsfjärden (16 gillnets) August 2003 /Borgiel, 2004/.

Functional group	Species	Weight per Unit Effort (WPUE, kg)	Biomass per hectare (kg ww ha^{-1})	Total biomass in Lake Bolundsfjärden (kg ww)	Total biomass in Lake Bolundsfjärden (kgC)
Z-fish	Perch	0.0003			
	Roach	0.0025			
	Rudd	0.0004			
	Z-fish total	**0.0032**	**0.1**	**4.32**	**0.43**
M-fish	Perch	0.3533			
	Ruffe	0.0186			
	Roach	0.4698			
	Tench	1.0049			
	White bream	0.0016			
	Crucian carp	0.2344			
	Rudd	0.0026			
	M-fish total	**2.0851**	**68.8**	**2,783.9**	**273.9**
F-fish	Perch	0.3198			
	Pike	0.0436			
	F-fish total	**0.3634**	**12.0**	**485.2**	**47.7**
Total		**2.45**	**80.9**	**3,273.4**	**322.1**

A fish survey was performed in Lake Bolundsfjärden also in 2001. The results from that inventory are presented in Table 3-62. In the earlier study, only 4 gillnets were used, compared to 16 in the study in 2003. Any comparison between the two surveys should therefore be interpreted with great caution. In the carbon budget, only data from the sampling in 2003 has been used.

Table 3-62. Results from earlier sampling of freshwater fish with multi-mesh gillnets in Lake Bolundsfjärden 2001 (Data received from the National board of Fisheries) and from the fish survey in 2003 /Borgiel, 2004/.

Species	Weight per unit effort (WPUE) (g) 2001	 2003
Roach	621	470
Perch	1,421	670
Ruffe	71	20
Tench	2,677	1,000
Pike	4	40
Total	4,794	2,200

Lake Fiskarfjärden

There are no data concerning zooplankton or benthic fauna from Lake Fiskarfjärden.

In the fish survey, six species were caught in Lake Fiskarfjärden. Perch followed by roach and crucian carp dominated in number. Crucian carp made up 57% of the biomass, followed by tench (19%), perch (13%) and roach (10%) /Borgiel, 2004/. Data from the fish survey, divided into functional groups, is presented in Table 3-63.

Table 3-63. Compiled results of fish data from lake Fiskarfjärden (16 gillnets) August 2003 /Borgiel, 2004/.

Functional group	Species	Weight per Unit Effort (WPUE) (kg)	Biomass per hectare (kg ww ha^{-1})	Total biomass in Lake Fiskarfjärden (kg ww)	Total biomass in Lake Fiskarfjärden (kg C)
F-fish	Perch	0.018			
	Roach	0.014			
	Crucian carp	0.005			
	Z-fish total	**0.037**	**1.2**	**46.3**	**4.6**
M-fish	Perch	0.138			
	Ruffe	0.005			
	Roach	0.457			
	Tench	0.879			
	Crucian carp	2.640			
	M-fish total	**4.119**	**135.9**	**5,176.0**	**509.3**
F-fish	Perch	0.434			
	Pike	0.041			
	F-fish total	**0.475**	**15.7**	**597.1**	**58.8**
Total		**6.631**	**152.8**	**5,919.4**	**572.6**

Lake Gunnarsbo-Lillfjärden

There are no data concerning zooplankton or benthic fauna for Lake Gunnarsbo-Lillfjärden.

In the fish survey, three species were caught in Lake Fiskarfjärden /Borgiel, 2004/. Crucian carp dominated in numbers as well as in biomass. Crucian carp made up 64% of the biomass, whereas perch made up 36%. The third species was roach which made up only 0.3% of the biomass. Data from the fish survey, divided into functional groups, is presented in Table 3-64.

Table 3-64. Compiled results of fish data from Lake Gunnarsbo-Lillfjärden (4 gillnets) August 2003 /Borgiel, 2004/.

Functional group	Species	Weight per Unit Effort (WPUE) (kg)	Biomass per hectare (kg ww ha^{-1})	Total biomass in Gunnarsbo-Lillfjärden (kg ww)	Total biomass in Gunnarsbo-Lillfjärden (kg C)
Z-fish	Perch	0.007			
	Z-fish total	**0.007**	**0.24**	**0.43**	**0.04**
M-fish	Perch	0.327			
	Roach	0.010			
	Crucian carp	2.048			
	M-fish total	**2.385**	**78.70**	**141.1**	**13.9**
F-fish	Perch	0.802			
	F-fish total	**0.802**	**26.48**	**47.5**	**4.7**
Total		**3.195**	**105.42**	**189.0**	**18.6**

General characteristics for lakes in the Forsmark area

Data concerning zooplankton and benthic fauna are only available from one of the lakes in the area, Lake Eckarfjärden. However, considering the large similarities in lake morphology and water chemistry between lakes in the area, data from Lake Eckarfjärden can be regarded as valid also for the other lakes, at least those with similar size and habitat distribution.

Fish data from all four investigated lakes in the area show that benthivorous fish generally is the dominating functional group. This is not surprising since species which are not sensitive to low oxygen levels belong to this group. The share of benthivorous fish of the total fish biomass range from 68% in Lake Eckarfjärden to 89% in Lake Fiskarfjärden. The share of planktivorous fishes is generally low, ranging from 0.1% in Lake Bolundsfjärden to 8% in Lake Fiskarfjärden.

3.9 Marine biota

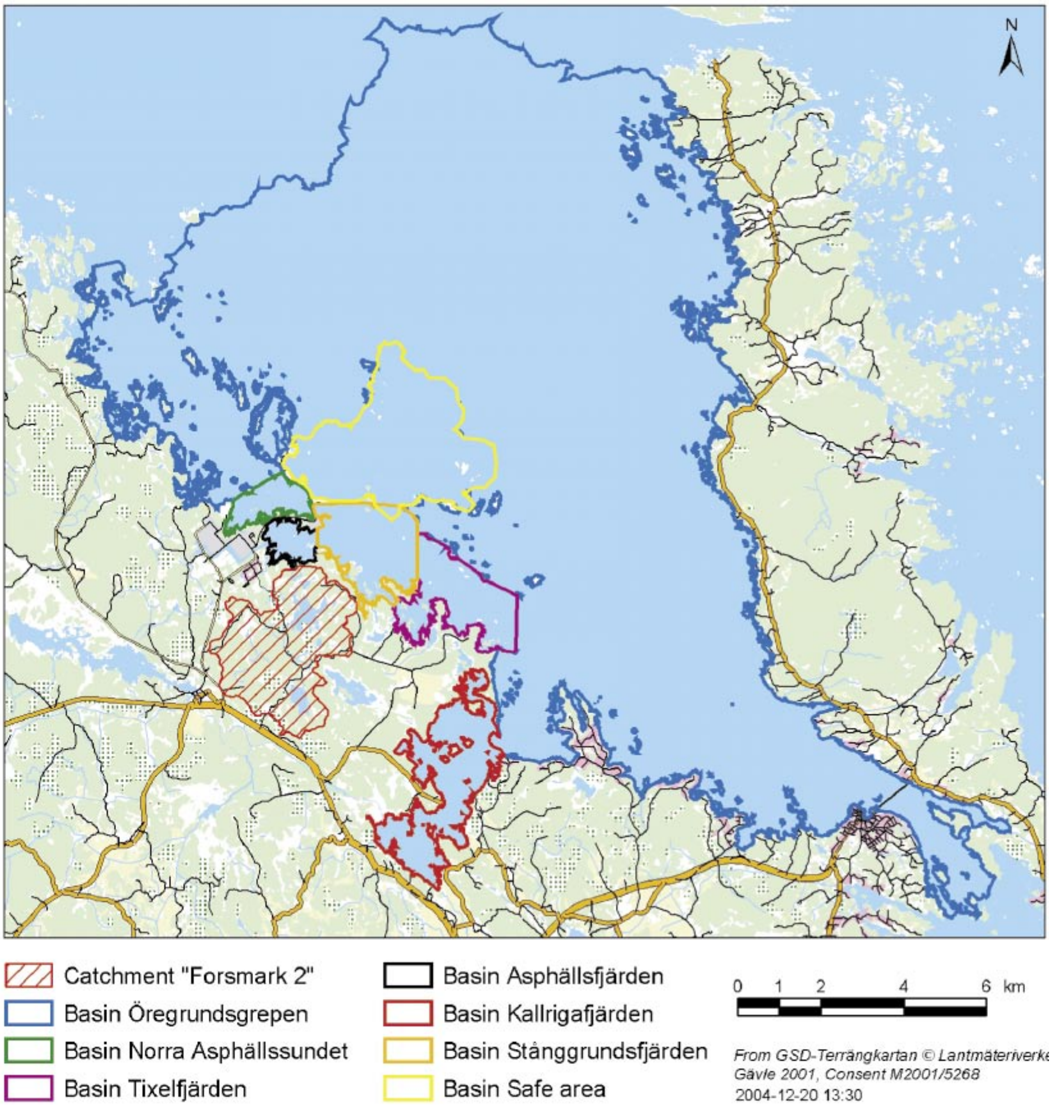
This section presents a description of the marine ecosystems of Forsmark, based on site specific data with emphasis on biological components. The overview section is a brief description of the ecosystems, including abiotic characteristics, followed by presentation of data on producers and consumers in which site-specific data is presented. The basins are all parts of the marine environment that are more or less bathymetrically separated from each other. The basins are treated like separate units, based on the assumption that relevant flow of matter between them will be possible to quantify either with estimations of abiotic carbon flow (runoff and oceanographic flows) or biotic (migration of organisms).

3.9.1 Overview of the ecosystem

The marine system in the Forsmark modelling area is located in Öregrundsgrepen, Southern Bothnian Sea. The marine are in Forsmark has been divided into seven basins (Figure 3-112). Two of these basins, Basin SAFE-area and Basin Stånggrundsfjärden are described below and ecosystem models for these basins are presented in Section 4.3.

The marine system in the Forsmark area is a relatively productive coastal area in a region of otherwise fairly low primary production. This is due to up-welling along the mainland /Eriksson et al. 1977/. The surface water has a nutrient concentration ranging from 330 to790 µg/l tot-N and 12 to 25 µg/l tot-P /Nilsson et al. 2003/. The seabed is dominated with erosion and transport bottoms with heterogeneous and mobile sediment consisting mainly of sand and gravel with varying fractions of glacial clay /Mo and Smith, 1988/. The seabed close to the mainland has some strains of rocky bottoms, which partly is covered with coarse moraine /Sigurdsson, 1987/.

The water retention time of the water in the Basin Öregrundsgrepen is estimated to an annual average retention time (ATR) of approximately 4.4 days (cf Section 3.5), whereas the retention times for the smaller separate basins varies from between 0.2 and 1.6 days. Basin SAFE-are and Basin Stånggrundsfjärden have an ATR of 0.6 and 0.3 respectively. Annual averages of pH, salinity, oxygen concentration and light penetration depth for the area are 7.9, 3.9 ‰, 11.6 mg/l and 2.4 m, respectively /Nilsson et al. 2003/.



From GSD-Terrängkartan © Lantmäteriverke
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Figure 3-112. *The Forsmark model area including its seven basins with Basin SAFE-area and Stånggrundsfjärden indicated. In the map the location of the drainage area for catchment Bolundsfjärden (Forsmark 2) is indicated, which other sections of this report are concerned with.*

Several studies on flora and fauna have been carried out in the Öregrundsgrepen area of which many were conducted in the defined modelling area. In the photic zone the seabed is to a large extent covered with a layer of micro algae, mainly diatoms, and a relatively high species diversity and large amount of macrophytes (both macroalgae and vascular plants) /Kautsky et al. 1999; Snoeijs, 1985, 1986/. The macrophyte species that contribute most to the macrophyte biomass in the benthic community in Forsmark are the red algae *Polysiphonia nigrescens*, the brown algae *Fucus vesiculosus* and *Sphacelaria arctica* and the vascular plant *Potamogeton filiformis* /Kautsky et al. 1999/. Herbivorous gastropods together with both herbivore and omnivore crustaceans dominate the grazing macrofauna and the most common filter feeder in the area has been found to be the bivalve *Cardium spp*. /Kautsky et al. 1999/. The major meiofauna taxa present in the area are nematodes, acarins, cladocerans, copepods and ostracods /Snoeijs and Mo, 1987/. The seabed below the photic zone have a lower species diversity which may be due to the heterogeneous and mobile sediment /Mo and Smith, 1988/. Among the macrobenthos found in this community, the detritus- and filter feeding bivalve *Macoma baltica* strongly dominates the biomass /Kautsky et al. 1999/. The phytoplankton are strongly dominated by diatoms and dinoflagellates during springtime, while the plankton community in summer and autumn mainly consists of blue-green algae and small flagellates /Lindahl and Wallström, 1980/. The zooplankton community has low species diversity. Two copepod species constitute about 80% of the zooplankton biovolume while the rest is composed of cladocerans, rotatorians, ciliates and different larvae stages from benthic animals /Eriksson et al. 1977; Persson et al. 1993/. The most common fish species in Öregrundsgrepen are herring (*Clupea harengus*), roach (*Rutilus rutilus*) and perch (*Perca fluviatilis*) /Neuman, 1982/. (The method used in the fish survey was not sensible enough to catch small sized species such as sticklebacks (*Gasterosteidae*) and gobies (*Gobiidae*), which possibly have affected the results of the species distribution.)

3.9.2 Habitats

The marine basins in the Forsmark area were classified into three different habitats; the phytobenthic habitat, the soft bottom habitat and the pelagial.

The phytobenthic habitat was defined as the benthic community in the photic zone. In this habitat the functional groups macrophytes, microphytes, grazing macrofauna, filter feeders, benthic meiofauna and microfauna were assumed to be present. This habitat may be very heterogeneous depending mainly on the substrate and the extent of wave exposure. The major part of the data used initially to describe organisms in this habitat were collected from diving transects that were scattered in Basin SAFE-area. The averages from the diving transects were used, which probably gives a good approximation of the biota in the area.

Soft bottom habitat was defined as the benthic community below the photic zone. In this habitat benthic macrofauna, meiofauna and microfauna were assumed to be the major functional groups.

The pelagic habitat includes the open water, where a pelagic food-web based on plankton organisms (bacterioplankton, phytoplankton and zooplankton) is developed. To this habitat the fish have also been assumed to belong although they consume food from all three habitats.

3.9.3 Functional groups

The marine biota present in the area sharing ecological functions and residing the same habitat were all combined to into the functional groups: producers (which in turn were divided into phytoplankton, microphytes and macrophytes), and consumers (divided into benthic herbivores, filter feeders, benthic meiofauna and microfauna macrofauna, bacterioplankton, zooplankton, fish, seal, birds and humans) (Table 3-65).

Table 3-65. Description of the functional groups in the marine system of Forsmark.

Functional group	Definition/Description
Phytoplankton	Pelagic micro algae (> 3µm)
Bacterioplankton	Pelagic bacteria (< 3 µm)
Zooplankton	Planktonic animals (other than bacteria)
Microphytes	Benthic micro algae
Macrophytes	Benthic macroalgae, phanerogams, bryophytes
Benthic herbivores	Grazing macrofauna (> 500µm)
Fish	Fish (both demersal and planktonic)
Filter feeders	Filter feeding macrofauna (> 500 µm)
Benthic macrofauna	Soft bottom living macrofauna (> 500 µm)
Benthic meiofauna	Meiofauna (3–500 µm) in/on the seabed
Benthic microfauna	Benthic bacteria (< 3 µm)
Seal	Grey seal
Bird	Bird
Human	Human

Producers

Input data and methodology

The site-specific input data used in the descriptive modelling of the primary producers at the site is compiled in Table 3-66. The dominating groups of primary producers present in the area are phytoplankton in the pelagic habitat and macrophytes and microphytes in the benthic habitat.

The light penetration depth was of major importance to enable estimates of the total biomass of the various groups of primary producers. This was because the borders between different habitats where the organisms reside, in each basin were defined after the light penetration depths, i.e. by dividing each basin into a photic and an aphotic zone assuming that the photic zone reaches twice the light penetration depth.

Phytoplankton has been studied in the area twice, in a recent study performed by /Huononen and Borgiel, 2005/ in Asphällsfjärden, where the biomass were determined at five occasions during 2003 and 2004, and in an earlier study by /Lindahl and Wallström, 1980/ in Öregrundsgrepen, where both biomass and in primary production were measured during 1977 and 1978. These estimates were integrations of the phytoplankton biomass in 0–20 m water pillars, which were normalized to square metres. In this study the estiamtes per square metre were normalised to volumes (cubic metres) by assuming that phytoplankton mainly were present in the photic zone, i.e. in the uppermost ten metres. The phytoplankton productivity was estimated with the ^{14}C-method /Steemann-Nielsen, 1952/ and presented as net primary production and therefore was their respiration omitted in the further calculations in this study. In the descriptive model presented in this report the biomass from the most recent study /Huononen and Borgiel, 2005/ were used while the primary production was estimated from the P/B-relationship found by /Lindahl and Wallström, 1980/ and the biomass by /Huononen and Borgiel, 2005/.

The temporal variation of phytoplankton biomass has been extrapolated from the five measurements performed during 2003 and 2004 /Huononen and Borgiel, 2005/. The results are shown in Figure 3-113.

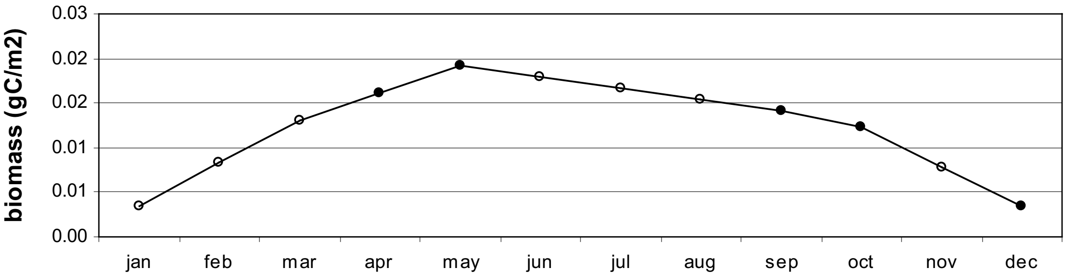

***Figure 3-113.** Biomass of phytoplankton in Forslingens grund (in Asphällsfjärden) during a year. Extrapolated from five measurements (filled circles) performed September 2003 to May 2004.*

Macrophytes comprise both macroalgae and vascular plants and the biomass estimates for this group originate from diving surveys conducted during 1999 /Kautsky et al. 1999/. These data were sampled for establishing a carbon flow model of the marine area above the SFR-1 repository (SAFE-project) /e.g. Kumblad, 1999; Kumblad, 2001/. The original data were reported as biomass per square metre depth interval (0–1 m, 1–2 m, 2–4 m, 4–6 m, 6–10 m and 10–15 m) at species level, which then were integrated by calculating the biomass of each species per depth interval, sum the depth interval and divide with the surface of the photic zone to normalize the biomass per square metre (m^2). Those values where then used in the budget calculations for the basins in this study. The model area of the SAFE-project is located within the present model area (Basin SAFE-area). The results from the estimates of macrophyte species distribution and cover degree /Kautsky et al. 1999/ indicated the area being fairly rich. An eroded moraine (boulders, stones, gravel and sand) dominated the substrate with occasional rock outcrops. At several sites, on the hard, more stable substrates (boulders, rock) a luxuriant growth of the bladder wrack (*Fucus vesiculosus*) could be seen. Also, the moss *Fontinalis dalecarlica* was not unusual. This moss is frequently observed in the Gulf of Bothnia but does not occur in the Baltic proper /Kautsky et al. 1999/. Compiled data on macrophytes and consumers (benthic macro fauna) are presented in Figure 3-114.

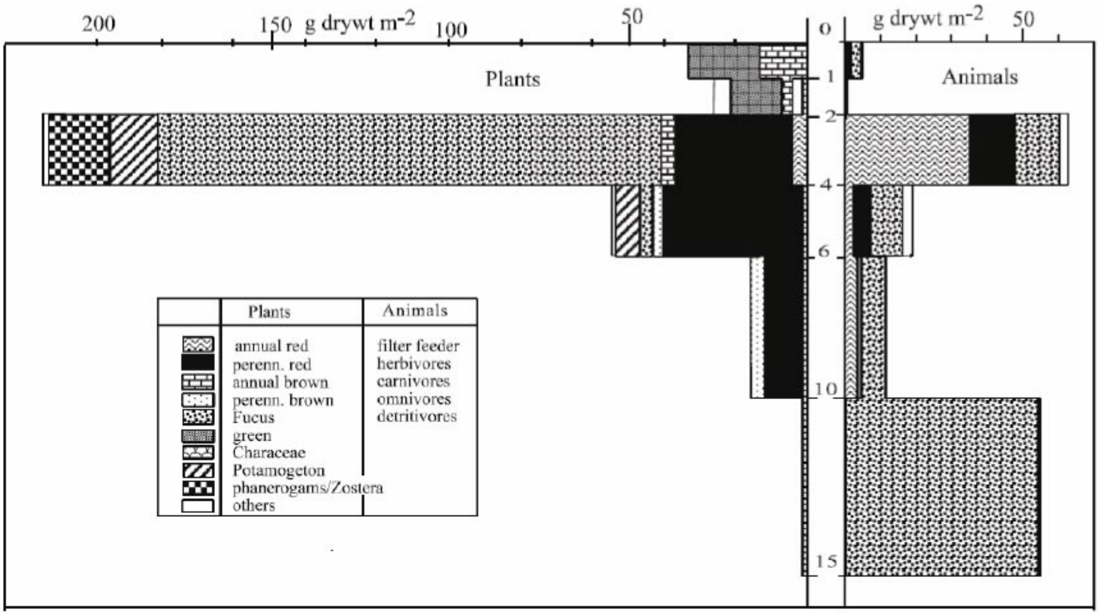

***Figure 3-114.** Depth distribution of plant and animal biomass in the Basin SAFE-area, Öregrundsgrepen (Sweden). From Kautsky et al. 1999.*

The microphyte biomass data originate from studies performed in and around the biotest basin off Forsmark nuclear power plant during 1985 and 1986 /Snoeijs, 1985, 1986/. In the budget calculations it was assumed that the microphytobenthos were present in the benthic habitat in the whole photic zone.

Table 3-66. Site-specific data sources of primary producers in the marine system of Forsmark.

Parameter	Basin	Value	Year	Reference
Light penetration depth	Kallriga norra	1.41 m	2002–2004	SICADA
	Kallriga södra	1.19 m	2002–2004	SICADA
	Asphällsfjärden	3.78 m	2002–2004	SICADA
	Trixelfjärden	3.35 m	2002–2004	SICADA
Phytoplankton				Huononen and Borgiel, 2005//
– Biomass	Asphällsfjärden	0.012 gC×m^{-3}	2003–2004	P/B-ratio from /Lindahl and
– Production	Öregrundsgrepen	10.06 gC×m^{-3}yr^{-1}	1977–1978	Wallström, 1980/
Macrophytes				
– Biomass annual	Basin SAFE-area	8.27 gC×m^{-2}	1999	/Kautsky et al. 1999/
– Biomass perennial	Basin SAFE-area	9.26 gC×m^{-2}	1999	/Kautsky et al. 1999/
Microphytobenthos				
– Biomass	Öregrundsgrepen	5.32 gC×m^{-2}	1985–1986	/Snoeijs, 1985, 1986/

Consumers

Input data and methodology

The site-specific input data used in the descriptive modeling of the consumers at the site is compiled in Table 3-67.

The major groups of consumers present in the area have been identified to be bacterioplankton, zooplankton, fish (zooplankton feeding, benthic feeding and carnivorous), benthic herbivores, benthic filter feeders, benthic detrivores (including meiofauna), benthic carnivores, benthic bacteria, birds (fish feeding and benthic feeding), seals and humans.

The light penetration depth was of major importance also for the consumers to estimate the total biomass of the various organism groups. This was because the borders between different habitats where the organisms reside, in each basin were defined after the light penetration depths, i.e. by dividing each basin into a photic and an aphotic zone assuming that the photic zone reaches twice the light penetration depth.

The results from the estimates of benthic macro fauna distribution from /Kautsky et al. 1999/ show that the blue mussel (*Mytilus edulis*) was to a large extent missing, although suitable substrate was present. In the Bothnian Sea the marine mussel *M. edulis* extends up to the Northern Quark, but usually only scattered, few individuals are found at each site along the whole coast. The blue mussel never has the same mass-occurrence as can be observed in the Stockholm archipelago and further south in the Baltic proper. Thus, the ecosystem of the SAFE-basin has a function somewhat different from the Baltic proper as the filter feeders lack to a large extent. /Kautsky et al. 1999/ Compiled data on benthic macro fauna are presented in Figure 3-114.

Bacterioplankton, benthic meiofauna and microfauna and seals has not been studied in the area. Generic data for these groups were used (see further Section 4.3).

Zooplankton biomass were studied both in a survey by /Eriksson et al. 1977/ and more recently by /Huonen and Borgiel, 2005/. In this report, the SKB data were used which were sampled at five occasions during 2003 and 2004.

Fish in the Forsmark area were sampled by The National Board of Fisheries (*Sw: Fiskeriverket*) /e.g. Neuman, 1982/. Unfortunately, the result in these surveys were presented as catches per unit effort (e.g. individuals per gill net), which is very difficult to convert to a biomass estimate per unit surface or volume. Also these types of surveys mainly samples medium to large size pelagic fish and can not estimate the abundance of small sized fish, benthic fish or fish larvae. There is an ongoing survey on fish biomass in the sea in the Forsmark area which probably can be used in a future version of this report. In this study, fish data from another area were used instead (see further Section 4.3).

As for the macrophytes the biomass estimates for grazing macrofauna, filter feeders and other macrofauna originate from diving surveys conducted during 1999 /Kautsky et al. 1999/. These data were also reported as biomass per square metre depth interval (0–1 m, 1–2 m, 2–4 m, 4–6 m, 6–10 m and 10–15 m) at species level, which then were integrated by calculating the biomass of each species per depth interval, sum the depth interval and divide with the surface of the photic zone to normalize the biomass per square metre (m^2). The resulting biomass values where used in the budget calculations for the basins in this study. The model area of the SAFE-project is located within the present model area (Basin SAFE-area).

There has been an extensive bird investigation in the terrestrial part of the modeling area /Green, 2003, 2004/ describing e.g. the amount of bird species and territories, abundance of terrestrial birds along transects and in certain areas. However, since the abundance of the waterfowl was not estimated it was difficult to use the presented data.

No site specific data on humans or seal is available and has thus not been included in this report.

Table 3-67. Site-specific data sources for consumers in the marine system of Forsmark.

Parameter	Basin	Data	Year	Reference
Light penetration depth	Kallriga norra	1.41 m	2002–2004	SICADA;
	Kallriga södra	1.19 m	2002–2004	/Nilsson et al. 2003/
	Asphällsfjärden	3.78 m	2002–2004	
	Trixelfjärden	3.35 m	2002–2004	
Bacterioplankton	–	–	–	–
Zooplankton biomass	Asphällsfjärden	0.0035 $gC \times m^{-3}$	2003–2004	/Huononen and Borgiel 2005/
Grazing macrofauna				
– Herbivores biomass	Basin SAFE-area	0.48 $gC \times m^{-2}$	1999	/Kautsky et al. 1999/
– Omnivores biomass	Basin SAFE-area	0.29 $gC \times m^{-2}$	1999	/Kautsky et al. 1999/
Filter feeder biomass	Basin SAFE-area	0.15 $gC \times m^{-2}$	1999	/Kautsky et al. 1999/
Other macrofauna				
– Detrivores	Basin SAFE-area	8.77 $gC \times m^{-2}$	1999	/Kautsky et al. 1999/
– Carnivores	Basin SAFE-area	0.13 $gC \times m^{-2}$	1999	/Kautsky et al 1999/
Benthic meiofauna	–	–	–	–
Benthic microfauna	–	–	–	–
Fish				
– Herring	Öregrundsgrepen	78%*	1982	/Neuman, 1982/
– Roach	Öregrundsgrepen	10%*	1982	/Neuman, 1982/
– Perch	Öregrundsgrepen	4.7%*	1982	/Neuman, 1982/
– Other	Öregrundsgrepen	7.3%*	1982	/Neuman, 1982/
Seal	–	–	–	–
Bird	–	–	–	–

* Distribution (%) of species of total catch in gill nets.

3.9.4 Confidence and uncertainties concerning the initial data

The confidence and uncertainties of the site-specific initial data used for the various functional groups have been evaluated in Table 3-68 and the spatial variations in biomass and coverage is discussed below.

Table 3-68. Confidence and uncertainties concerning the site-specific initial data.

Functional group	Confidence/Uncertainty
Primary producers	
Phytoplankton	The quality of the data is good but the replicates are very few and thus are the uncertainties fairly high.
Microphytes	The quality of the data is high but as only a few data points have been used in this study (because the other data point were located in the biotest basin and were therefore considered to be unrepresentative) and thus area the uncertainties fairly high. No information on the annual variation.
Macrophytes	The quality of the data is good and the amount of replicates is sufficient. However, the macrophytes were only sampled once during a year and as a consequence they do not present any information on the annual variations. (More information below.)
Consumers	
Bacterioplankton	–
Zooplankton	The quality of the data is good but the replicates are very few and thus are the uncertainties fairly high.
Benthic herbivores	The quality of the data is good and the amount of replicates is sufficient. However, the grazing macrofauna were only sampled once during a year and as a consequence they do not present any information on the annual variations. (More information below.)
Filter feeders	The quality of the data is good and the amount of replicates is sufficient. However, the filter feeders were only sampled once during a year and as a consequence they do not present any information on the annual variations. (More information below.)
Benthic macrofauna	The quality of the data is good and the amount of replicates is sufficient. However, the benthic macrofauna were only sampled once during a year and as a consequence they do not present any information on the annual variations. (More information below.)
Fish	Quantitative biomass estimates not available.
Benthic meiofauna	–
Benthic microfauna	–
Seal	–
Bird	Quantitative biomass estimates not available.
Humans	Quantitative biomass estimates not available.

Macrophytes and macrofauna

The knowledge of the quantitative distribution of macroscopic (> 1 mm) plants and animals on the seafloor (the phytobenthic communities) above the SFR (in the SAFE-basin) is relatively good. In the investigated area divers have described the sea floor substrate and the dominating plant and animal communities along transect lines. In addition, the divers collected quantitative samples. Five transects were placed in the SAFE-basin and in total, divers collected 54 quantitative samples.

The species biomass was determined by collecting quantitative samples (usually 12 samples per transect). At comparable depths, when excluding the bladder wrack (*Fucus vesiculosus*) and the blue mussel (*M. edulis*) the total depth distribution of plant and animal biomass was similar those of the Gräsö-Singö area (ranging between 30–60 g dry weight m^{-2} of plants and 20–50 g dry weight m^{-2} of animals). However, the total biomass of both the bladder wrack (*Fucus vesiculosus*) and the filter feeding blue mussel (*M. edulis*) was considerable lower in the Forsmark area. This can to some extent be explained by the difference in dominating substrate (mostly rocky) as well as a larger influence from the Baltic proper in the Gräsö-Singö area.

3.10 Human description

3.10.1 Input data and metodology

The human description is based on the results presented in the report Human population and activities in Forsmark /Miliander et al. 2004/. The absolute numbers and calculated numbers per km^2 in the report are for Forsmark parish, since much of the data were available only at the parish level. For the modelling area, Forsmark 2, the numbers have been calculated based on data for higher levels, such as county.

Most of the data were obtained from Statistic Sweden (*Sw: SCB*). Other sources such as The National Board of Fisheries (*Sw: Fiskeriverket*), The County Administrative Board of Uppsala (*Sw: Länsstyrelsen i Uppsala län*) and The Swedish Association for Hunting and Wildlife Management (*Sw: Svenska Jägareförbundet*) have also been used.

Wherever possible, data have been collected for a time series of ten years. By assembling data for time series, mean values could be calculated and trends could be analysed. Data for a time period of ten years has not been available for all variables, so shorter time series occur as well.

The variables in the description are most often shown as an actual value from the latest year for which data were available (normally 2002), a mean value with a standard deviation, a minimum value, a maximum value and a figure per unit area (ex. $kg \times km^{-2}$).

For more detailed information and discussion of the various issues relating data and processing, see /Miliander et al. 2004/.

3.10.2 Human population

In total, 168 people lived in Forsmark parish in 2002. The population density has been low but fairly stable during the last ten years. The density has on average been 1.8 inhabitants per square kilometre. In 2002, the population density in Forsmark parish was 24 times lower than in Uppsala County. Fifty two percent of the inhabitants were over 45 years, compared to 40% in Uppsala County.

The inhabitants live in one- or two- family houses (29.9% of the properties) or in farm houses (28.2%). There are no multi-dwelling houses in the parish. In 2002, there were 65 holiday houses in the parish and they dominate (37.4%). There are in total 1.8 buildings per square kilometre in the parish, compared to 12.7 in Uppsala County. No multi-dwellings or one- or two dwellings have been constructed in the parish since 1993. Three building permits for dwellings were granted two years in a row, 1997 and 1998.

The ill-health (number of days with sickness benefit or early retirement pension per year and person between 16 and 64) has increased remarkably in the parish from 17.4 in 1998 to 70.8 in 2002. The increase is 300%. Meanwhile, ill-health has increased by 30% in Uppsala County. The ill-health in women is higher than the ill-health in men. When calculating the ill-health figure for a small population, such as Forsmark parish, it is important to point out that the individual ill-health has a significant impact on the statistics, due to small population.

The dominant employment sector within the Forsmark parish is electricity-, gas- and water supply, sewage and refuse disposal and it relates to 79% of the employed day-time population (working in the area). Within the employed night-time population (living in the area) on the other hand, only 19.7% is working in that sector. Thus, there is a major ongoing commuting due to Forsmark nuclear power plant. The net commuting is positive in Forsmark parish, meaning the immigration is larger than the emigration. The net commuting is, on the other hand, negative in Uppsala County. Financial intermediation and business activities is the second largest type of business within the day population and the largest within the night population. There were in total 17 work places within the parish in 2002. The majority, nine sites, are within financial intermediation and business activities.

In Forsmark parish, 15.3% of the total population was non-employed, which is more than in Uppsala County. The early retired and unemployed are proportionately more numerous in the parish than in Uppsala County. This is also true of the category “Other”. Students, on the other hand, are proportionately less in the parish. The proportion of non-employed inhabitants is approximately the same in 2001 as in 1997.

3.10.3 Human activities in terms of land use

The land use in Forsmark parish is assumed to be similar to the land use in Forsmark area. The land use within the Forsmark area differs from the average land use in Uppsala County, as there is proportionally more forest, wetlands and water in the Forsmark area and the area of agricultural and developed land is smaller.

Forestry

The forests are heavily influenced by forestry; some 45% of the productive forest within the regional model area is younger than 30 years. The average age is 46 years. About half of the logging products are used for pulp production, and half for timber /Sveaskog, 1999/.

Agriculture

Agricultural activities are scarce in Forsmark parish when compared to Östhammar municipality and Uppsala County. The farm density in Forsmark parish is on average only 0.05 farms$\times$km^{-2}, which is considerably less than in the county (0.43 farms$\times$km^{-2}). There were in total four farms (> 2 ha) in Forsmark parish in 1999.

Only a few percent of the total land area in Forsmark parish is classified as arable land, compared to 22% in the county. Besides, the crop data shows that only a quarter of the land classified as arable (on average 1990–1999) is actually being used for cultivating. In the county 60% is actually being cultivated. The amount of arable land is almost equal to the amount of grazed grassland in Forsmark parish, while the amount of arable land is 6–10 times larger than the grassland in the municipality and county.

The main part of the arable land (89%) is used for fodder production, and only barley is produced in Forsmark parish according to data from 1999. The fertility of the arable land is poor. The standard yield of barley in harvest area 0322, in which the Forsmark parish is located, is only 66% of the average standard yield in Sweden in 2003. The arable land area in Forsmark parish is small but fairly unchanged between 1990 and 1999. It is not very likely that the agricultural land use will increase in the future.The total amount of arable land has generally decreased in Uppsala County between 1990 and 1999, whereas the amount of land classified as grassland has increased significantly in Forsmark parish. The total number of farms has decreased as well, but large farms have increased in number, which means that farms became fewer but larger.

The number of livestock decreases in the parish with only one exception, which are cattle for slaughter. The production of beef per unit area is nevertheless 4.5 times lower than in Uppsala County. There were (in 1999) also livestock's with dairy cows, sheep and chicken in Forsmark parish, but no pigs.

Horticulture, aquaculture, mineral extraction

There is no horticulture or aquaculture in Forsmark parish, and no active leases for mineral extraction.

Water supply

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

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

The number of work places in the parish is very low, only 0.5% of the work places in Östhammar municipality. The water use within the industry sector, excluding the nuclear industry, is therefore estimated to be very low (0.2%). In Sweden, the industry stands for approximately 65% of the water use. The total withdrawal of water in the parish is calculated to 275,700 m^3 per year.

Coastal fishing

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

The catch per unit area is considerably lower in the EU-grid for fisheries off the coast of Uppsala County compared to the southeast of Sweden. The fisheries are most productive in EU-square 47G9, approximately 115 km southeast of the Forsmark area, with a mean catch of 781 $kg \times km^{-2}$ (1995–2002), according to data from The National Board of Fisheries. In EU-square 49G8, which includes Forsmark parish, the catch has on average been 224 $kg \times km^{-2}$. The two dominating species in the off-shore grid outside the coast of Uppsala County are Baltic herring (*Sw: strömming*) and sprat (*Sw: skarpsill*).

Only two commercial receivers of fish are located in Uppsala County, one in Öregrund and one in Östhammar. In 2002, these two received only 8.3% of the weight of fish that the fishermen in Östhammar caught that year. It is also possible that they sell their fish to a commercial receiver outside the county border. The received fish were used for consumption.

Outdoor life

Wildlife hunting

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

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

According to these figures, the harvest of roe deer has on average been 1.9 individuals×km^{-2} in the parish during the period 1997–2001. In 2001, the harvest was 1.0 individuals×km^{-2}. The harvest of common hare (*Sw: fälthare*) has on average been 0.28 individuals per square kilometre in the parish during the period 1997–2001. In 2001, the harvest was 0.10 individuals×km^{-2}. The harvest of alpine hare (*Sw: skogshare*) has on average been 0.13 individuals per square kilometre in the parish during the period 1997–2001. In 2001, the harvest was 0.03 individuals×km^{-2}.

According to the survey based on pellet sampling conducted by /Cederlund et al. 2004/ the population density was estimated to be 1.23 moose×km^{-2}, 9.36 individuals×km^{-2} of roe deer, 0.32 individuals×km^{-2} of European/common hare and 0.23 individuals×km^{-2} of mountain/alpine hare in the Forsmark area in the spring of 2003.

Picking of wild berries and mushrooms

According to /Berggren and Kyläkorpi, 2002/, 23.0 million litres of berries and 15.3 million litres of mushrooms were picked for own-consumption in Sweden in 1997. The main part of the berries (83%) was lingon berries and blue berries. The total area of forest and mires in Sweden gives an average amount of 81 litres×km^{-2} of wild berries and 54 litres×km^{-2} of mushrooms in the forests and mires. The total amount of picked berries has been calculated for Forsmark area, Östhammar municipality and Uppsala County based on the forest area. There are no available data of berry picking from forests area in Forsmark parish, but the picking is assumed to be similar to the amount picked in Forsmark area. The picked amount per unit area is higher in Forsmark area (and Forsmark parish) than in Östhammar municipality and Uppsala County, as the forest area is more dominating in Forsmark area.

Fishing

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

A theoretical value of the annual catch has been calculated based on the data in /Fiskeriverket, 2000/ presuming that the recreational fishers (55% of the population between 16 and 64 years) are sport fishermen that catch 18 kg per year.

Other

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

Table 3-69 A-C. Compilation of data from Forsmark parish – an overview.

A.

Variable group	Results	
Demography		
Population 2002	1.8 per km^2	
mean 93-02	1.8 per km^2	
Age structure 2002	0–15 y	17.9%
	16–24 y	6.0%
	25–44 y	23.8%
	45–64 y	31.5%
	≥ 65 y	20.8%
Properties and buildings		
Type of properties 2002		
farms	0.52 per km^2	
one-or two dwellings	0.55 per km^2	
holiday houses	0.69 per km^2	
multi dwellings	0.00 per km^2	
other	0.08 per km^2	
Building permits		
dwellings 2002	0	
mean 96-02	0.9	
business premises 2002	3	
mean 96-02	0.4	
Completed dwellings 2002	0	
mean 93-02	0	

Employment		
Employed night-time population (20–64 y) 2001	0.75 per km^2	
mean 97-01	0.74 per km^2	
The employed night-time population by type of business[1] (20–64 y)	1	5.6%
	2	9.9%
	3	19.7%
	4	4.2%
	5	7.0%
	6	28.2%
	7	7.0%
	8	9.9%
	9	5.6%
	10	0.0%
	11	0.0%

B.

Variable group	**Results**	
Employment		
Employed day-time population (20–64 y) 2001	9.9 per km^2	
mean 97-01	10.2 per km^2	
The employed day-time population by type of business[1] (20–64 y)	1	0.0%
	2	0.0%
	3	79.0%
	4	1.0%
	5	0.3%
	6	18.4%
	7	0.0%
	8	0.0%
	9	1.2%
	10	0.0%
	11	0.0%
The number of work places 2002	0.18 per km^2	
mean 97-02	0.12 per km^2	
Work places by type of business[1]	1	0.0%
	2	0.0%
	3	0.0%
	4	17.6%
	5	0.0%
	6	52.9%
	7	0.0%
	8	0.0%
	9	17.6%
	10	0.0%
	11	0.0%
Commuting (20–64 y) 2001		
Ingoing	32	
Outgoing	902	
Net commuting	870	
The non-employed population (20–64 y) 2001	0.28 per km^2	
mean 97-01	0.27 per km^2	
% of total population 2001	15.3%	

C.

Variable group	Results
Forestry	
Wood extraction	176 m^3 sk×yr^{-1}×km^{-2}
Agriculture	**kg per km^2**
Barley (1999)	438
Potatoes	47
Hay. Silage. Green Fodder	6,252
Veal/beef	95
Mutton	5
Chicken meat	11
Eggs	18
Milk	5,092
Water supply (estimated)	**m^3**
Water use	
households	11,500
holiday houses	1,200
agriculture	4,300
industry	600
nuclear	257,000
other	1,200
Water withdrawal	
public supply	6,800
private supply	269,000
Water withdrawal	
ground water	7,200
surface water	268,500
Sea water or unknown	
Outdoor life	
Harvested moose 2003	0.53 per km^2
mean value (99-03)	0.53 per km^2
Harvested moose in utilized carcass weight 2003	52 kg per km^2
mean value	51 kg per km^2
Harvested roe deer 2001	1.0 per km^2
mean 97-01	1.9 per km^2
Harvested roe deer in utilized carcass weight 2001	9.0 kg per km^2
mean 97-01	18 kg per km^2
Picking of wild berries[1]	73 litres per km^2
Picking of fungi[1]	49 litres per km^2
Catch by sport fishermen	10.9 kg per km^2

[1] Values for Forsmark area.

3.10.4 Quantitative model – Forsmark 2

The carbon flow from flora and fauna to humans in the subarea Forsmark 2, within the Forsmark area, has been calculated as described below. The result is shown in Table 3-70.

Humans

There are no inhabitants within Forsmark 2 today. As there are no working sites within the area, there is no immigration into the area and no day population. There is, however, three holiday houses within the area /Miliander et al. 2004/. Statistics Sweden uses the assumption that there are in average three persons per holiday house for 60 days per year, when calculating the water use /SCB, 2003/. Thus, the holiday population would consist of approximately 9 persons.

For modelling carbon flows in the biosphere we apply the population density in the main drainage area (54/55) to Forsmark 2. The population density was 0.2 inhabitants×km^{-2} in 2002, which gives us a population of 1.7 (approximately 2) within Forsmark 2.

Agriculture

A theoretical population can be estimated based on a figure given by /LivsmedelsSverige, 2004/, showing that each person needs 3,000 m^2 (0.3 hectare) to be self-sufficient. A good half of that is needed for fodder production. The total area of grazed grassland and arable land in Forsmark 2 is 130,550 m^2 /Boresjö Bronge and Wester, 2003/. An area of that amount could feed 43.5 persons.

There is no agricultural production within Forsmark 2 today. Fictitious values have to be used when modelling. Assuming that Forsmark 2 is inhabited by two persons and the need of land area for self-sufficiency is 3,000 m^2 per person (of which 50% are needed for fodder production), these two persons would need 3,000 m^2 altogether for crop production. The only crop that is produced in Forsmark parish is barley /Miliander et al. 2004/. The crop production in Forsmark 2 is therefore assumed to be barley and the production is based on the standard yield in SKO-area 0322 in 2003 (2,834 kg/ha), in where Forsmark 2 is located.

The carbon content is proposed to be 2% in milk and 45.3% of the dry weight in crop /Lindborg and Kautsky (ed), 2004/. The crop dry weight is 85% of the fresh weight according to /Jordbruksverket, 2003/.

Based on the fact that one cow needs 1.8–3.0 hectares for fodder production and grazing /Arnesson, 2001/, we can estimate that the remaining arable- and grassland in Forsmark 2 (127,000 m^2) can feed 5.3 cows.

One dairy cow produces in average 7,735 kg of milk per year (2002). An average dairy cow is slaughtered at the age of five years after she has given birth to three calves /Miliander et al. 2004/. Five cows, 1–5 years old, can together produce three calves per year. One calf per year would have to be kept for breeding, which leaves two for slaughter. The average weight of slaughtered cattle is 290 kg, of which 165.3 kg (57%) can be utilised and the carcass weight for a calf is 110 kg, of which 62.7 kg (57%) can be utilised /Miliander et al. 2004/. The carbon content in mammals is proposed to be 10% of the fresh weight /Lindborg and Kautsky, 2004/.

The total meat consumption is in average 38 kg per person and year (meat delicatessen not included) and the milk consumption is 194 litres (including cream, cheese and butter) /Miliander et al. 2004/. The export from Forsmark 2 is calculated based on these figures (see Table 3-70)

Hunting

The species that are mainly hunted for consumption are moose, roe deer and hare. The average harvest of moose in Forsmark parish and the average harvest of roe deer and hare in Östhammars jaktvårdskrets that are demonstrated in /Miliander et al. 2004/ are applied to Forsmark 2. The carcass weights are calculated according to /Miliander et al. 2004/. The carbon content in mammals is proposed to be 10% of the fresh weight /Lindborg and Kautsky (ed), 2004/.

The total consumption of game meat is in average 2 kg per person and year. The hunters eat of course larger amounts. If the inhabitants in Forsmark 2, in spite of that fact, are assumed to eat 2 kg moose per person and year, there will be a considerable export of game meat from Forsmark 2. The total amount of the harvested hares, roe deer, red deer and birds (carcass weights) are assumed to be exported, as the inhabitants meat consumption is covered through beef meat and some moose meat.

The birds that are hunted for consumption are demonstrated in Table 3-70. The figures have been collected from Östhammars jaktvårdskrets. The live weights for a few species have been applied to the other species. According to /Jägarnas Riksförbund, 2004, website/ the carcass weight of a Mallard (*Sw: Gräsand*) is approximately 67% of the fresh weight. The biomass data are based on that figure.

Fishing

A theoretical value of the annual recreational catch of fish can be calculated based on the data in /Fiskeriverket, 2000/ presuming that the recreational fishers (55% of the population between 16 and 64 years) are sport fishermen that catch 18 kg per year. If there are two people within Forsmark 2, a theoretical caught would be approximately 18 kg. 1 kg carbon is equal to 30 kg fish biomass, i.e. 3.3% carbon, according to /Lindborg and Kautsky, 2004/. The catch within EU-square 49G8, in which Forsmark 2 is situated, is also presented in Table 3-70.

Picking of berries and mushrooms

An average amount of 81 litres of wild berries per square kilometre forests and mires, are picked for own-consumption in Sweden /Miliander et al. 2004/. The land area of forest and other (including mire) is 7,696,937 m^2 in Forsmark 2. The weight of 1 litre berries is assumed to be equal to 500 gram. The total available amount of wild berries can be calculated based on the fact that 5–7% of the available amount was picked in 1977, which was 75.3 millions litres /Berggren and Kyläkorpi, 2002/. That gives a total amount of 1,255 millions litres. The total area of forest and mires in Sweden is 284,000 km^2 /SCB, 1998/. The total available amount per unit area is therefore 4,419 litres×km^{-2}.

An average amount of 54 litres of mushrooms per square kilometre forests and mires, are picked for own-consumption in Sweden /Miliander et al. 2004/. The land area of forest and other (including mire) is 7,696,937 m^2 in Forsmark 2. The weight of 1 litre berries is assumed to be equal to 200 gram. The total available amount of fungus that can be consumed is 40kg×ha^{-1} according to /Berggren and Kyläkorpi, 2002/.

The carbon content is proposed to be 1.2% in fresh fungi and 10% in fresh berries /Lindborg and Kautsky (ed.), 2004/.

Table 3-70. The carbon flow to humans from the flora and fauna in Forsmark 2.

Species		Amount		Biomass						Export
		Number per km^2 (individuals or litre)	Total number in Forsmark 2	Kg/ind (utilized carcass weight) or kg/litre	Biomass g/m^2/y (utilized carcass weight for meat)	Biomass C gC/m^2/y utilized carcass weight	Biomass C Tot Forsmark 2 gC/y utilized carcass weight	Biomass C living weight mgC/m^2/y	Biomass C Tot in Forsmark 2 or EU-square 49G8 living weight gC/y	Export C Tot utilized carcass weight from Forsmark 2 gC/y
Humans[1]	Humans	0.2	2							
Agriculture[2]	Cropproduction-barley							109,123	327,370	0
	Milkproduction				244			4,872	618,800	611,040
	Meatproduction-calves+cow			96.9	2.3	0.23	29,070	520	66,068	21,470
Hunting[4]	moose	0.53	4.6	96	0.056	0.0056	44,141	13	100,320	43,741
	roe deer	1.9	16	9.4	0.020	0.0020	15,450	4.5	35,113	15,450
	European (common) hare	0.28	2.4	2.2	0.00068	0.000068	534	0.16	1,214	534
	Alpine (mountaine) hare	0.13	1.13	1.8	0.00025	0.000025	198	0.058	451	198
	Birds				0.0013	0.00013	1,012	0.18	1,446	1,012
	Sum intake of meat						**90,405**		**204,612**	
Fishing[3]	EU-square 49G8				0.22			7.4	10,452,288	
Recreational fishing[5] (kg)			18						594	0
Picking of fungus[6] (litre)		54	416	0.2	0.011			0.13	998	?
Picking of berries[6] (litre)		81	623	0.5	0.041			4.1	31,173	?
Sum berries and mushrooms									**32,170**	
Available amount of consumable fungus (litre)				0.2	4.0			48	369,453	?
Available amount of berries (litre)		4,419	34,013	0.5	2.2			221	1,700,638	?
Sum berries and mushrooms (available)									**2 ,070,091**	
	Sum intake of vegetation								**359,540**	
	Max theoretical intake of vegetation (available)								**2,397,461**	

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[1] The density figure for the main drainage area (54/55) has been used in these calculations.

[2] The biomass per unit area is expressed as gram per estimated arable land respectively grazing land.

[3] The commersial fishing refers to EU-square 49G8 in which Forsmark 2 is situated. The biomass per unit area is expressed as gram fresh weight per water area.

[4] The figures for Forsmark parish and Östhammars jaktvårdskrets has been applied on Forsmark 2.

[5] A theoretical value based on a fictitious population.

[6] The total amount in Forsmark 2 is calculated based on the landarea of forest and other (including mire).

3.10.5 Confidence and uncertainties

Most of the data were obtained from Statistics Sweden. When only a single object is found within a geographic area, Statistics Sweden adjusts this single object to a "false" zero for reasons of secrecy. If two objects are found, the count is adjusted to three /SCB, 2003/. This can result in incoherence between the sum of values for different categories and the total number (as an example the total number of inhabitants and the sum of inhabitants per age class). As Forsmark parish is a very sparsely populated area this is a potentially significant source of error. Also in sparsely populated areas the data becomes more statistically unreliable, irrespective of this deliberate reporting bias.

Furthermore, there are some uncertainties concerning the data from The National Board of Fisheries. The catch statistics within the offshore grid (EU-grid) only comprise the catch from the logbook-keeping vessels, as they report the tackle position. The catch is registered in the square where the tackle is placed, but that does not necessarily mean that the fish has been caught in that particular square. Fishing boats may trawl a long distance and therefore catch the main part of the fish in a neighbouring square. The catch data at each EU-square varies therefore considerably between years.

4 Ecosystem models

4.1 The terrestrial ecosystem

The ecosystem concept integrates various fields of abiotic and biotic parameters with the aim of describing the organisms, the physical environment and the interactions between these in a given area. The ecosystem approach is here used with the purpose of describing accumulation and flow of matter in a temporal and a spatial context. A budget of organic matter is described by estimating the different pools of matter and the fluxes between these pools. The foundation in such a ground-based estimate of stocks makes this method close to direct, but is limited by the accuracy with which the stocks, the stock change, and the decomposition rates are known. Another approach is to use a comprehensive ecosystem model to explore balances between energy, water and matter. This approach may simulate all the pools and fluxes in the ecosystem or it may also use site-specific input data setting starting conditions. This approach requires running the model to equilibrium and adapting parameters accordingly. Using this method it will be possible to estimate factors that are difficult to measure under field conditions. In brief this chapter is devoted to:

1. the building of a conceptual model describing the terrestrial ecosystem,
2. combining estimates of the different carbon pools and fluxes in the conceptual model for a number of habitats,
3. the construction of a carbon budget for a discharge area,
4. presentation of a comprehensive numerical ecosystem model, the COUP model, used to estimate different parameters.

4.1.1 A definition of the terrestrial ecosystem

The terrestrial ecosystem is defined as land above the sea that is not part of a lake. The terrestrial ecosystem extends one metre below the surface (the upper regolith), which is the part of the regolith layer that is most affected by climate, hydrology, vegetation and soil fauna etc (see 3.3). The terrestrial system also includes wetlands, such as wetland forests and mires.

4.1.2 The conceptual model of the terrestrial ecosystem

The conceptual model of carbon pools and net fluxes in the terrestrial ecosystem is put together using information from mainly three chapters in this report; biota, soil and hydrology (Figure 4-1). Information is also used from Section 3.10 to estimate fluxes to humans from biota. Some pools have been joined and some fluxes have been left out due to their small impact on the system as a whole e.g. dissolved organic carbon (DOC) washed out from the vegetation during rainfall. The premises behind these simplifications have been elaborated within the chapter covering the specific field. Below follows a description of the principal functioning of pools and fluxes within the conceptual model (Figure 4-1).

Biota and functional groups

The biota is divided into three main groups according to their ecosystem functioning so-called functional groups.

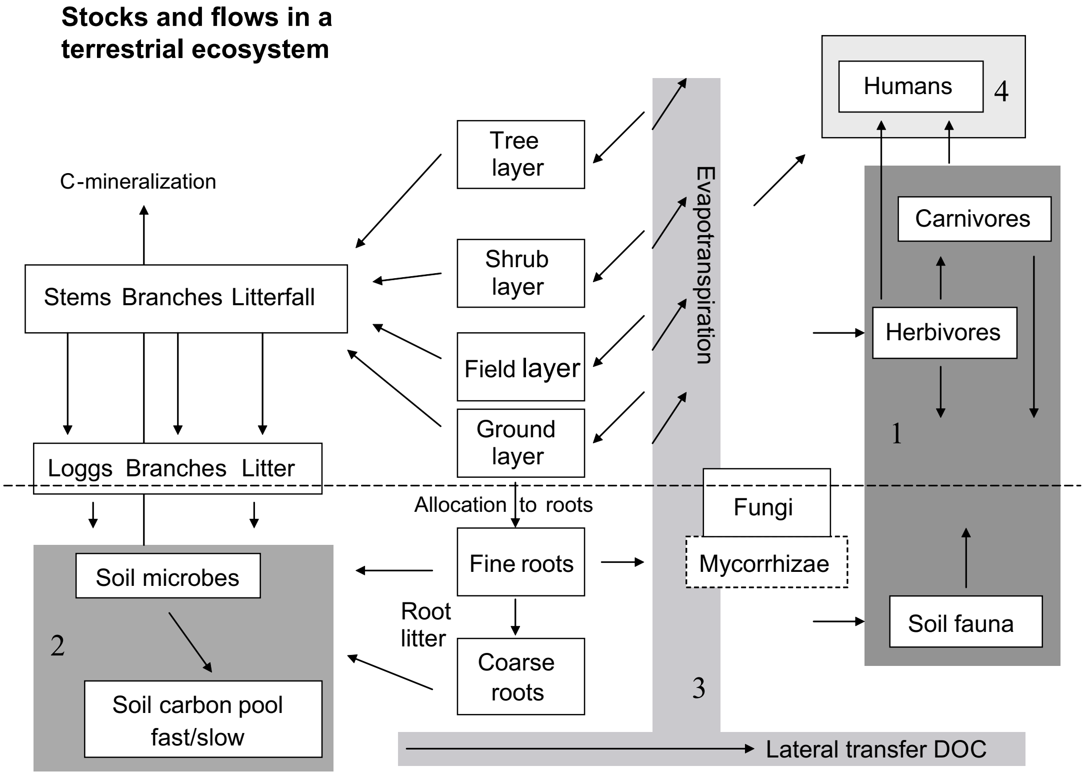

Figure 4-1. *The conceptual terrestrial ecosystem model. The boxes/fluxes that are not a member of the boxes 1–4 are treated within the section describing terrestrial producers. Boxes indicate carbon pools while arrows indicate fluxes of carbon. Respiratory fluxes have been omitted in the figure. Arrows within subsystem 3 indicate water flow.*

Producers

The vegetation is the main producer binding carbon dioxide during the photosynthesis. This group is further divided into the functional layers, tree, shrub, field and ground layer. These are further divided, if possible, into woody and green parts above ground, and coarse and fine roots below ground. Fungi are also treated within this group although they function as consumers and decomposers. The main reason for this is the tight linkage with plants via mycorrhizal fungi. Producers are presented more exhaustively in Section 3.7.1.

The dead organic matter pool has an important function for biodiversity in the landscapes today. This pool is quantified and we also have figures describing the flux of dead matter (except for logs) but we have so far no data describing the actual turnover of dead organic material.

Consumers

Although terrestrial animals consume a relatively small proportion of net primary production (NPP), they may strongly affect energy flow and nutrient cycling. Moreover, the flow of carbon through individuals may be considerable, making potential accumulation of substances similar to carbon large. Soil microbes are left out of the following calculations. This is because of the lack of site specific data and the fact that the total carbon content in the soil includes the carbon from the microbial biomass. Consumers are presented more exhaustively in Section 3.7.2.

Decomposers

This is one of the most important functional groups because of the importance of the carbon mineralization process in the carbon cycle. There is no data from the site describing this group or the process of decomposition and is therefore left out in the quantitative descriptive model described below.

Soil

The soil is an important factor setting the abiotic conditions both in regard of nutrients but also for important hydrological parameters, such as hydraulic conductivity and field capacity. Most of the organic carbon in the ecosystem is entering this pool where it is decomposed leaving the system as carbon dioxide. In most terrestrial ecosystems is the soil carbon pool the largest carbon pool /e.g. Chapin et al. 2002/. There are two more or less easily identified layers; the humus layer that consists of more or less decomposed organic matter; and the mineral soil. A measure of the carbon content in the humus layer or the thickness of the humus layer gives a good indication of how fast the decomposition goes. High carbon contents in the mineral soil layer are often an indication of well-drained nutrient rich soils. These soil types often have a less obvious border between humus and mineral soil layers. Partly because of the bioturbation that may be significant. Bioturbation is the movement of matter in the soil caused by soil fauna e.g. earthworms. Typically goes bioturbation deep in well drained and well buffered soils making the horizon between humus layer and mineral soil layer difficult or impossible to identify. Most of the carbon mineralization is occurring close to the surface while some is transported further down in the soil, either by bioturbation or by water movement. This carbon is often referred to as the slow decomposing carbon pool and constitutes of humins and humic acids /Schlesinger, 1997/, see also below.

Peat is the most extreme soil type where little of the carbon has been mineralised due to the anaerobic environment induced by the near surface water table. Peat forming wetlands are carbon sinks where a thick layer might be accumulated over time. Data of the accumulation rate in peat, using some sort of dating technique, gives information about decomposition if the carbon input to soil is known.

Hydrology

Water movements control transport of matter in the plant, on the ground and in the soil. There are three main flows of water (see 3.4); 1) the downward flow (infiltration and percolation), 2) the upward flow (evapotranspiration), and 3) the lateral flow (surface runoff).

The largest water flow (1) results in leaching of organic matter and a transport of humic acids downward in the soil profile. This transport consists mainly of silicon, aluminum and iron ions that are tied up as hydroxides and oxides in lower soil horizons. Dissolved organic carbon (DOC) is also transported downwards but the majority is decomposed within a short time period /e.g. Cleveland et al. 2004/. Some of the DOC may travel down where non-humic hydrophilic substances, that are considered more easily biodegradable, are dominating the soil organic matter (SOM) while humic substances are tied up in soil sorption processes /Neff and Ashner, 2001/.

The upward transport (2) of water is driven by a combination of evaporation from the leaf/needle surface and transpiration from the vegetation. This is a passive process linking the water around roots with the water in the plants and the water in the atmosphere /Larcher, 1995/. This transport is of importance for the upward transport of substances in the soil due to hydralic lift /Caldwell et al. 1998/ and to the actual plant uptake of substances dissolved in water, but is of minor importance for transport of DOC.

The lateral flow of water (3) is large enough to cause transport of substances, mainly DOC but also particulate organic carbon (Canham et al. 2004; unpubl data from Forsmark), from terrestrial to limnic and marine ecosystems. This water originates from precipitation that infiltrates the surface and reaches the satured zone (see Section 3.4) and further transported into streams and lakes. However, the unsatured overland flow is assumed to be negligible in the quantitative hydrological modelling. Moreover, is the transport between terrestrial ecosystems, not classified as wetlands, regarded as of minor importance compared to the actual carbon fluxes within an ecosystem. However, the transport to and from wetlands may be of significance for accumulation of allochtonous matter.

4.1.3 Ecosystem properties

There are a number of different emergent properties at the ecosystem scale. Some of these are of particular interest when aiming at understanding the accumulation and flow of matter in a patchily distributed landscape. Moreover, there is also a temporal aspect of the different pools and fluxes that in some cases may be insignificant but in some cases crucial to understand.

Production and accumulation

Net primary production

Net primary production (NPP) is here the sum of all materials that have been produced and are retained by live plants at the end of the interval and the amount of organic matter that was both produced and lost by the plants during the same interval /Clark et al. 2001/. Some of the input data to the model is in the form of net annual biomass increment (i.e. the tree layer, 3.7.1) and a number of fluxes, such as litter fall, other fall (small branches), root litter and input to mycelia have to be added to get an estimate of NPP.

Net ecosystem production

Net ecosystem production (NEP) is the net annual carbon accumulation in the ecosystem by plants (B_{plant}), animals (B_{animal}) and the soil (Soil Organic Matter) plus or minus lateral transport among ecosystems.

$$NEP = \frac{(\Delta B_{plant} + \Delta B_{animal} + \Delta SOM)}{\Delta t} \pm F_{lateral} \qquad \text{(Equation 4-1)}$$

ΔB_{plant} is the net gain of biomass in plants and is described by

$$\frac{\Delta B_{plant}}{\Delta t} = NPP - (F_{pl-soil} + F_{herbiv} + F_{emiss} + F_{pl-fire} + F_{harv})$$

ΔB_{animal} is the net gain of biomass in animals and is described by

$$\frac{\Delta B_{animal}}{\Delta t} = F_{herbiv} + F_{microb-anim} - (R_{anim} + F_{anim-soil})$$

Net heterotrophic production is equal to plant biomass eaten (F_{herbiv}), the soil animals eating microbial biomass ($F_{microb-anim}$) minus losses to animal respiration and fluxes from animals to the soil due to excretion and mortality ($F_{anim-soil}$). Transfers of carbon within the animal box are often subsumed in the overall carbon budget equations /Chapin et al. 2002/.

The second largest avenue of carbon loss from plants, after respiration, is the carbon flux to the soil $F_{pl-soil}$ through litter fall, secretion of soluble organic compounds by roots into the soil, and carbon fluxes to microbes that are symbiotically associated with roots e.g. nitrogen fixers and mycorrhizae /Chapin et al. 2002/. These are also the largest inputs to soil organic matter. ΔSOM is the net gain of biomass in the soil organic matter pool and described by

$$\frac{\Delta SOM}{\Delta t} = F_{pl-soil} + F_{anim-soil} - (R_{microb} + F_{microb-anim} + F_{CH_4} + F_{leach} + F_{soil-fire})$$

$F_{anim-soil}$ is the input of organic matter from animals, while respiration, consumption of microbes by animals, methane emission and leaching of organic and inorganic carbon to groundwater and fire are the carbon losses in the soil. The dead organic materials in the uppermost soil layers are after decomposition again available for the vegetation if not emitted or leached. The accumulation and decomposition rate is affected by factors such as hydrology, soil type, soil chemistry, soil fauna and vegetation.

Temporal variation

The temporal variation may have few implications for the overall carbon budget but may be of importance when collecting data or studying specific transport events, such as a short term release of radionuclides and their potential accumulation during their transport through the landscape. Two important factors behind temporal variation in ecosystem properties are temperature and precipitation.

Growing season

The growing season is a function of the diurnal mean temperature, which is important to e.g. decomposition that has a positive exponential relationship to soil temperature. This means that the decomposition is much lower in the winter then in the summer /Widén, 2002/. This is also detected in the total amount of DOC in running water at the Forsmark site, which is much higher during the winter months. This relationship also means that the variation between years may be large due to variation in climatic factors such as precipitation and temperature. Consequently may NEP vary between years, e.g. /Waddington and Roulet, 2000/ showed this for a boreal bog in northern Sweden. They also concluded that because of the low difference in mean annual air temperature and total precipitation between these years the variation within the growing season is important for the season carbon balance.

Water flow

Water flow is also an important factor contributing to temporal variation in ecosystem properties, with a large variation within the year. Water flow control most transport processes in ecosystems, such as lateral transport of DOC. The largest flows are (see also 3.4.3) found in spring and autumn. This means that available matter is more prune to be transported during these periods, which is also illustrated by the example above. The transport of water within the plants is also highly dependent on the growing season.

4.1.4 Quantitative descriptive model

This section describes how estimations of carbon pools and fluxes are introduced into the conceptual model and is divided into the following topics:

1. A description of the data and how the data was used.
2. Results describing carbon pools and fluxes are extracted for three habitats and compared with other studies.
3. The stocks and flows of carbon are presented for a drainage area in Forsmark.

Methodology and modelling assumptions

Spatial distribution of data

The quantitative descriptive model is the quantification of the components in the conceptual model (Figure 4-1) and further transferred into GIS, thereby giving the data a spatial distribution. The data that was used to turn the conceptual model into a quantitative descriptive model was taken from sources in accordance with Table 4-1 and from tables presented within this section. The spatial resolution of data is different depending on the property and is presented in detail within the section of relevance in accordance with Table 4-1. Generally, the aim is to have a resolution that is a trade-off between what is possible to identify using digitalised maps (e.g. the vegetation map) and what is biologically relevant in relation to the overall aim. In many cases this is equivalent to a resolution that is based on the vegetation map (Figure 4-1). However, there are still much data that are under preparation or sampled and therefore have a poor resolution today. The overall result is a GIS database that consists of spatially distributed information layers describing each property listed in the different sections in Table 4-1.

Table 4-1. Presentation of the properties that was used to characterise the entities in the quantitative descriptive ecosystem model and where they are more thoroughly treated.

Entity	Section	Table no	Property
Producers	3.7.1	3-28 to 3-30	Biomass, NPP and turnover
Consumers	3.7.2	3-50	Biomass and consumption
Humans	3.10	3-70	Hunting, utilized berries and fungi
Hydrology	3.4	–	Evaporation, transpiration, specific runoff

Vegetation types

Most terrestrial habitats behave in a similar way, in regard of accumulation and flows, making the conceptual model easy to apply to the different vegetation types at the site. However, wetlands having periodically inundated soils creating anaerobic conditions do accumulate organic matter in a high rate compared to the other terrestrial habitats found at the site. Therefore are these habitats of particular interest when describing accumulation and transport of organic matter in the descriptive ecosystem model.

The wetlands are characterised by a high calcareous influence making the extremely to moderate rich fen types common in this area. These fen types lacks the dominance of Sphagnum species in the ground layer and is instead dominated by brown mosses e.g. Scorpidium scorpioides. However, the bog is also present and is continuously created as the land rise and leaching starts. Bogs are not yet so numerous in this area, partly depending on the young age. Roughly there may be two types of wetlands identified. Those that accumulate peat and those were decomposition is fairly high thereby minimising peat formation. The later have a more or less thick humus layer on mineral soil thereby having less carbon in the soil organic carbon pool (SOC) (which is also confirmed from site specific measurements in Forsmark, /Lundin et al. 2004/). The two types are spatially identified by over layering GIS maps describing the wetlands and the Quaternary deposits /Boresjö Bronge and Wester, 2002/.

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

Studies of DOC loading to lakes, as a function of vegetation types, in a drainage area have shown that wetlands export more DOC than other vegetation types /e.g. Canhem et al. 2004; Humborg et al. 2004/. /Canhem et al. 2004/ calculated the export from conifer wetlands, "emergent marches" and forests to 17.5 $gCm^{-2}y^{-1}$, 12.5 $gCm^{-2}y^{-1}$ and 3.5 $gCm^{-2}y^{-1}$ respectively, using a predictive model based on 2,750 lakes and their drainage areas in Canada. /Waddington and Roulet, 2000/ estimated the lateral transport from a boreal bog in Sweden to be 4.2 gCm^{-2} and 6.7 gCm^{-2} in two consecutive years. These figures are small in comparison to the local carbon budgets (see Table 4-5 to 4-7 for the forest and the mire) but their impact on the recipient may be large depending on the size of the drainage area.

Carbon content and turnover in the soil

The carbon content in the soil is separated into humus layer and mineral soil layer (Table 4-2). The soil microbial biomass is included in this carbon pool. There is no site data describing the microbial biomass and is therefore not treated separately. However, some generic data describing biomass for soil fauna is presented in Table 3-49.

Today we have no data describing the decomposition rates at the site and we therefore assume that the yearly flux of carbon from the standing stock is in a steady–state with decomposition. This is of course a rough simplification especially as most forests are carbon sinks /Chapin et al. 2002/.

For wetlands there is data describing the accumulation of carbon using the age of the site and the thickness of the peat layer (Table 4-3). By comparing this rate of accumulation with the input of carbon to the soil it will be possible to evaluate how they correspond to each other.

Table 4-2. Soil carbon content in different vegetation types in Forsmark /Lundin et al. 2004/. These classes correspond to the vegetation types used in Section 3.7.1.

Description of the class	Class in /Lundin et al. 2004/	Humus layer	Below humus layer
Shore line (bedrock excluded)	AR/GL	863	3,194
Forested wetlands	GL	2,594	7,171
Herb dominated moist soils on fine texture parent material	GL/CM	0	14,536
Agriculture land	RG/GL-a	0	14,062
Mires	HI	43,282	0
Thin soils with lichen rich heath vegetation	LP	3,322	5,655
Woodland, coniferouos forest	RG/GL	2,921	6,256

Table 4-3. A rough estimate of accumulation rate of carbon in four wetlands in the Forsmark area. These values are calculated using information of the depth of the peat soil and the approximate age since the wetland emerged from the sea.

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

Transport of DOC

The downward flow of carbon is not treated in this version, because of the comparatively larger immobility of DOC in lower soil horizons /Neff and Ashner, 2001, Berggren et al. 2003/, (see also 4.1.2).

The upward water movement due to evapotranspiration from plants is regarded as unimportant in affecting transport of carbon. However, this flow of water is considerable and may be important for transport of other substances and is therefore presented but not further treated in this section. This upward flow is estimated using the Mike She model (see Section 3.4).

Lateral transport is dependent on the specific runoff for the whole site. The lateral transport between neighbouring terrestrial ecosystems is, however, in lack of data assumed to be of minor importance (3.5 $gCm^{-2}y^{-1}$ is transported from conifer forests, see 4.1.2 Wetlands). Nevertheless it is calculated for the drainage area thereby making comparisons with DOC transport data from the limnic ecosystem possible. Transport to and from wetlands may be larger due to a discharge area that concentrates water flow to a smaller area. A number of properties describing parameters related to water transport to and from a wetland is presented for each wetland within the discharge area (Table 4-4).

/Brydsten, 2004a/ found that data from six investigated lakes in the Forsmark area suggested that sediments had a high degree of material of autochtonous origin. Several other factors supported that, such as small topographic variation (small watersheds), low current velocities and low abundance of fine-grained sediments. Nevertheless was an example calculated to illustrate how much the carbon dynamics within the wetland may be influenced by input of carbon from the local discharge area. This was based on literature data from /Canhem et al. 2004/ who estimated leaching of DOC from conifer forests to 3.5 $gCm^{-2}y^{-1}$. The size of the drainage area was multiplied with this figure to get a measure of the DOC loading to the wetland. Output from emergent marshes was estimated by /Canhem et al. 2004/ to 12.5 $gCm^{-2}y^{-1}$. This figure was multiplied with the wetland size to get a measure of the transport DOC from the wetland (Table 4-5). These results were compared with the local input to SOC and the SOC pool (Table 4-5).

Table 4-4. Properties describing the wetlands within the catchment area of Forsmark 2. First column shows the id number of the wetland, which is related to the spatial location of the wetlands in the drainage area (Figure 4-2). When several wetlands together constitutes a discharge area, the GIS tool was not able to separate the individual discharge areas. The specific runoff that have been used to calculate the incoming water flow to the wetland is 6.5 lm^{-2}s^{-1} (3.4.3). These parameters were calculated using the hydrology extension in ArcGIS 8.3 (see 3.4.4). The wetlands that are missing a discharge area were not identified as having one by the GIS tool.

Id no	Wetland id no	Area (m^2)	Discharge area (m^2)	Inflow (m^{3}s^{-1})	Inflow (m^{3}y^{-1})
1	139	3,188	24,416	0.0016	50,000
2	134,135,138,142,144	29,636	201,388	0.0131	410,000
3	85, 86, 95	72,662	299,131	0.0194	610,000
4	128	3,676	17,576	0.0011	36,000
5	104	34,681	170,347	0.0111	350,000
6	170	5,092	83,682	0.0054	170,000
7	166	8,785	59,296	0.0039	120,000
8	137	21,828	588,012	0.0382	1,200,000
9	110, 114	32,048	682,964	0.0444	1,400,000
10	88	5,389	54,536	0.0035	110,000
11	112	3,651	18,115	0.0012	37,000
12	59, 62	17,301	–	–	–
13	67	3,099	–	–	–
14	40	4,522	–	–	–

Few figures have been published presenting the carbon mineralization in wetlands. /Moore et al. 2002/ presented the figure 245 gCm^{-2}y^{-1} from a boreal bog in Canada. This figure was used to describe the C-mineralization rate in the wetlands. The peat accumulation in the wetlands was calculated subtracting the C-mineralization rate (245 gCm^{-2}y^{-1}) from the flux of litter and incoming DOC (Table 4-5). The calculated rates were on average 6.4 times higher than field estimates from four wetlands in Forsmark Table 4-3 and also very high compared to literature sources e.g. /Ohlson and Okland, 1998/. The C-mineralization rate used in the calculations is from a bog. Most of the wetlands in this area are more fen-like /e.g. Brunberg et al. 2004/ and may therefore have a much higher mineralization rate. Most of the figures used in the calculations of the wetland carbon budgets are from different literature sources and the introduction of more site specific data will make it more easily to assess the correctness of the wetland carbon budgets. This will serve as base for a better understanding of how the wetlands in the Forsmark area act as carbon sinks in the landscape perspective.

The results suggest that the average accumulation of external DOC is 4% of the total input from the local wetland to the SOC as litter (field layer and roots). Consequently, the external input of DOC from the drainage area is low in relation to the local flux of carbon to the SOC. In lack of better data it is therefore assumed that the majority of the carbon deposited in wetlands is from the production within the wetland.

Table 4-5. Input, output and accumulation of dissolved organic carbon (DOC) in the two wetlands within the drainage area. All figures are in 1x10^6 gCy^{-1}. The flux of litter is produced within the wetland. Calculation of peat accumulation was done in two ways; (1) by generic data of decomposition and adding column 4 and 5, and subtracting column 6, and (2) from estimated peat accumulation from Table 4-3.

Wetland id	Input DOC	Output DOC	Accumulation of external DOC	Flux litter	C-mineralization	Peat acc (1)	Peat acc (2)
1	0.09	0.04	0.05	1.93	0.78	1.19	0.19
2	0.70	0.37	0.33	17.93	7.26	11.00	1.79
3	1.05	0.91	0.14	43.96	17.80	26.30	4.39
4	0.06	0.05	0.02	2.22	0.90	1.34	0.22
5	0.60	0.43	0.16	20.98	8.50	12.65	2.09
6	0.29	0.06	0.23	3.08	1.25	2.06	0.31
7	0.21	0.11	0.10	5.31	2.15	3.26	0.53
8	2.06	0.27	1.79	13.21	5.35	9.64	1.32
9	2.39	0.40	1.99	19.39	7.85	13.53	1.94
10	0.19	0.07	0.12	3.26	1.32	2.06	0.33
11	0.06	0.05	0.02	2.21	0.89	1.33	0.22

Carbon budget within some vegetation types

The large amount of information describing pools and fluxes and the different spatial resolution of this information called for an implementation of the conceptual model on a number of vegetation types before a carbon budget is presented for a complete catchment area. Three vegetation types were therefore chosen using the vegetation map, to represent a forest, a mire and an agriculture land (Table 4-6). Data describing pools and fluxes was extracted for these vegetation types (Table 4-7 to 4-10) and compared with available data from other studies in order to assess the validity of the resulting descriptive ecosystem model and control for inconsistencies. Moreover, was data describing some of the water fluxes extracted for these habitats (Table 4-11).

Table 4-6. The three vegetation types and their location chosen for the typification of the conceptual model in Forsmark. The grid codes follows the vegetation map by /Boresjö Bronge and Wester, 2002/.

Vegetation type	Grid code (veg. map)	X	Y
Old spruce forest, mesic - moist	Old spruce-dominated forest, mesic-wet types, 11	1632365	6699367
Open wetland	Open wetland, reed-dominated, less wet, 77, peat land	1632042	6697987
Arable land	81	1631710	6696370

Table 4-7. The different pools of carbon presented for the three different vegetation types. The number after the sum sign is showing the net annual increase of biomass. Those without such a number are supposed to be in a steady state in regard of biomass (gCm^{-2}) between years. Soil Organic Carbon (SOC) is presented for the humus layer and the mineral soil separately. (AG = above ground, BG = below ground).

Properties	Carbon pools in (gC m^{-2})		
	Forest	Wetland	Agriculture land
Carnivores*	1.6×10^{-3}	1.6×10^{-3}	1.6×10^{-3}
Herbivores*	0.078	0.078	0.078
Soil fauna	Is a part of the soil organic carbon pool below		
Tree layer AG	6,048 + 178	–	–
Tree layer BG	1,632 + 120	–	–
Field and ground layer AG	401	264	210
Field and ground layer BG	0	1,261	90
Fungi	117	–	–
Dead wood	103	9	–
Litter layer	154	322	–
SOC humus layer	2,921	43,282	
SOC Below humus layer	6,256	–	14,062
Overall sum	16,947	45,137	14,384

* Figures from Section 3.7.2.

Table 4-8. Fluxes affecting the Soil Organic Carbon pool during one year and the total SOC pool.

Properties	Carbon fluxes in (gC m^{-2}y^{-1})		
	Forest	Wetland	Agriculture land
Litter fall	128	202	0
Root litter	665	403	90
Mycel litter	137	0	0
Sum Input to soil	930	605	90
SOC humus layer	2,921	43,282	–
SOC below humus layer	6,256	–	14,062

Table 4-9. Fluxes affecting the plant biomass during one year. NPP is the total biomass produced during one year.

Properties	Carbon fluxes in (gC m^{-2}y^{-1})		
	Forest	Wetland	Agriculture land
NPP trees	1,091	–	–
NPP plants	34	667	300
NPP mycel	137	–	–
Sum production	1,262	667	300
Litterfall	128	202	0
Root litter	665	403	90
Mycel litter	137	0	0
Harvest	–	–	210
Sum removal	930	605	300
Accumulation in biomass	332	62	0

Table 4-10. Fluxes related to humans and animals during one year. The carbon flux from hunting to humans is the actual utilized meat after slaughter. These fluxes are more thoroughly presented in Section 3.7.2.

Properties	Carbon fluxes in (gC $m^{-2}y^{-1}$) Forest	Wetland	Agriculture land
To humans from vegetation*	0.71	0.71	142
To humans from animals (hunting)*	0.012	0.012	–
Sum input to humans	0.7	0.7	142
Carnivory	0.03	0.03	0.03
Herbivory	4.6	4.6	4.6
Sum input to animals	4.6	4.6	4.6
Faces and mortality carnivores	6×10^{-3}	6×10^{-3}	6×10^{-3}
Faces and mortality herbivores	2.3	2.3	2.3
Sum input to SOC	2.3	2.3	2.3

Table 4-11. Estimates of different water flows in the three exemplified vegetation types. See 3.4 for a description of how the estimates were obtained.

Properties	Water fluxes in ($m^{-3}y^{-1}$) Forest	Wetland	Agriculture land
Transpiration	73 mm	–	–
Evaporation (intercept.)	203 mm	–	–
Lateral flow	6.5 $lm^{-2}s^{-1}$	See Table 4-4	–

Forest

Productive forestland in Sweden has been calculated to have approximately 80 metric tonnesC/ha (8,000 gCm^{-2}) down to one metre /Olsson, 2000/. The corresponding value for Forsmark is 9,331 gCm^{-2} (Table 4-7). This is also in agreement with the figures from Skogaby /Persson et al. 2001/ where they had a carbon content in the humus layer of 2,200 gCm^{-2} and 10,000 gCm^{-2} in 0.5 m of the mineral soil. The later value is higher than the value from Forsmark but is partly explained by the rather young soils in Forsmark where the carbon has had much less time to accumulate in the deeper soils (see Section 3.4).

If it is assumed that the carbon pool in the soil is in a steady state with incoming organic matter the C-mineralization would be 385 $gCm^{-2}y^{-1}$. This can be compared with estimations from the Skogaby plots /Persson et al. 2001/ of 266 $gCm^{-2}y^{-1}$. Their plots had a similar amount of carbon in the soil pool 10,500 gCm^{-2}. The high C-mineralization value obtained for the Forsmark forest is high. Further calculations and more site specific data will reveal the accuracy of this value.

Wetland

Peatland in Sweden have a general carbon content of 260 $kgCm^{-2}$, 600ton/ha /Olsson, 2000/. This figure does not fit the figure 43 $kgCm^{-2}$ from Forsmark well. This is partly an effect of the comparatively young soils in Forsmark, which is equivalent to a shallow peat layer. The figure from Forsmark does also only cover the first metre of the regolith, which therefore is an underestimation if the peat layer is deeper.

If it is assumed that the SOC pool is in a steady state with incoming organic matter the C-mineralization would be 605 $gCm^{-2}y^{-1}$. This is a very high value and can be compared with the value 245 $gCm^{-2}y^{-1}$ from a boreal bog in Canada /Moore et al. 2002/. Field estimations of the carbon accumulation in four peat forming wetlands at the site are also much lower (Table 4-3). Further investigations will add more knowledge concerning the carbon budget of the wetlands at the site.

Agriculture land

The agriculture land has most of the biomass above ground that is regularly harvested leaving some amount of root litter. Typically this land is ploughed once or twice a year creating a more or less homogenous soil where no humus layer horizon is found. Here it is assumed that everything above ground is removed, which is a simplified assumption because a small part of the straw is left after harvest. The difference between what is harvested (Table 4-9) and what is utilized by humans (Table 4-10) is the treshing loss and straw. Fungi is present in this vegetation type and is known to form mycorrhiza with fertilized crop /Chapin et al. 2002; van der Heijden and Sanders, 2002/ but has not been accounted for here.

A carbon budget for a drainage area

The descriptive ecosystem model is applied at the landscape level covering a discharge area. Pools and fluxes for all vegetation types are summed using GIS (described earlier). The resulting carbon budget is somewhat reduced in comparison to the conceptual model using aggregated pools and fluxes.

The Drainage area

The drainage area is situated in the Forsmark area (Figure 4-2) and is 8.67 km^2. The dominating vegetation types are old Norway spruce and Scotch pine forests of mesic-wet type together constituting 35% of the area. Clear-cuts represent 11%, water 9%, young conifer forest 8% and reed-dominated wetlands 8% of the vegetation types in the drainage area /Brunberg et al. 2004/.

The descriptive model

The descriptive model has been reduced in number of boxes and fluxes, and is presented in Figure 4-3. The carnivore box is the sum of all carnivores presented in Section 3.7.2. Where measure of biomass, faeces or mortality were missing, the simple assumption was made that it was on average the same as for those animals there these figures were known. The arrow from vegetation to humans represents crops from the agriculture land in the discharge area, and berries and fungi that are utilized (see 3.10 for more information behind these values). The arrow from herbivores to humans is the actual utilized meat after the slaughter. If a steady state between carbon input to SOC and C-mineralization is assumed the C-mineralization should approximate 1.24×10^9 gCy^{-1}.

Flow of matter

The total lateral transport of DOC was calculated using a figure from /Canhem et al. 2004/ that estimated leaching of DOC from conifer forests into lakes to 3.5 $gCm^{-2}y^{-1}$. This figure was multiplied with the total discharge area (lake area subtracted). This resulted in the total amount of 0.03×10^9 gCy^{-1} that was transported as DOC from the terrestrial land types in the discharge area.

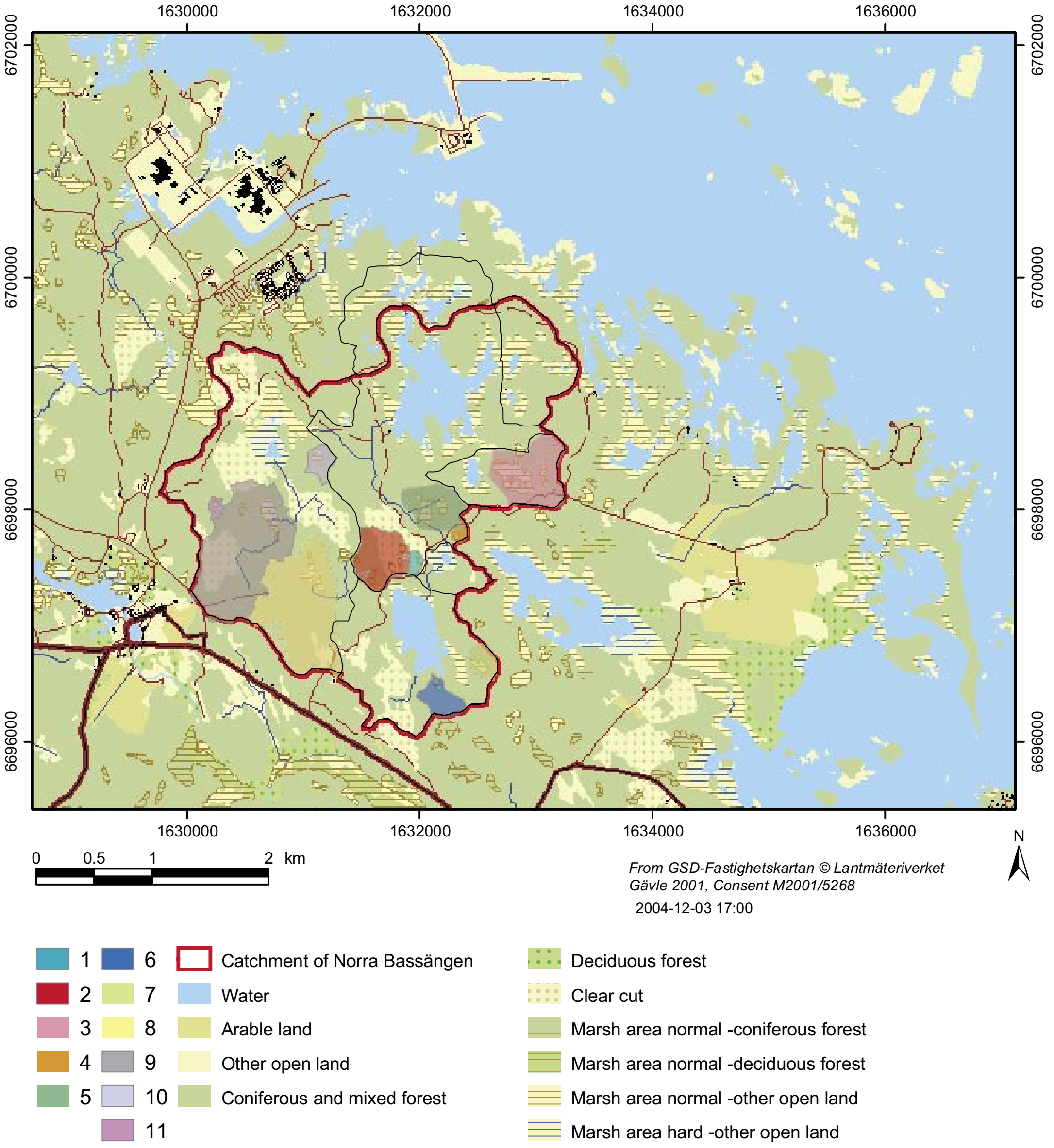

Figure 4-2. *The drainage area in Forsmark on which the descriptive ecosystem model was applied in order to construct a large scale carbon budget. The wetland id number corresponds to the numbers in Table 4-4. The wetlands 12–14 are missing a discharge area because they were not identified as having one by the GIS tool.*

Net Ecosystem Production

The NEP, which is the net accumulation of carbon in the discharge area during a time step (see Equation 4-1), is difficult to estimate due to lack of estimates describing the decomposition in different vegetation types. The accumulation in the vegetation (trees) is estimated to 1.5×10^{9} gCy^{-1} (Figure 4-3), while the fauna (except soil fauna) is assumed to be in a steady-state (Section 3.7.2).

The Skogaby experiment /Persson and Nilsson, 2001/ found that the accumulation of carbon in the SOC pool was 160 gCm^{-2}y^{-1} while the accumulation in the vegetation was 190 gC^{-2}y^{-1}. A similar relationship for this discharge area that is dominated by conifer forests would indicate that the net accumulation in SOC pool is somewhat less than the accumulation in the vegetation. This would generate a NEP of approximately 3.0×10^{9} gCy^{-1} in this discharge area.

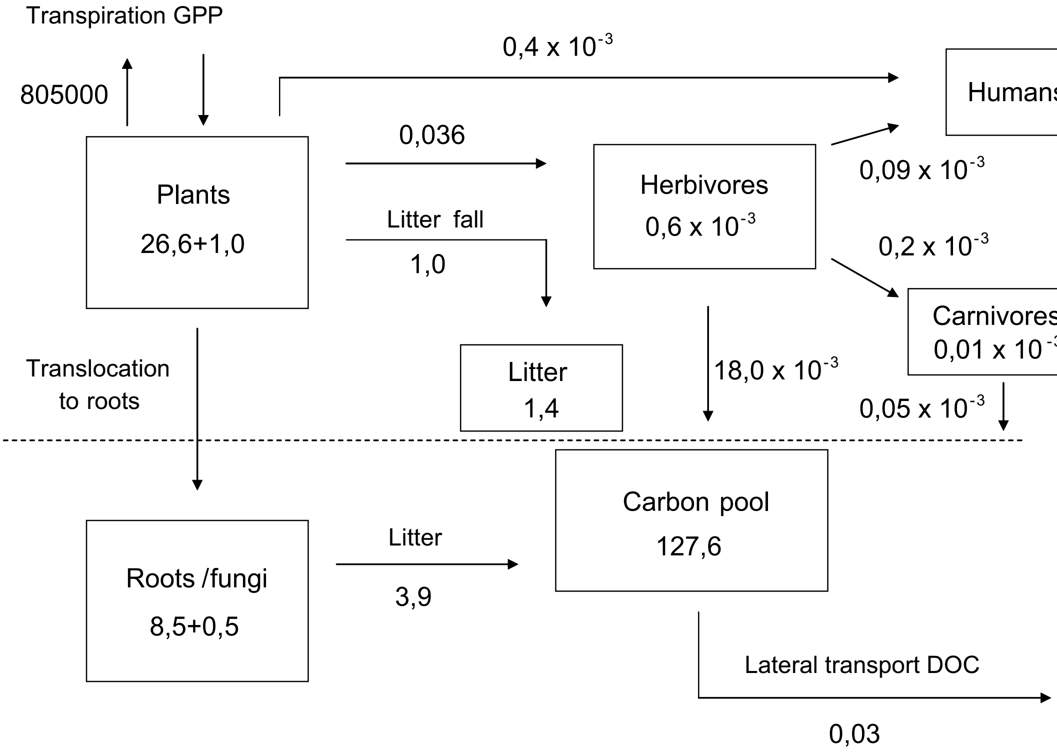

Figure 4-3. *Major pools and net fluxes of carbon for the overall drainage area in Forsmark 2. Transpiration is in m^3y^{-1}, figures in boxes are in $1x10^9gC$ and figures describing fluxes in $1\times10^9gCy^{-1}$. Net change in a pool is shown within the box.*

Confidence and uncertainties

For the overall carbon budget is the importance of the different pools and fluxes set by there relative size. This means that large variation or uncertainties in relative large pools/fluxes overshadow the influence of relatively smaller pools/fluxes. This has often been an argument to why some smaller pools or fluxes have been left out. There is a large spatial variation within a regional area as an effect of different abiotic conditions and to disturbances, such as logging and thinning in the forestry industry. The biomass of trees is probably the data that have the best estimations in this carbon budget and that was sampled from a fairly large regional area covering a large number of age classes and abiotic conditions (3.7). This means that local deviance from the general spruce forest ecosystem may be large but that these deviancies should even out when a sufficient large area is used for the calculations /Svensson, 1984/ see also /Banfield et al. 2002/. Therefore should calculations of the carbon budget get less sensitive to spatial variation when the area of interest gets larger. The carbon budget for the discharge area should therefore be more robust (relative deviance from the actual pools and fluxes) than the carbon budgets for the local forest, mire and agriculture land presented earlier. See also the discussion under 3.7.

4.1.5 The coup model

Objectives

The CoupModel is a one-dimensional model for simulations of fluxes of water, heat, carbon and nitrogen in soil-plant-atmosphere systems. A trace-element sub-module has been implemented for simulation of radionuclide turnover in terrestrial ecosystems.

The main objective for this application was to model near surface hydrology and carbon turnover of typical forest ecosystems in the Forsmark area, as a base for a sensitivity analysis with the radionuclide module. Specific objectives were to:

- Simulate water balance for mature coniferous forest stands in Forsmark.
- Simulate long-term carbon and water flows for a 100-year rotation time.

An updated analysis and more detailed description of the applications to both Forsmark and Simpevarp will be given by /Gustafsson et al. 2005/.

Model description

CoupModel /Jansson and Karlberg, 2004/ is an integration of the SOIL /Jansson and Halldin, 1979/ and SOILN /Eckersten et al. 1998/ models. SOIL and SOILN correspond to the water and heat part and the nitrogen and carbon part of the CoupModel, respectively.

Simulations of soil temperature, soil moisture conditions, and soil water flows are based on physical equations. Water and heat exchange between the atmosphere and the soil is caluclated for three types of surface compartments: bare soil, snow, and one or several vegetation (canopy) layers. Evapotranspiration from the canopy layers includes transpiration and interception evaporation, and is calculated with the analytical approach suggested by /Penman, 1953/ as modified by /Monteith, 1965/, hereafter referred to as the 'Penman-Monteith' equation. Meteorological data, soil hydraulic properties, boundary conditions for runoff (drainage and surface runoff), and vegetation characteristics governing evapotranspiration are the most important input data for the water and heat part of the model.

The carbon and nitrogen part of the model is based on three basic assumptions: 1) carbon input is governed by solar radiation, 2) carbon flows govern nitrogen flows, and 3) nitrogen content of plants determines growth. Carbon and nitrogen pools for stem, leafs (needles), and roots represent the plant biomass. The stem compartment represents all woody material including stem, branches, and roots except fine roots.

Two pools of different turnover rate represent the organic material in the soil. One of these is named Litter and has a high turnover rate. The other one is Humus and represents a low turnover rate. These pools are represented in each soil horizon in the model, and should not be confused with the labeling of litter and humus layers in soil profile descriptions. Soil organisms, such as microorganisms, decompose the organic matter, and their activity is accounted for in the fluxes of carbon and nitrogen between different soil organic pools.

The most important interaction between the carbon turnover and the physical conditions is governed by the leaf area index (LAI) and the ratio between actual and potential transpiration. Both will in turn influence the input of carbon to the system and both are strongly related to soil temperature and moisture.

Input data

A 30-year dataset with hourly values of air temperature, wind speed, relative humidity, precipitation, global radiation, and cloudiness was created based on the available data from a number of different stations. The primary data sources were the SKB measurements at Forsmark (Högmast and Storskäret) 2003–2004 and the SMHI station Örskär 1988 /Larsson-McCann et al. 2002/. Secondary data sources were observations of air temperature and precipitation from the SMHI stations Örskär, Östhammar, Lövsta, and Films Kyrkby 1994–2003. A complete set of meteorological observations from Uppsala airport 1970–1996, and Marsta Meteorological Observatory (Uppsala) 1997–2000 were used to extend the data set to 1970–2004.

Data from other stations than Forsmark were corrected to get the best possible representation of the local climate conditions at Forsmark. Correction factors were derived from common time periods /Gustafsson et al. 2005/.

On average, precipitation in Forsmark was lower than at the inland stations in Uppsala. However, wintertime precipitation was generally higher (frequent snowstorms from the sea). These seasonal differences were accounted for in the correction of the Uppsala precipitation data. Further more, precipitation observations were corrected with 6% at air temperatures above 1°C and 10% below 1°C.

Soil hydraulic properties were based on investigations in the Forsmark area (see Section 3.4). However, parameters from Norunda determined for every 10 cm were used to achieve a more realistic resolution of the upper 100 cm.

Water and heat processes (i.e. transpiration, interception, snow melt, soil heat and water flows) were parameterised based on an earlier application to a mature pine/spruce forest in Norunda, Uppland, Sweden /Gustafsson et al. 2004/. Two canopy layers of different height and densities were used to represent tree and field layer. LAI and canopy height were simulated by the carbon and nitrogen model. For the hydrological simulations without the carbon and nitrogen model, LAI was prescribed to be 4.5 for the tree layer and 0.5 for the field layer.

Boundary conditions for groundwater flow (i.e. drainage level) were determined by comparison of simulated saturation level to observed groundwater levels from the Forsmark area. Four groundwater observations were selected, which represented different type of soil moisture conditions (Table 4-11).

Input parameters for carbon and nitrogen processes were based on previous applications of SOILN and CoupModel to several Swedish forest sites, Skogaby, Halland /Eckersten and Beier, 1998; Gärdenäs et al. 2003/, Asa, Småland /Svensson, 2004/, and Jädraås /Gärdenäs et al. 2003/ and Knottåsen /Svensson, 2004/ in Hälsingland. All these applications rely on site-specific calibrations of critical parameters governing carbon and nitrogen flows related to plant growth. Some of these parameters were re-calibrated using data on stem biomass development estimated from /Marklund, 1988/ and Swedish forestry statistical yearbook 2003 /Skogsdata, 2003/ for the Uppsala region. Parameters for carbon and nitrogen turnover rates in the soil were assumed to be more site-independent and were taken directly from the simulations of Skogaby (mineral N processes) and Knottåsen (organic processes).

Table 4-11. Groundwater tubes used to calibrate drainage levels for the simulations of Forsmark forest soils of different soil moisture conditions.

Moisture class	Groundwater tube	Level below ground (m)*
Wet	SFM0021	0.43
Fresh (slope)	SFM0004	0.5
Fresh (typical 'elevated' area)	SFM0005	1.04
Dry (local extreme)	SFM0008	2.87

* Average values for the simulation period, 2003-08-01 to 2004-07-31.

Water balance

Simulations without the interaction of the carbon and nitrogen model using constant leaf area index and vegetation heights were used to calculate the water balance representative for mature forest stands. Simulations were run for the period 2003-08-01 to 2004-07-31 using climate input data from the local measurements at Forsmark.

Accumulated precipitation was 645 mm, partitioned on about 410 mm (64%) evapotranspiration and 235 mm (36%) runoff in the simulations characterized as ‘ Fresh’ and ‘Dry’ (Table 4-13). Transpiration and thus also total evapotranspiration was about 100 mm lower in the ‘Wet’ simulation than in the ‘Fresh’ and ‘Dry’. However, the reduction of transpiration due to decreased root water uptake from saturated soil layers may be somewhat exaggerated in the present simulations (Tables 4-13 and 4-14). The same root depth (0.7 m) was used in all simulations. It is probably more realistic to assume that plants adapt their root distribution to the prevailing soil moisture conditions.

The relation between evapotranspiration components (Table 4-14) was similar to the results of /Gustafsson et al. 2004/. Interception evaporation was about 30% of the total evapotranspiration. Verification of the partitioning between soil evaporation and transpiration is difficult without measurements of either one of these components or soil water content in the root zone.

The simulated evapotranspiration was about 70% of the ‘potential evapotranspiration’ calculated with the original Penman equation /Penman, 1953/ (Table 4-15). This relation corresponds well with measurements from the similar forest site in Norunda /Grelle et al. 1999/. However, simulated winter evapotranspiration was higher than predicted by the Penman equation due to a considerable amount of interception evaporation, see also Figure 4-4.

Table 4-13. Simulated water balance for the Forsmark forest 2003-04 with the CoupModel.

Water balance	mm			% of precipitation		
component	Wet	Fresh	Dry	Wet	Fresh	Dry
Precipitation	645	645	645	100	100	100
Evapotranspiration	329	415	407	51	64	63
Runoff	316	230	239	49	36	37

Table 4-14. Simulated evaporation components for the three Forsmark forest area, accumulated fluxes 2003-04.

Evaporation	mm			% of evapotranspiration		
component	Wet	Fresh	Dry	Wet	Fresh	Dry
Interception evaporation	133	132	133	40	32	33
Transpiration	100	196	193	31	47	47
Soil evaporation	93	84	78	28	20	19
Snow evaporation	3	3	3	1	1	1

Table 4-15. Simulated monthly sums (mm) of precipitation, runoff and evaporation components for the 'wet/fresh' simulation, and 'potential evaporation' from a short crop calculated with the Penman equation /Penman, 1953/.

Month	Precipitation	Runoff	Evapo-transpiration	Interception	Transpiration	Soil+Snow	Potential evaporation
Jan	42	23	4	3	0	1	–1
Feb	15	33	6	4	1	1	6
Mar	25	56	12	7	2	3	24
Apr	30	15	31	5	15	11	61
May	42	8	56	13	30	12	102
Jun	45	5	73	11	45	17	131
Jul	84	5	77	25	38	13	108
Aug	110	4	77	28	36	14	95
Sep	49	7	41	8	23	10	46
Oct	74	8	17	9	5	3	9
Nov	58	25	7	7	0	1	–1
Dec	71	40	13	12	0	1	3
Sum	645	230	415	132	196	87	585

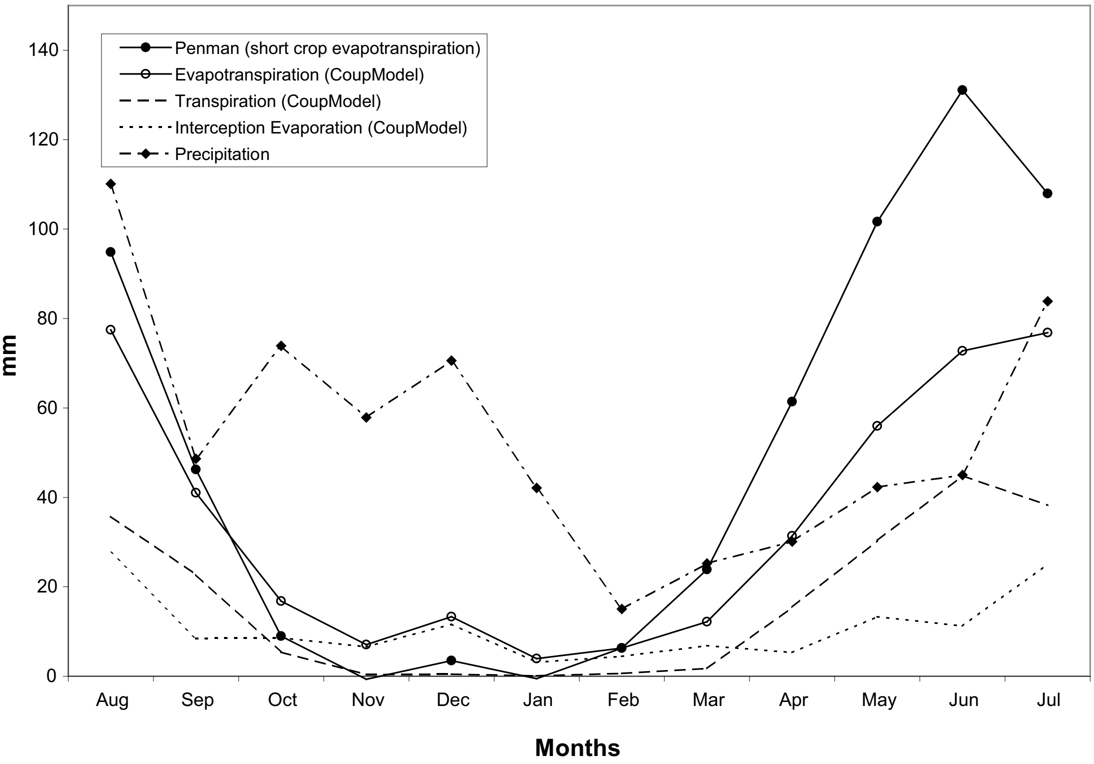

Figure 4-4. *Monthly sums of 'potential evapotranspiration' estimated with the Penman equation for a short crop, compared to total evapotranspiration, transpiration, and interception evaporation simulated with the CoupModel for a forest stand in Forsmark, simulation period 2003-08-01 to 2004-07-31.*

The difference between the original Penman and Penman-Monteith equations is the representation of turbulence efficiency and canopy surface control on the evapotranspiration. These two control mechanisms are separated on two parameters in the Penman-Monteith equation; the aerodynamic and the surface resistance, whereas the Penman equation combines them into one single parameter, the wind function. Formally, the wind function corresponds to the aerodynamic resistance. The equations are basically identical if the surface resistance is set to zero in the Penman-Monteith equation.

First of all, the aerodynamic resistance is about one order of magnitude lower for a rough forest surface compared to a short crop. This explains the large amount of interception evaporation in the CoupModel calculations, especially during winter. On the other hand, the stomatal control of canopy transpiration is much higher and more sensitive to atmospheric conditions for a forest than for a crop or grassland. The surface resistance in the Penman-Monteith equation can be modelled in various ways; in this case as a function of global radiation and vapour pressure deficit. Typically, the annual sum of evapotranspiration is rather similar for a forest and an agricultural crop, but the seasonal patterns differ due to the difference in seasonal variations of surface and aerodynamic resistances /see e.g. Gustafsson et al. 2004/.

Carbon budget

A 100-year development of a spruce/pine forest was simulated with a full coupling between the water and heat part and the nitrogen and carbon part of the model. Two vegetation layers were simulated to represent tree and field layer. Initial values of carbon contents in the vegetation layers were chosen to represent small tree seedlings and a fully developed field layer. Three consecutive 100-year cycles were simulated with harvest of the tree layer stem biomass at the end of each cycle. Such long simulation cycles are necessary for a proper initialization of the soil organic pools of carbon and nitrogen in the model. Simulated growth is very sensitive to nitrogen availability, which mainly – apart from the deposition – is governed by mineralisation or immobilisation of soil organic nitrogen. The latter is governed by the C/N ratio of the soil organic matter and the activity of the soil microbes. Climate data from 1970-08-01 to 2004-07-31 was repeated three times as input to the model

As indicated above, allocation of nitrogen and carbon to different parts of the plant and the availability of nitrogen were used as calibration parameters. The simulation was calibrated by comparing the tree layer stem biomass to an approximate stand development derived from /Marklund, 1988; Skogsdata, 2003/ (Figure 4-5). The overestimated growth and unrealistic increase of soil organic carbon during the first two 100 year rotations visualize the need for iterative initialization of the model. In this particular case, model results were more stable after 200 years. Results from the last 100 years were selected for the further analysis.

The simulation reached the present estimated carbon content in the tree layer (above and below ground) in Forsmark, 7.89 kg C m^{-2}, at a stand age of 63 years (Table 4-16). At this stage, the carbon content in the field layer vegetation was about two times higher than the measurements (1.2 kg compared to 0.66 kg). However, the simulated relationship between the tree and the field layer with respect to carbon and nitrogen content was reasonable. The ratio between the simulated carbon content in the tree and the field layer was approximately 9:1 at the end of the simulation period, and the corresponding ratio for nitrogen was 4:1. In other words, relatively more nitrogen compared to carbon is stored in the field layer.

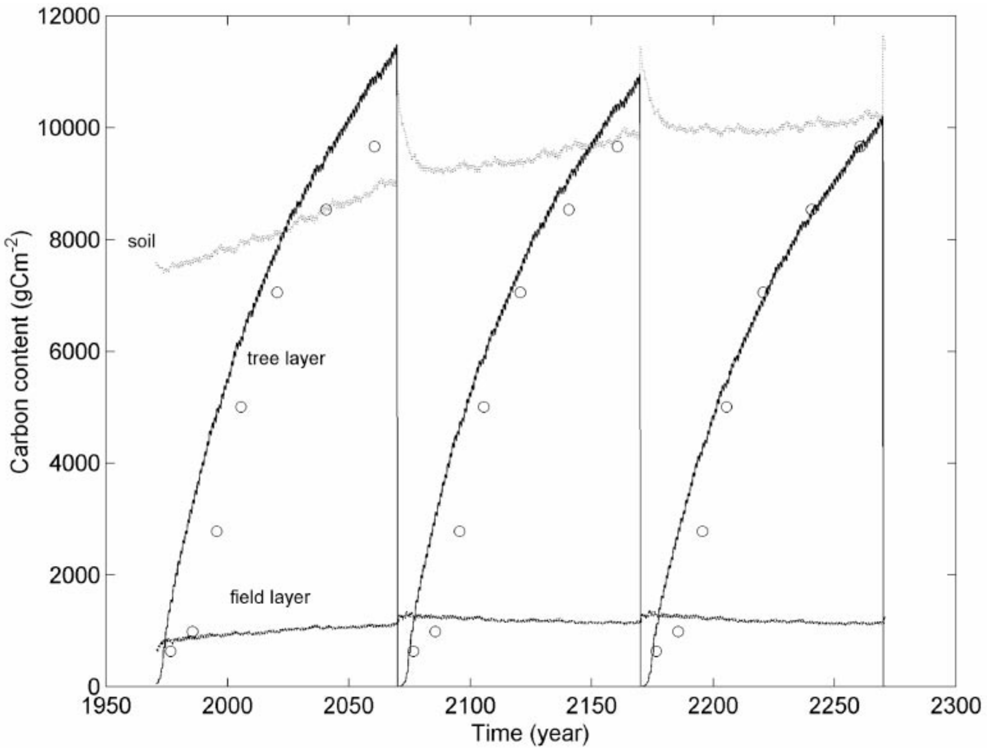

***Figure 4-5.** Simulated carbon storage in the tree (solid line) and field (dashed line) layer and in the soil (dotted line) during three consequtive 100-year rotation periods, compared to approximate stand development derived from tree volume of different age classes from the Uppsala region /Skogsdata, 2003/ and transformations according to /Marklund, 1988/.*

These figures indicate that the current simulations present a reasonable model of the long-term carbon and nitrogen turnover in the Forsmark forest, and might be used for the sensitivity analysis of the radionuclide model. However, the model do not account for any changes in allocation patterns with stand age. For instance, the net annual growth seems to be exaggerated in the early stages of tree development compared to the available reference data (Figure 4-6). This might be a result of for instance changed allocation patterns and plant morphology with age, but also responses to changed environmental conditions. It should be noted that the reference data used here also is a result of the forest management in the area. More detailed models of allocation pattern and morphology as function of age and environmental conditions are available in the literature and could be included in the model. However, the final ‘steady-state’ carbon budget will depend more on the nitrogen deposition (and fixation which is not represented in the model explicitly) and the average net growth (assimilation-respiration) than the distribution of carbon flows within the rotation time and between plant compartments.

Table 4-16. Simulated annual average carbon pools for forest sites with different soil moisture conditions at a stand age of 63 years (kg C m^{-2}), compared with the corresponding observations for the Forsmark area on average. Average annual increases for stand age 60–70 are given after the sum signs.

Compartment	Simulated (kg C m^{-2})	Observed (kg C m^{-2})
Tree layer (stem+needles+roots)	7.9 + .074	7.89*
Field layer (stem+needles+roots)	1.2 + 0	0.66**
Soil organic carbon (litter+humus)	10 + 0	

* Tree layer in old coniferous forest, ** other layers, average of Pinus and Picea forest

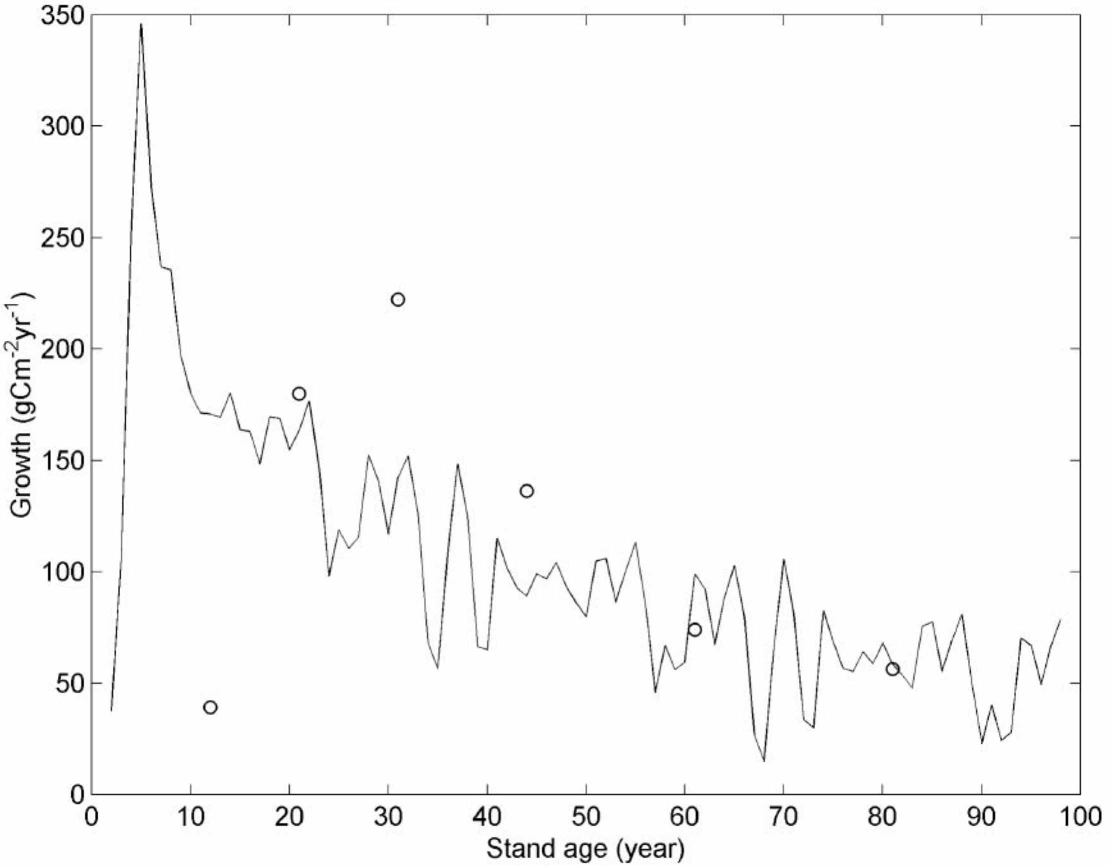

Figure 4-6. *Simulated annual change of carbon storage in the tree layer (solid line) compared to growth data derived from tree volume of different age classes from the Uppsala region /Skogsdata, 2003/ and transformations according to /Marklund, 1988/.*

4.2 The limnic ecosystem

4.2.1 Introduction

The limnic system includes both lakes and running waters. Lakes can be regarded as sedimentation traps, where accumulation of particles, nutrients and trace elements occur, and where biological processes such as primary production, consumption and respiration may have considerable impact on accumulation and transport of matter. Streams, on the other hand, may principally be regarded as transport routes, where deposition and accumulation of matter is of minor importance, and where biological processes of importance for accumulation of matter is insignificant. This simplified view of the limnic ecosystem will be used in this version of the Site Descriptive Model.

In the Forsmark area, the running waters are mainly made up by dug ditches. The water flow varies very much over the year, with high flow in spring and low flow during summer. During dry years, many streams may even be completely drained for long periods. There are, however, certainly processes which may affect turnover of nutrients and accumulation of matter also in streams. For example, due to the flat topography in Forsmark, wetland areas adjacent to streams will regularly be flooded during periods of high discharge. There may potentially be a significant accumulation of matter in such areas. No attempt has, however, been made to estimate the magnitude of such stream processes in this model version.

4.2.2 Conceptual model of the lake ecosystem

Habitats and functional groups

The lake ecosystem is usually divided into three major habitats or zones; the littoral, the pelagial and the profundal, which are described in detail in Section 3.8.2. In short, the bottom of the lake basin is separated from the free open water, the pelagial zone. The littoral zone covers the bottom area of the photic zone, while the remainder of the bottom, which consists of exposed fine sediments free of vegetation, is referred to as the profundal zone /Wetzel, 2001/ (Figure 4-7). The littoral zone can be further divided into a number of subhabitats. /Brunberg et al. 2004/ distinguished between three different littoral types; the Littoral Type I with emergent and floating-leaved vegetation, Type II with hard bottom substrate, and Type III with submerged vegetation (cf Section 3.8.2). As the lakes in the Forsmark area are so shallow, the water depth never exceeds the depth of the photic zone. This means that the profundal zone is lacking in the Forsmark lakes, and no areas of littoral hard bottom (Littoral Type II) is present either.

Primary producers

The major groups among primary producers in lakes in the Forsmark area are macrophytes, macroalgae (*Chara sp*), microphytobenthos, phytoplankton, and epiphytic algae. This grouping of primary producers has been used also in the quantitative model of the lake ecosystem.

In the littoral, both biomass and primary production is dominated by macrophytes. The macrophyte taxa that contribute most to the biomass in the littoral of Lake Eckarfjärden are *Phragmites australis* (reed) and *Typha sp* /Andersson et al. 2003/, and this has been assumed to be applicable for all lakes in the Forsmark area.

The benthic habitat of the Forsmark lakes consists almost exclusively of light-exposed soft-bottom, and the major part of lake primary production occurs in this habitat. The dominating primary producers in the benthic habitat are microphytobenthos (mainly cyanobacteria and diatoms /Blomqvist et al. 2002/), occurring in the microbial mat, and the macroalgae *Chara sp* Since *Chara* differ greatly from *P. australis* and *Typha sp* in terms of primary production, and in their assimilation of carbon from the water and not from the air, macroalgae has been treated separately from macrophytes in the carbon budget.

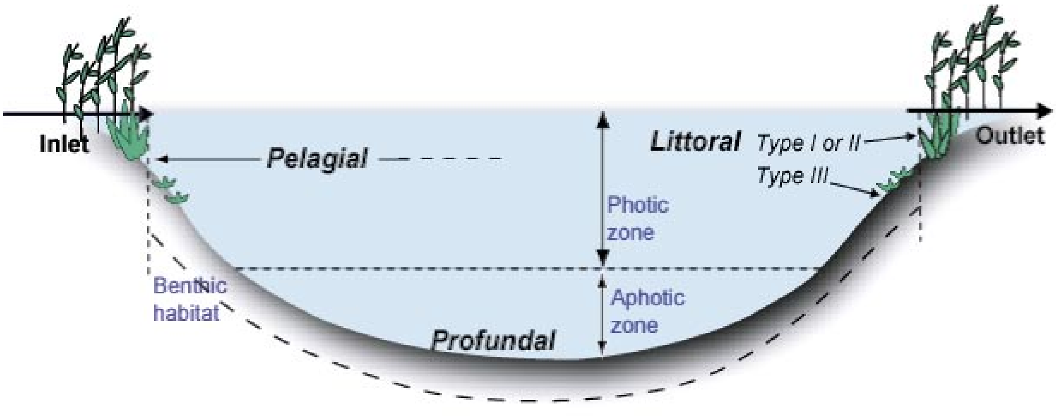

Figure 4-7. *Conceptual illustration of a lake ecosystem with the conventional division into littoral, pelagial and profundal habitats. In the quantitative modelling, the benthic habitat includes all bottom areas, except the littoral areas with emergent vegetation (Littoral Type I).*

The major taxonomic groups of phytoplankton in Lake Eckarfjärden are crysophyceae, cyanophyceae, dinophyceae and euglenophyceae /Blomqvist et al. 2002/. Half of the phytoplankton community consist of potentially mixotrophic species /Blomqvist et al. 2002/. The same taxonomic composition of phytoplankton was assumed to be valid for all lakes in the Forsmark area. The total biomass of all the taxonomic groups was used in the budget and model.

The fifth group of primary producers are the epiphytic algae, which are attached to the surfaces of macrophytes and *Chara*. No site-specific data describing the taxonomic composition or production/respiration of this plant group is available, and we therefore have to use literature data.

Consumers

Consumers include all heterotrophic organisms, i.e. herbivores, carnivores and detrivores. These are divided into four major taxonomic groups; bacteria, zooplankton, benthic fauna and fish.

The taxonomic composition of bacteria in the lakes is not known, and is not assumed to be of importance for the carbon budget calculations. Because bacteria occurring on different substrates are assumed to assimilate different carbon pools and be eaten at different rates, bacteria were divided into three groups, bacterioplankton, benthic bacteria and epiphytic bacteria.

The groups of zooplankton, benthic fauna and epiphytic fauna are all very heterogenous concerning organism size, life cycle and food choice. However, a higher level of detail was not assumed to be of importance for the carbon budget calculations, and therefore no further division has been used for these groups. Data concerning zooplankton and benthic fauna has been collected in Lake Eckarfjärden, whereas generic data was used for epiphytic fauna.

Fish are also very heterogeneous, especially concerning food choice, and fish data was therefore divided into the functional groups zooplanktivore fish (Z-fish), benthivore fish (M-fish) and piscivore fish (F-fish), according to /Holmgren and Appelberg, 2000/ (cf Section 3.8.3).

Food web relationships

All primary producers; macrophytes, *Chara*, microphytobenthos, phytoplankton and epiphytic algae utilize 100% of their carbon need as dissolved inorganic carbon (DIC). However, as the macrophytes are mainly made up of emergent species, they utilize DIC from the air and do not influence the DIC pool in the water. The group phytoplankton also includes mixotrophic plankton. These plankton can migrate vertically /Smayda, 1997/, and are thus capable to utilize both bacterioplankton and, at least to some extent, benthic bacteria.

Bacteria can assimilate both DOC (Dissolved Organic Carbon) and POC (Particulate Organic Carbon) and therefore bacterioplankton and epiphytic bacteria are assumed to consume DOC and POC in proportion to the occurrence of the two fractions in the water. Benthic bacteria, on the other hand, have access to a large POC pool and are assumed to consume only POC.

Zooplankton can consume bacterioplankton, phytoplankton and zooplankton. All bacterioplankton and phytoplankton are assumed to be available as a food source for zooplankton, whereas only 50% of the zooplankton is assumed to be available.

Benthic fauna is composed of functionally different groups, such as benthic filter feeders, detritus feeders, predators, scrapers and shredders, but these were in the budget calculations treated as one group. Benthic fauna is assumed to consume microphytobenthos, *Chara*, benthic bacteria, benthic fauna, bacterioplankton, phytoplankton, zooplankton and POC in proportion to the occurrence.

Fish feeding on zooplankton (Z-fish) are assumed to consume zooplankton, whereas POC and phytoplankton are assumed to be too small to be ingested by fish.

Fish feeding on benthic fauna (M-fish) are most probably feeding selectively. However, we have no data on food preferences, and therefore the M-fish are assumed to eat in proportion to the availability of the benthic fauna, epiphytic bacteria, epiphytic algae and epiphytic fauna, respectively.

Predatory fish (F-fish) are assumed to consume only fish. Most likely, the shift from other food sources to fish will not be complete, but in this budget/model it is assumed that all F-fish above a certain size are obligate piscivorous. Moreover, it is assumed that there are no preferences for any specific prey species or sizes, and the consumption is assumed to be in proportion to what is available in biomass of Z-, M- and F-fish.

4.2.3 Quantitative site specific model

Overview

In this section, quantitative ecosystem models for Lake Eckarfjärden and Lake Bolundsfjärden are described. These two lakes are the largest within the drainage area Forsmark 2. The drainage area contains totally nine other lakes/ponds, of which most are considerably smaller. The section starts with an account of the assumptions made in the development of the models, and then the models are presented, followed by a section where these two lakes are compared with each other and with the rest of the lakes in the drainage area. The section ends with a discussion about confidence and uncertainties.

Modelling assumptions

Distribution of organism groups

Bacterioplankton and plankton are assumed to be evenly present within the pelagial. Microphytobenthos, benthic bacteria and benthic fauna are assumed to be present over the whole lake area, except for in the reed belt (Littoral I). Macrophytes (mainly represented by reed) are assumed to occur in the whole area of Littoral I. Epiphytic algae, epiphytic bacteria and epiphytic fauna are assumed to be present in the reed belt on straws of *P. australis* and *Typha sp*, and it is assumed that these groups are present in the whole area of Littoral I. Literature data on epiphyte biomass per substrate area were converted to biomass per bottom area, based on site specific data on straw density in Lake Eckarfjärden (Andersson and Kumblad, unpubl). The calculated epiphyte biomass per area is used for all lakes in the Forsmark area. *Chara* covers 75% of Littoral III in Lake Eckarfjärden /Blomqvist et al. 2002/ and this coverage is assumed to be valid for all lakes in the drainage area Forsmark 2. Fish are assumed to be evenly distributed in the pelagial.

Biomass

The biomasses of bacterioplankton, phytoplankton, zooplankton, benthic bacteria, microphytobenthos and macrophytes have been measured in Lake Eckarfjärden only, and these biomasses have been used for budget calculations in the other lakes of the drainage area Forsmark 2. Biomass of benthic fauna has also been measured in Lake Eckarfjärden, but only on bottoms lacking *Chara*. These biomass values are used for *Chara*-free bottoms only, as it is known that the occurrence of benthic fauna usually is much higher on bottoms with vegetation. For areas covered with *Chara*, biomass values for the benthic fauna were taken from a study performed in the coastal area of Simpevarp /Fredriksson and Tobiasson, 2003/ since no data from the Forsmark area was available.

Fish has been sampled in both Lake Eckarfjärden and Lake Bolundsfjärden. The biomasses in these two lakes were roughly the same, but the proportion of carnivorous fish was lower in Lake Bolundsfjärden than in Lake Eckarfjärden. Since the other lakes in the drainage area Forsmark 2 are very shallow, it is assumed that a high proportion of the fish in these lakes will belong to species adapted to the low oxygen concentrations that will occur in shallow lakes during winter. The fish community in Lake Bolundsfjärden is more typical for such lakes, and therefore species composition and biomasses of fish from Lake Bolundsfjärden were used for the remaining lakes. Three of the lakes within the drainage area Forsmark 2 are so shallow (maximum depth is lower than 0.7 m) that we assume that no fish can live here. In two of these small lakes, pool frogs are known to breed which indicates that fish are lacking.

Literature values are used for biomasses of epiphytic algae /Meulemanns, 1988/ (oligotrophic lake), and epiphytic fauna /Ahlkrona et al. 1998/ (mesotrophic lake). The biomass of epiphytic bacteria is assumed to be equal to the biomass of epiphytic algae. Based on observations it can be concluded that the biomass of *Chara* in the Forsmark lakes is high, Since no quantification has been done, it is assumed that the *Chara* biomass is equal to the average value from several lakes reviewed in /Kufel and Kufel, 2002/. The biomass of *Chara* is reduced during winter, and therefore a lower biomass was used for the winter season in budget calculations.

Primary production

Net primary production of phytoplankton and microphytobenthos has been measured in Lake Eckarfjärden, and these values have been used for all lakes in the drainage area Forsmark 2. Macroalgae production is obtained from literature data /Pereya-Ramos, 1981/. The macrophyte production is assumed to be equal to the maximum biomass at the end of the summer. This may lead to an underestimation of the production, but the underestimation is probably less than 10% /Mason and Bryant, 1975/. The carbon used for macrophyte production is assumed to be obtained from the air. About half of the carbon fixed by macrophytes is assumed to decompose within the reed belt as this is dried out for large parts of the year. The remaining carbon was assumed to contribute to the POC compartment in the lake. Since no site specific data on epiphytes is available, epiphyte primary production was obtained from a study in an oligo-mesotrophic lake with similar straw density as in Lake Eckarfjärden /Meulemanns, 1988/.

All autotrophs excrete DOC during primary production. However, there are large variations in the amount of fixed carbon that is released as DOC from phytoplankton (5–80% /Kato and Stabel, 1984; Chranowski and Hubbard, 1989; Camarero et al. 1999/), from microphytobenthos (30–73% /Goto et al. 1999; Smith and Underwood, 2000/) and from macroalgae (a few percent up to 10% /Sorrell et al. 2001/). In this budget, the proportion of fixed carbon excreted as DOC from phytoplankton and epiphytic algae is assumed to be 40%, from microphytobenthos 60%, and from macroalgae 10%. The DOC release from the macrophytes during primary production is assumed to be negligible.

Respiration

Respiration of bacteria is assumed to be 3 times the bacterial production (measured as thymidine incorporations). Production of bacterioplankton and benthic bacteria was obtained from (Andersson and Brunberg, unpubl), and the production of epiphytic bacteria was obtained from /Meulemanns, 1988/. The respiration of the remaining consumers are calculated from site specific data on biomass, using conversion factors given in /Kautsky, 1995/ and measured temperature variation in Lake Eckarfjärden /Blomqvist et al. 2002; Andersson et al. 2003/.

Consumption

For bacteria, consumption is assumed to be the sum of bacterial production (thymidine incorporations) and calculated respiration (Andersson and Kumblad, unpubl). Consumption by other consumers is assumed to be 3 times the respiration, except for fish where the consumption is assumed to be 1.73 times the respiration.

Many species of zooplankton, benthic fauna and F-fish are to some extent cannibalistic or consume organisms belonging to the same functional group, and this has been accounted for in the budget calculations; half of the biomass of zooplankton was assumed to be available for consumption by other zooplankton, the total biomass of benthic fauna was assumed to be available for consumption by other benthic fauna, and the total biomass of F-fish was assumed to be available for consumption by F-fish.

Conversion factors

Data presented in other units than gC were converted with the aid of conversion factors given in /Kautsky, 1995/ (see Table 4-17).

Table 4-17. Conversion factors used to calculate biomass and respiration rates for various organism groups (compiled from /Kautsky, 1995/). The respiration conversion factors are valid for a temperature of 20 ºC. They were used together with temperature measurements from the lake /Blomqvist et al. 2002; Andersson et al. 2003/ to calculate the respiration, assuming a direct linear relationship between respiration and temperature.

Functional group	Biomass ($gdw \times gww^{-1}$)	Biomass ($gC \times gdw^{-1}$)	Respiration ($gC \times gC^{-1} \times day^{-1}$)
Pelagic habitat			
Zooplankton	–	–	0.115
Fish	0.200	0.492	0.033
Benthic habitat			
Benthic bacteria	–	–	0.069
Benthic filter feeders	0.222	0.196	0.028
Benthic detrivores	0.204	0.300	0.032
Benthic herbivores	0.154	0.251	0.029
Benthic carnivores	0.197	0.430	0.033
Littoral habitat			
Macrophytes	–	0.395	–
Epiphytic fauna	–	0.400	0.030

Transport of matter

To get a complete view of the carbon turnover in the lake ecosystem, knowledge about inflow and outflow of different carbon fractions, as well as sedimentation of organic matter, is needed. Measurements of particulate, dissolved and total organic carbon (POC, DOC and TOC) have been performed in the inlet as well as the outlet of Lake Eckarfjärden and Lake Bolundsfjärden. These data can be used to give an indication on whether the lakes act as sinks or sources of organic carbon on an annual basis.

For reliable calculations of the transport of matter, site specific discharge data is needed, in addition to the already available chemical measurements. Such data will be available in later model versions, and at the present we have to use the long term monthly averages for specific discharge at the hydrological station Vattholma /Larsson-McCann et al. 2002/ as an approximation for the site specific discharge. This assumption introduces a considerable amount of uncertainty into calculations of matter transport; however, calculations will give an indication on the magnitude of the transport of organic matter. Similarly, no data on sedimentation rates in Forsmark lakes is available. Preliminary measurements indicate an annual sedimentation rate in the deep part of Lake Eckarfjärden of 30 gC m^{-2} (Brunberg, unpubl), and for a rough estimation of the actual sedimentation in the larger lakes in the area, we assume a sedimentation rate in the whole area of the open water surface of 15 gC m^{-2} y^{-1}.

Ecosystem models for lakes in the Forsmark area

The ecosystem model for the Forsmark lakes is, as far as possible, based on the site specific data presented in Section 3.8. For those parameters where site specific data is missing, generic data available in the literature has been used. The data sources for different parameters in the model are compiled in Table 4-18. As mentioned previously, the main part of the site specific data available is from Lake Eckarfjärden. However, surface and volume info is available from all lakes in the area, whereas fish data is available from four of the larger lakes.

Table 4-18. Data sources used in the carbon budget calculations for Lake Eckarfjärden.

Budget parameter/parameter group	Site specific data	Generic data	References
Biomass per functional group			
Pelagic habitat			
Phytoplankton	X		Andersson et al. 2003
Bacterioplankton	X		Andersson et al. 2003
Zooplankton	X		Andersson et al. 2003
Fish (Z-, M- and C- fish)	X		Borgiel, 2004
Benthic habitat			
Macroalgae		X	Kufel and Kufel, 2002
Microphytobenthos	X		Andersson et al. 2003
Benthic bacteria	X		Andersson et al. 2003
Benthic fauna	X	X	Andersson et al. 2003; Fredriksson and Tobiasson, 2003
Littoral habitat			
Macrophytes	X		Andersson et al. 2003
Epiphytic algae		X	Meulemanns, 1998
Epiphytic bacteria		X	Assumed to have the same biomass as epiphytic algae
Epiphytic fauna		X	Ahlkrona et al. 1998
Production per functional group			
Pelagic habitat			
Phytoplankton	X		Andersson et al. 2003
Bacterioplankton	X		Andersson and Brunberg, submitted
Benthic habitat			
Macroalgae		X	Andersson and Kumblad, submitted
Microphytobenthos	X		Andersson et al. 2003
Benthic bacteria	X		Andersson and Brunberg, submitted
Littoral habitat			
Macrophytes		X	Andersson and Kumblad, submitted
Epiphytic algae		X	Meulemanns, 1998
Epiphytic bacteria		X	Meulemanns, 1988
Lake carbon pools	X		SICADA
Surface and volume info	X		Brunberg et al. 2004

Lake Eckarfjärden

Food web matrix

The consumption of different food sources for each functional group in Lake Eckarfjärden was obtained by first identifying the food web relationships between all groups in the system. Consumers were assumed to eat in proportion to what is available of their food item/prey (in biomass), and identified food web relationships (see Section 4-2), together with the availability of different food sources, was used to calculate the estimated proportions of different food sources for the functional groups in Lake Eckarfjärden (Table 4-19).

Table 4-19. Food web matrix, including estimated food proportions (based on the availability of different food sources), for Lake Eckarfjärden. Numbers in the matrix denote the estimated proportion of different food sources (columns) eaten by a given organism group (row).

	Phytoplankton	Microphytobenthos	Macro algae (Chara)	Macrophytes	Epiphytic algae	Epiphytic bacteria	Epiphytic fauna	Bacterioplankton	Zooplankton	Z-fish	M-fish	F-fish	Benthic bacteria	Benthic fauna	DOC	POC	DIC
Phytoplankton	■							0.33					0.17				0.49
Microphytobenthos		■															1.00
Macroalgae (Chara)			■														
Macrophytes				■													1.00
Epiphytic algae					■												1.00
Epiphytic bacteria						■									0.97	0.03	
Epiphytic fauna					0.50	0.50	■										
Bacterioplankton								■							0.97	0.03	
Zooplankton	0.33							0.42	■								
Z-fish									1.00	■							
M-fish					0.31	0.31	0.01				■			0.38			
F-fish										0.03	0.68	■					
Benthic bacteria													■			1.00	
Benthic fauna	0.00	0.20	0.49					0.00	0.00				0.20	■		0.04	

Carbon budget for Lake Eckarfjärden

Both production and biomass of primary producers in Lake Eckarfjärden is dominated by macrophytes (reed) and macroalgae (*Chara*), followed by microphytobenthos, whereas phytoplankton and epiphytic algae play a minor role (Table 4-20, Figure 4-8). Reed utilises DIC from the air and not from the water, and does accordingly not influence the DIC pool in the water. On the other hand, when decomposing, a relatively large part of the carbon incorporated into reed will probably be released to the pelagial as POC /Gessner et al. 1996/, contributing to the bacterial production and thereby influencing the carbon budget. The DIC pool in water is during most part of the year in contact with the pool in the air (as long as there is no ice on the lake) and a steady state situation is assumed. The size of this pool is therefore not of major interest and for this reason we have not calculated the DIC pool specifically.

Table 4-20. Biomass (gC) and annual metabolic rates (gC y^{-1}) of functional organism groups in Lake Eckarfjärden. Note that phytoplankton includes both autotrophic and mixotrophic species and hence this group shows primary production, as well as respiration and consumption.

Functional group	Biomass (gC)	Prod (gC y^{-1})	Cons (gC y^{-1})	Resp (gC y^{-1})	Supply[1] (gC y^{-1})	Graz. or pred[2] (gC y^{-1})	Excess[3] (gC y^{-1})
Pelagic habitat							
Phytoplankton	1.1E+04	4.8E+06	4.9E+06	2.5E+06	2.9E+06	2.4E+05	2.6E+06
Bacterioplankton	1.3E+04		1.7E+07	1.3E+07	3.5E+06	3.5E+06	8.3E+05
Zooplankton	1.7E+04		6.9E+05	2.3E+05	4.6E+05	2.5E+05	2.1E+05
Z-fish (zooplanktivore)	5.8E+03		5.5E+04	3.2E+04	2.3E+04	1.6E+04	7.0E+03
M-fish (benthivore)	1.5E+05		1.4E+06	8.3E+05	6.0E+05	4.2E+05	1.8E+05
F-fish (carnivore)	6.6E+04		6.2E+05	3.6E+05	2.6E+05	1.8E+05	7.9E+04
Benthic habitat							
Macroalgae	1.7E+06	2.0E+07			1.8E+07	1.5E+06	1.6E+07
Microphytobenthos	7.3E+05	1.0E+07			1.8E+07	0	1.8E+07
Benthic bacteria	7.0E+05		3.2E+07	2.4E+07	7.9E+06	2.3E+06	5.6E+06
Benthic fauna	2.1E+05		3.1E+06	1.0E+06	2.1E+06	3.8E+05	1.7E+06
Littoral habitat							
Macrophytes	2.8E+06	1.8E+07			1.8E+07	0	1.8E+07
Epiphytic algae	2.9E+04	1.3E+06			8.1E+05	1.6E+05	6.5E+05
Epiphytic bacteria	2.9E+04		9.0E+05	6.8E+05	2.3E+05	1.6E+05	6.5E+04
Epiphytic fauna	5.4E+02		7.1E+03	2.4E+03	4.8E+03	2.9E+03	1.9E+03
Lake total	**6.5E+06**	**5.4E+07**	**6.1E+07**	**4.3E+07**	**7.2E+07**	**9.2E+06**	**6.4E+07**
Lake carbon pools *gC*							
DOC	4.7E+06				1.1E+07	1.8E+07	–7.2E+06
POC	1.3E+05				5.0E+07	3.2E+07	1.7E+07

[1] Supply = For biota: consumption – respiration, for DOC: calculated from assumed DOC excretion by the different functional groups (see text for specification), for POC: excess from all functional groups.

[2] Grazing or predation upon the respective functional group/carbon pool.

[3] Excess = supply – grazing or predation.

Lake respiration is strongly dominated by bacteria, both benthic and pelagic, which together make up 87% of the total yearly respiration in the lake (Table 4-20, Figure 4-8). Accordingly, bacteria also make up the main part of the consumption in the lake (81%).

Carbon is transported to the top predator (F-fish) through two main pathways. One is through benthic bacteria to benthic fauna, to M-fish, and further to F-fish. The other pathway is through bacterioplankton to zooplankton (or through mixotrophic phytoplankton to zooplankton), to Z-fish and further to F-fish. The carbon budget indicates that the main part of carbon reaching F-fish goes through the first benthic pathway (Figure 4-9).

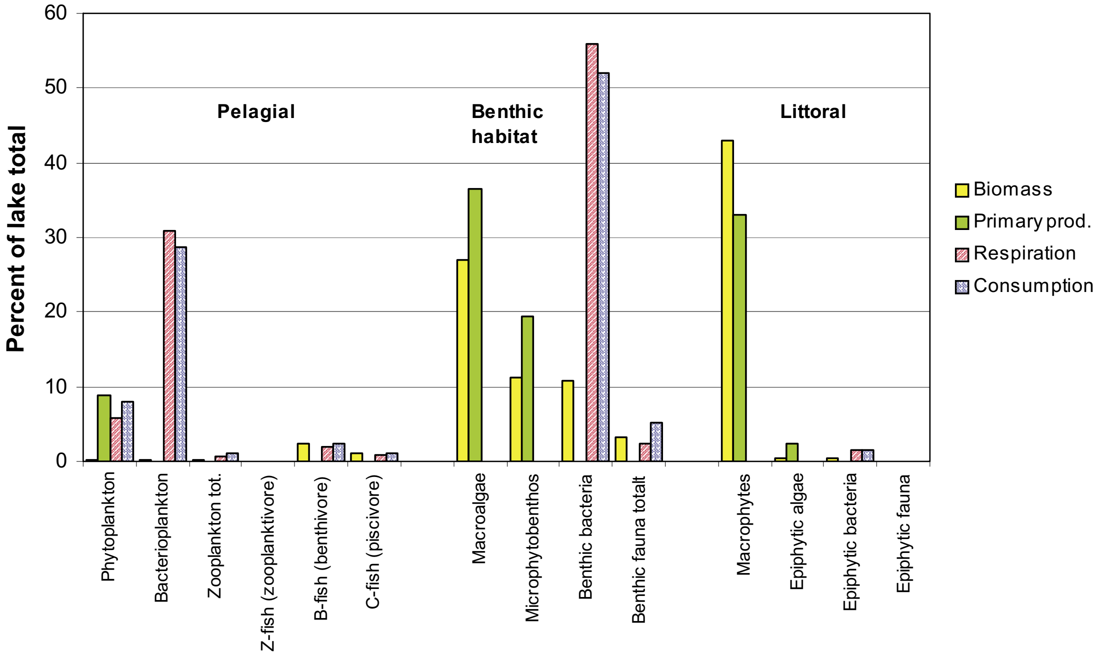

Figure 4-8. *Relative contribution of different functional groups to total biomass, primary production, respiration and consumption on a yearly basis in Lake Eckarfjärden.*

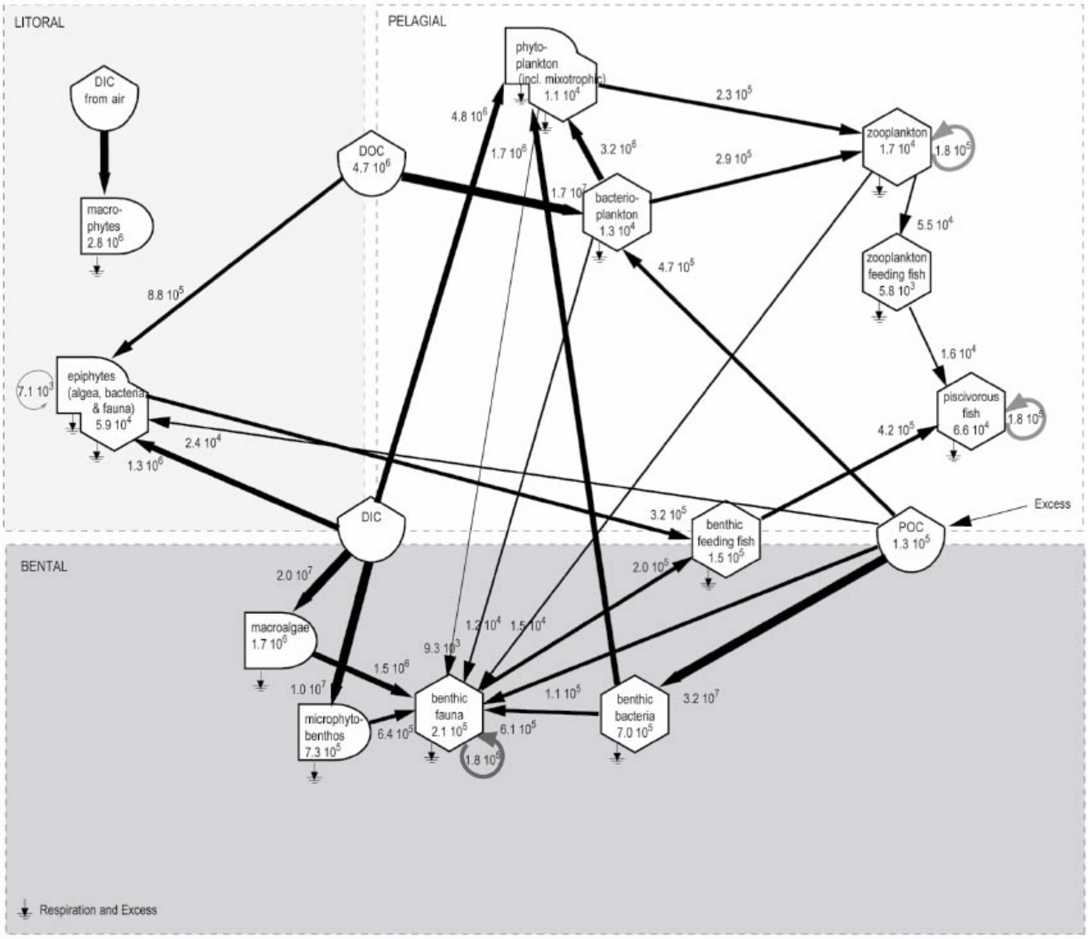

Figure 4-9. *Carbon budget for Lake Eckarfjärden. Arrow size indicates the magnitude of carbon flow between different functional groups. Since the biomasses of all epiphytic groups (algae, bacteria and fauna) are so small, they have been treated as a single epiphyte group in the figure.*

On an annual basis, all organism groups show a carbon excess when subtracting respiration and grazing from production/consumption. Since there is no increase in biomass over time, this excess carbon is assumed to contribute to the POC pool. Some of this POC will be incorporated into the sediments. However, the carbon budget indicates that total lake respiration on a yearly basis is of almost the same magnitude as total primary production (Table 4-20). According to the budget, there will be a deficit of DOC due to the large need by bacteria (both pelagic and epiphytic). Most likely, this situation will not occur since particulate organic carbon is continuously transformed into the dissolved form during the decomposition of POC by benthic and pelagic organisms. Accordingly, only a minor fraction of the POC excess will be permanently incorporated into the sediments. The assumed yearly sedimentation rate of 15 gC m^2 in the whole area of the pelagial, gives an estimated yearly sedimentation in Lake Eckarfjärden of 2.8×10^6 gC y^{-1}. According to the carbon budget, this sedimentation corresponds to about 16% of the estimated yearly POC excess in the lake.

Monthly mean values of organic carbon (TOC = Total Organic Carbon), measured in one of the inlets and in the outlet of Lake Eckarfjärden, indicate that the lake acts as a carbon source during the whole year (see Figure 4-10). By combining measured TOC concentrations with estimated specific discharge, the yearly net transport of carbon from Lake Eckarfjärden (amount of C transported from the lake minus amount of C transported to lake) is estimated to 3.0×10^6 gC y^{-1}, and the gross transport of carbon from the lake to 6.7×10^6 gC y^{-1}.

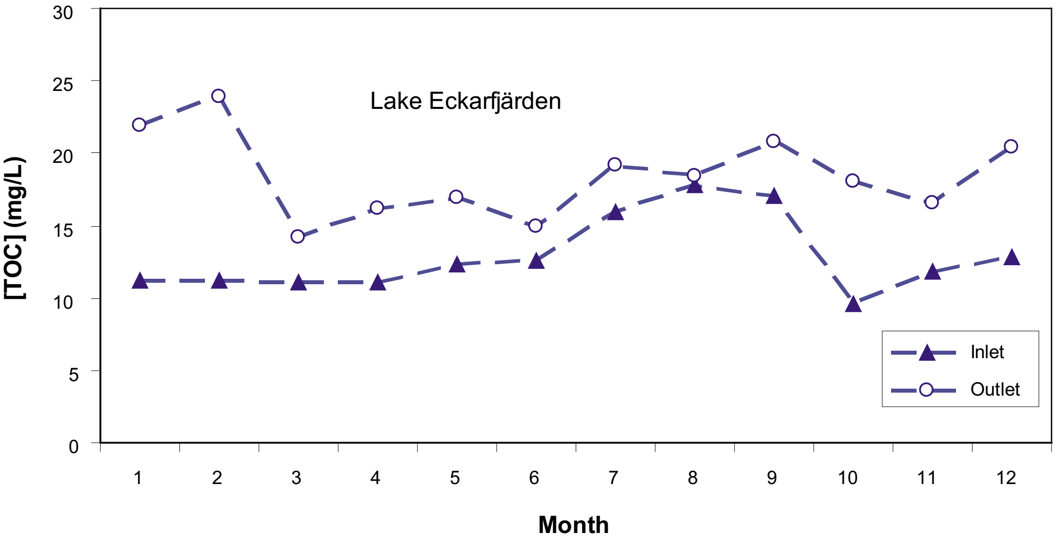

Figure 4-10. Monthly mean values for total organic carbon in the inlet and outlet of Lake Eckarfjärden, based on all sampling occasions during the period March 2002 to June 2004 (N varies between 2 and 6 for the different sampling sites/months).

Lake Bolundsfjärden

Food web matrix

The food web matrix for Lake Bolundsfjärden, calculated in a similar way as for Lake Eckarfjärden, is presented in Table 4-21. The estimated proportions of different food sources are principally the same in the two lakes; the only obvious differences are caused by the differences in the fish community between the two lakes, which were discussed in Section 3.8.

Table 4-21. Food web matrix, including estimated food proportions (based on the availability of different food sources), for Lake Bolundsfjärden. Numbers in the matrix denote the estimated proportion of different food sources (columns) eaten by a given organism group (row).

	Phytoplankton	Microphytobenthos	Macro algae (Chara)	Macrophytes	Epiphytic algae	Epiphytic bacteria	Epiphytic fauna	Bacterioplankton	Zooplankton	Z-fish	M-fish	F-fish	Benthic bacteria	Benthic fauna	DOC	POC	DIC
Phytoplankton	■							0.29					0.22				0.49
Microphytobenthos		■															1.00
Macroalgae (Chara)			■														1.00
Macrophytes				■													1.00
Epiphytic algae					■												1.00
Epiphytic bacteria						■									0.97	0.03	
Epiphytic fauna					0.50	0.50	■										
Bacterioplankton								■							0.97	0.03	
Zooplankton	0.33							0.42	■								
Z-fish									1.00	■							
M-fish					0.31	0.31	0.01				■			0.38			
F-fish										0.00	0.85	■					
Benthic bacteria													■			1.00	
Benthic fauna	0.00	0.21	0.50					0.00	0.00				0.20	■		0.03	

Carbon budget for Lake Bolundsfjärden

Since the relative areas of Littoral I and Littoral III in Lake Bolundsfjärden and Lake Eckarfjärden are almost identical, and since almost all of the site specific data that are used in the carbon budget for Lake Bolundsfjärden originates from measurements in Lake Eckarfjärden, there are no major differences in the carbon budgets between the two lakes. Similar to Lake Eckarfjärden, both production and biomass of primary producers in Lake Bolundsfjärden is dominated by macrophytes (reed) and macroalgae (*Chara*), while lake respiration and total consumption is strongly dominated by bacteria, both benthic and pelagic (Table 4-22, Figure 4-11).

By assuming the same sedimentation rate as for Lake Eckarfjärden (15 gC m^{-2} y^{-1} in the whole area of the pelagial), the annual sedimentation in Lake Bolundsfjärden is estimated to 6.1×10^6 gC y^{-1}. This corresponds to approximately 10% of the estimated annual POC excess in the carbon budget.

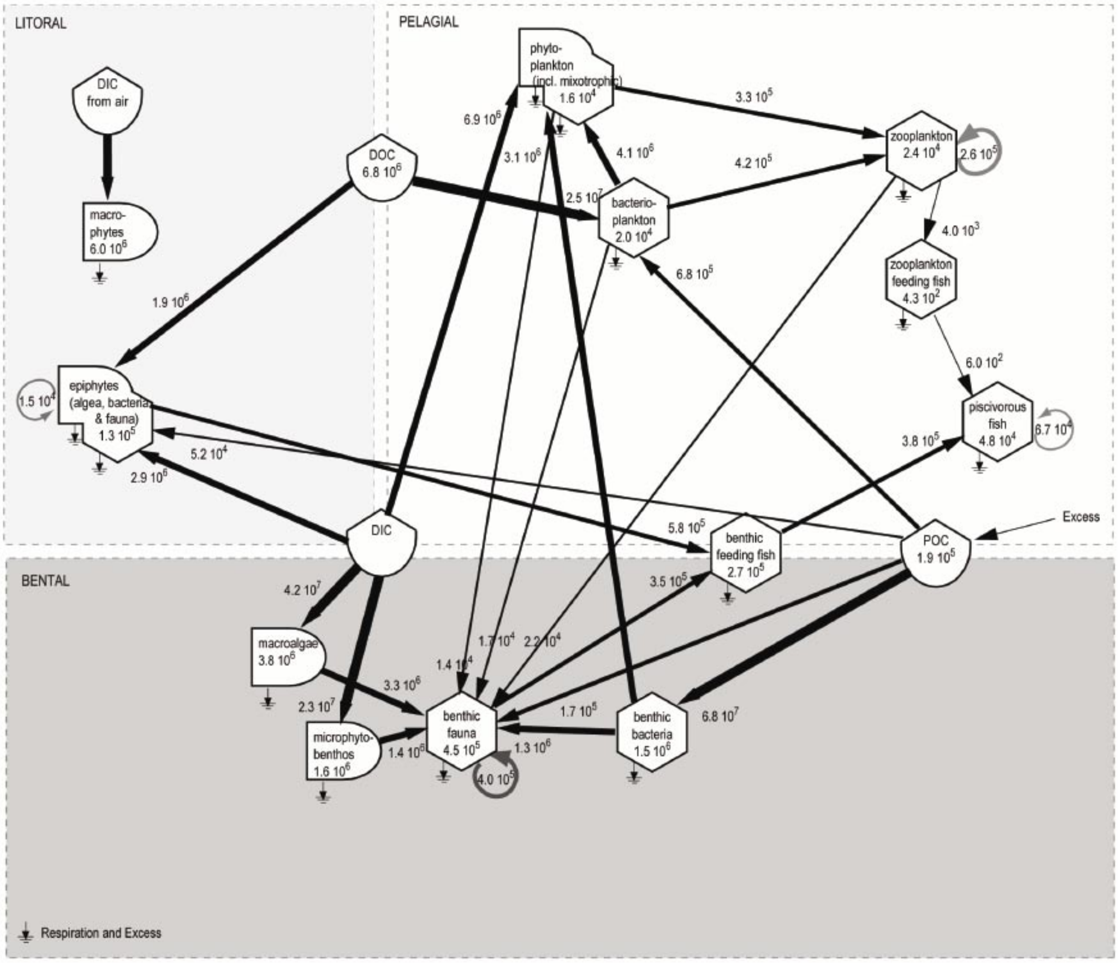

***Figure 4-11.** Carbon budget for Lake Bolundsfjärden. Arrow size indicates the magnitude of carbon flow between different functional groups. Since the biomasses of all epiphytic groups (algae, bacteria and fauna) are so small, they have been treated as a single epiphyte group in the picture.*

Despite the similarities in the carbon budgets of the two lakes, there seems, however, to be a principal difference in the carbon dynamics which is not revealed in the carbon budgets. While Lake Eckarfjärden constantly acts as a carbon source in a drainage area context, Lake Bolundsfjärden is a carbon sink during the main parts of the year (Figure 4-12). By combining measured TOC concentrations with estimated specific discharge, the annual net transport of carbon to Lake Bolundsfjärden (amount of C transported to the lake minus amount of C transported from lake) is estimated to 6.6×10^5 gC y^{-1}. The annual gross transport of carbon from the lake is estimated to 3.6×10^7 gC y^{-1}, and this figure can be viewed as a rough approximation of the total annual transport of carbon from the drainage area Forsmark 2 to the sea.

Table 4-22. Total average biomass (gC) and annual metabolic rates (gC y^{-1}) of functional organism groups in Lake Bolundsfjärden. Note that phytoplankton includes both autotrophic and mixotrophic species and hence has primary production as well as respiration and consumption.

Functional group	Biomass (gC)	Prod (gC y^{-1})	Cons (gC y^{-1})	Resp (gC y^{-1})	Supply[1] (gC y^{-1})	Graz. or pred.[2] (gC y^{-1})	Excess[3] (gC y^{-1})
Pelagic habitat							
Phytoplankton	1.5E+04	6.9E+06	7.2E+06	3.6E+06	6.9E+06	3.4E+05	6.6E+06
Bacterioplankton	2.0E+04		2.5E+07	1.9E+07	6.4E+06	4.5E+06	1.9E+06
Zooplankton	2.4E+04		1.0E+06	3.3E+05	6.7E+05	2.8E+05	3.6E+05
Z-fish (zooplanktivore)	4.3E+02		4.0E+03	2.3E+03	1.7E+03	6.0E+02	1.1E+03
M-fish (benthivore)	2.7E+05		2.6E+06	1.5E+06	1.1E+06	3.8E+05	7.1E+05
F-fish (carnivore)	4.8E+04		4.5E+05	2.6E+05	1.9E+05	6.7E+04	1.2E+05
Benthic habitat							
Macroalgae	3.8E+06	4.2E+07			4.2E+07	3.4E+06	4.0E+07
Microphytobenthos	1.6E+06	2.3E+07			2.2E+07	1.4E+06	2.1E+07
Benthic bacteria	1.5E+06		6.8E+07	5.1E+07	1.7E+07	4.4E+06	1.2E+07
Benthic fauna	4.5E+05		6.7E+06	2.2E+06	4.5E+06	7.5E+05	3.7E+06
Littoral habitat							
Macrophytes	6.0E+06	3.9E+07			3.9E+07	0	3.9E+07
Epiphytic algae	6.4E+04	2.9E+06			2.9E+06	3.0E+05	2.6E+06
Epiphytic bacteria	6.4E+04		2.0E+06	1.5E+06	4.9E+05	3.0E+05	1.9E+05
Epiphytic fauna	1.2E+03		1.5E+04	5.2E+03	1.0E+04	5.3E+03	5.05E+03
Lake total	**1.4E+07**	**1.1E+08**	**1.1E+08**	**7.9E+07**	**1.4E+08**	**1.6E+07**	**1.3E+08**
Lake carbon pools *gC*							
DOC	6.8E+06				2.2E+07	2.7E+07	–5.0E+06
POC	1.9E+05				1.3E+08	6.9E+07	5.9E+07

[1] Supply = For biota: consumption – respiration, for DOC: calculated from assumed DOC excretion by the different functional groups (see text for specification), for POC: excess from all functional groups.

[2] Grazing or predation upon the respective functional group/carbon pool.

[3] Excess = supply – grazing or predation.

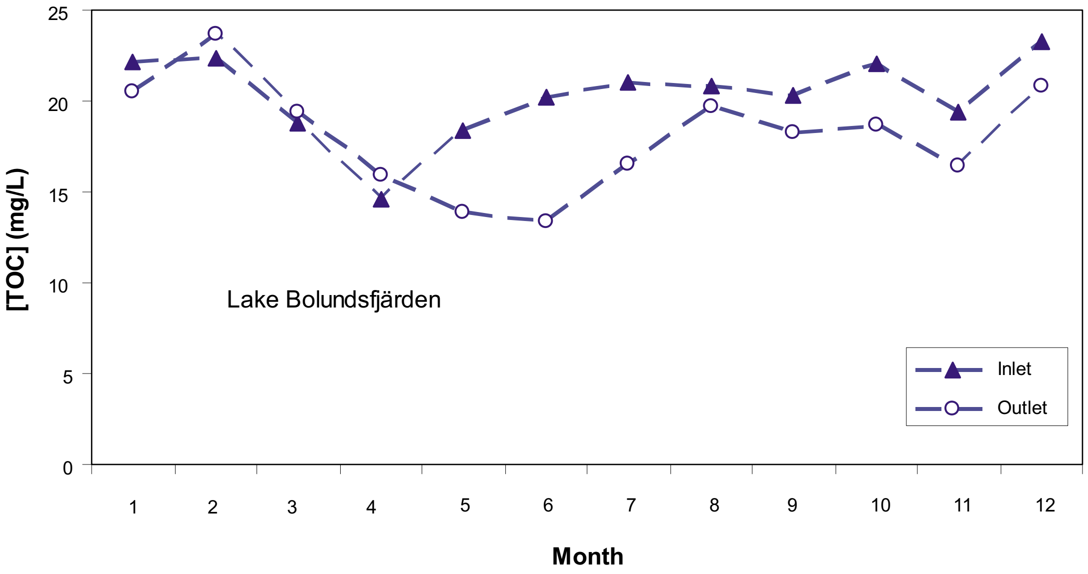

Figure 4-12. Monthly mean values for total organic carbon in the inlet and outlet of Lake Bolundsfjärden, based on all sampling occasions during the period March 2002 to June 2004 (N varies between 2 and 7 for the different sampling sites/months).

Overview of ecosystem models for all lakes in the drainage area Forsmark 2

The two carbon budgets presented above demonstrate the importance of the benthic and littoral habitats in the oligotrophic lakes in the Forsmark area (e.g. Figure 4-8). The major part of the biomass and primary production is clearly focused to these two habitats. Consumption and respiration is strongly focused to the benthic habitat, but in contrast to primary production, a large part of these processes occurs also in the pelagial while the littoral is unimportant.

There are strong interactions between habitats. The pelagial is mainly supported with carbon from the benthic habitat, but also from the littoral. The major flows of carbon originate from carbon fixed by macroalgae and microphytobenthos, which are further channelled up through the food web either by benthic herbivores, or by bacteria utilizing DOC exudates from the primary producers.

The carbon budgets of Lake Eckarfjärden and Lake Bolundsfjärden are very similar. This is not surprising since the only differences in input data are the areas of different habitats (the relative areas are the same though) and the lake specific fish data. Data on water chemistry suggest that the two lakes differ in carbon dynamics, in that Lake Eckarfjärden acts as a carbon source while Lake Bolundsfjärden acts as a carbon sink. At present, we have no explanation for this principal difference between the two lakes.

Compared to these two lakes, the other lakes/ponds in the drainage area are considerably smaller and shallower, and they are dominated by the reed belts in the littoral. For most of them, the reed belt (Littoral type I) constitute considerably more than 50% of total lake area, and in Lake Graven (which here represents the smaller lakes in the drainage area), the Littoral type I constitute 84% of total lake area. This means that the littoral habitat will play a more important role in Lake Graven compared to the two larger lakes, especially concerning biomass and production, while the importance of the benthic habitat and the pelagial will be reduced (Figure 4-13). Similar to the larger lakes, lake respiration in Lake Graven is strongly dominated by bacteria. In Lake Eckarfjärden and Lake Bolundsfjärden benthic bacteria make up about 2/3 of the respiration as well as the consumption, whereas bacterioplankton stands for the smaller part (1/3). In Lake Graven, bacterioplankton can be ascribed about half of the respiration and consumption, whereas benthic bacteria are of minor importance. Instead, epiphytic bacteria in the reed belt make up a large part of the respiration and consumption.

Also in the smaller lakes, all organism groups show a carbon excess on an annual basis. However, while primary production and respiration in the larger lakes are in the same order of magnitude, the carbon budget for Lake Graven indicates that primary production is about 10 times higher than the respiration. This will most probably lead to an increased accumulation of carbon in the smaller lakes, since there is no reason to assume that all of this excess carbon will be transported out of the lake. The smaller lakes in the area are therefore assumed to have reached a stage where the rate of succession from lake to wetland accelerates.

Confidence and uncertainties

The lake carbon budgets in this study are mainly based on site specific data from extensive studies in Lake Eckarfjärden. Since the biomasses of most functional groups, as well as many of important ecosystem processes, have been measured in directly the lake, and since missing data was estimated from studies in lakes similar to Lake Eckarfjärden, the uncertainties in estimated stocks and flows of carbon can be considered small. This makes the confidence of the carbon budget relatively high, although some uncertainties of course exist.

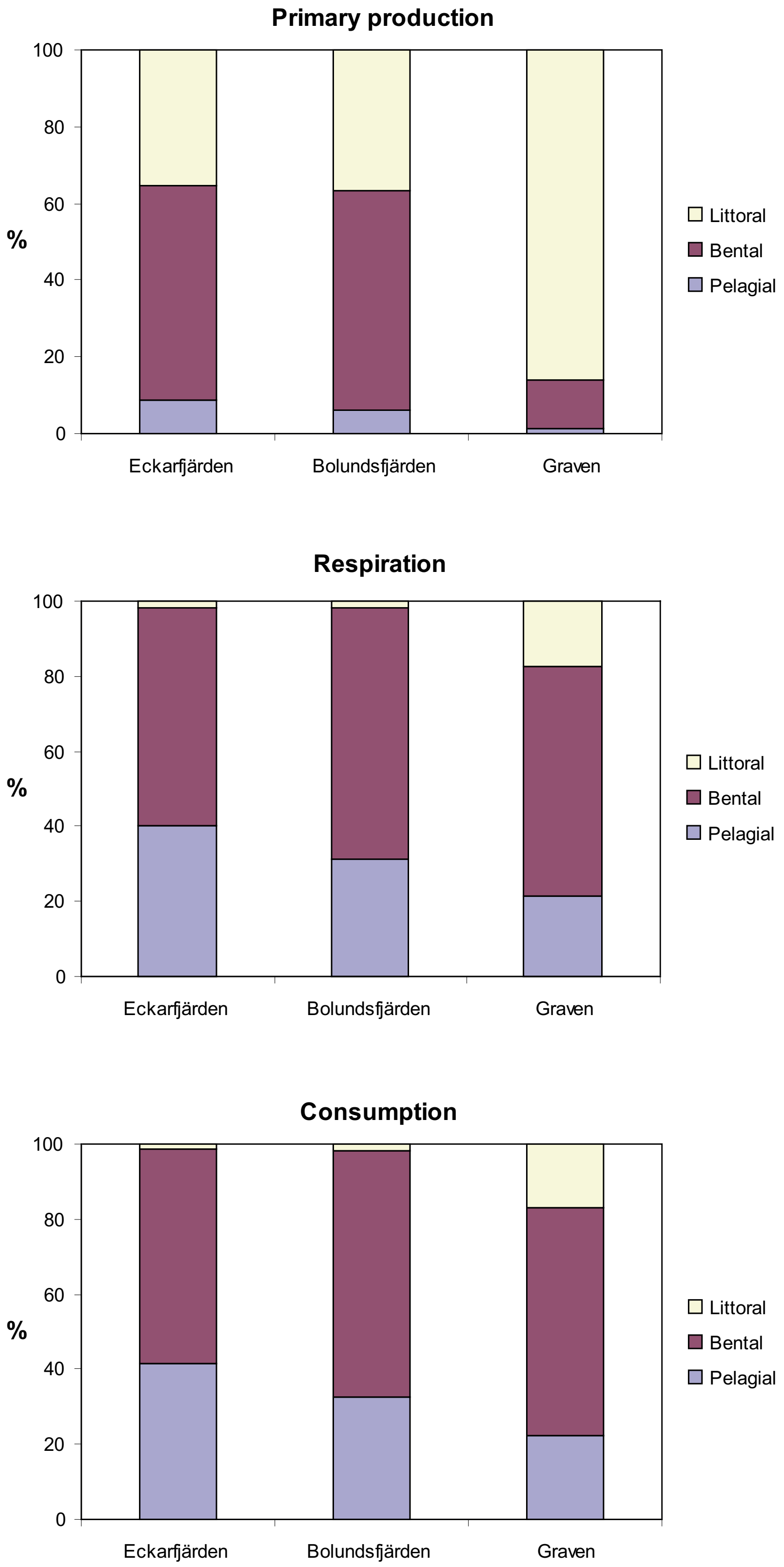

Figure 4-13. *The relative importance of different processes (primary production, respiration and consumption) in the different habitats (littoral, benthic and pelagial habitat) of Lake Eckarfjärden, Lake Bolundsfjärden (relatively large lakes with large areas of open water) and Lake Graven (a small lake, dominated by areas of emergent vegetation and with only minor parts of open water).*

Generic data were used for biomass and production of *Chara* and epiphytic algae, bacteria and fauna. The magnitude of these parameters may therefore be over- or underestimated. Concerning *Chara* it is likely that the two parameters have been underestimated, since observation by eye implies that the biomass is very high and the used literature value is the average biomass from several studies /Kufel and Kufel, 2002/. The used rate of primary production for *Chara spp*. /Perera-Ramos, 1981/ was also chosen from the low end of reported studies /Kufel and Kufel, 2002/.

Due to a small area available for colonisation by epiphytic algae, this functional group contributes little to the total primary production. The small substrate area is a consequence of that a large part of the reed belt is above the water surface during the summer. The estimates used for primary production by epiphytic algae per substrate area of *P. australis* /Muelemanns, 1988/ was about 10 times higher than productivity estimates reported by e.g. /Gessner et al. 1996/, but in the same order of magnitude as reported by /Allen and Oscevski, 1981/. However, because of the small area available for colonisation by epiphytes, a possible overestimation should have minor effects on the overall budget.

Fish data is collected by standardized and generally accepted methods. However, the generated data is only semi-quantitative. The conversion of catch per unit effort (CPUE) data to an absolute estimate of biomass per area unit is associated with large uncertainties. To our knowledge, no study exists to validate any conversion factor, and the proposed conversion factor which is used in this report may be regarded as an "expert guess".

The estimated net and gross transport of carbon from the lakes is of course associated with large uncertainties since site specific chemistry data has to be coupled with regional discharge data. This uncertainty will however be considerably reduced in coming model version, when site specific discharge data is available. Similarly, the values of annual sedimentation in Lake Eckarfjärden and Bolundsfjärden are associated with large uncertainties and the calculations should be regarded as an attempt to obtain rough estimate of the magnitude of sedimentation.

4.3 The marine ecosystem

The coastal ecosystems are the most productive parts of the marine environment and have often been regarded as an important filter and transition zone of organic matter and nutrients discharged from land. The marine ecosystem in Forsmark has a varied bathymetry, with a few enclosed bays clearly affected by fresh water effluence, a shallow but exposed archipelago and open sea areas heavily exposed to currents and wave action. As a result, elements discharged into the marine environment from the adjacent terrestrial and limnic environments will have a different fate depending on where they enter the marine system.

The Forsmark marine ecosystem has been divided into seven basins, shown in Figure 4-14. Two of these basins, Basin Stånggrundsfjärden and Basin SAFE-area, are described below, as these two are basins receive the main discharge from the drainage area Bolundsfjärden. The basins are parts of the marine environment, but are bathymetrically separated from each other. The basins have in the descriptions been treated as separate units, based on the assumption that relevant flow of carbon will be greater within the basins than between the basins. The flows of carbon between the basins are possible to quantify either with estimations of abiotic carbon flows (runoff and oceanographic flows) or biotic flows (i.e. migration of organisms).

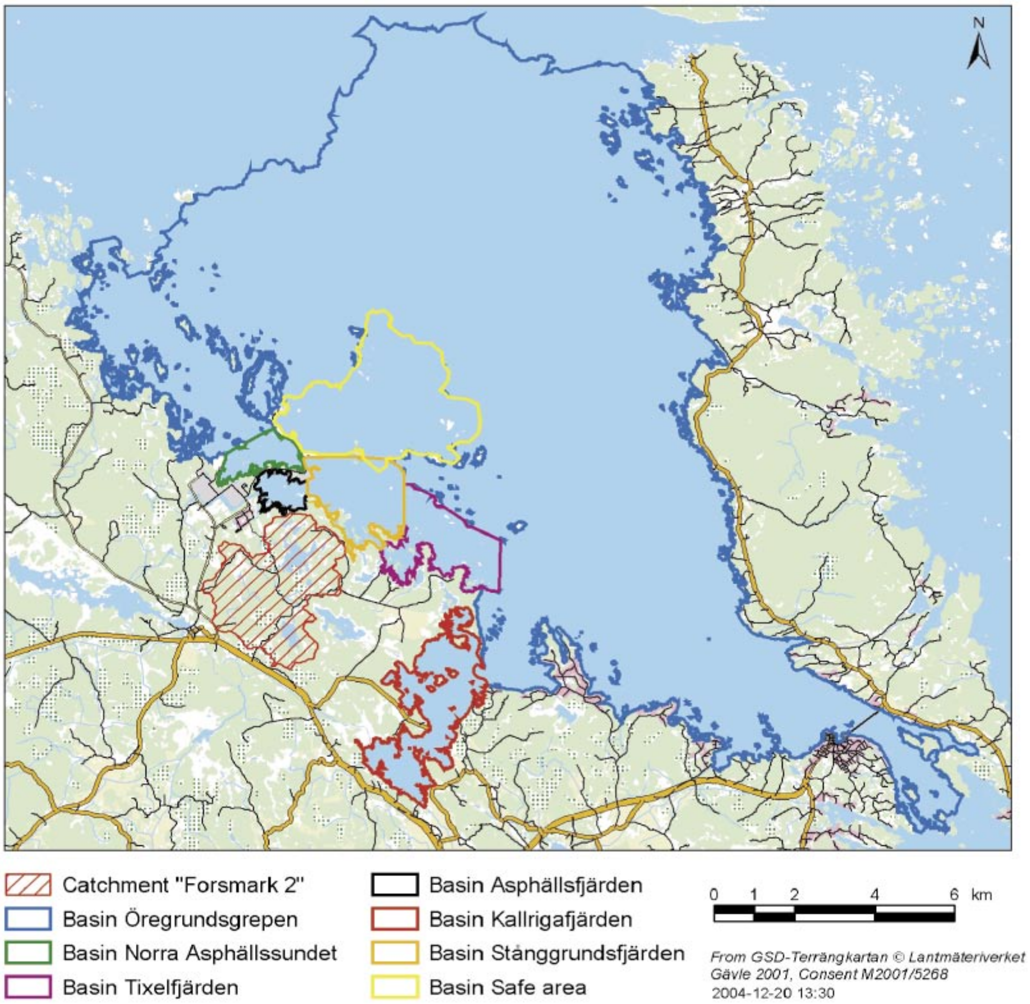

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Figure 4-14. *The basins in the marine ecosystem in Forsmark.*

4.3.1 Conceptual model of the marine ecosystem

Habitats and functional groups

Habitats

In Figure 4-15 the habitats of the marine ecosystem is illustrated. The phytobenthic habitat was defined to be the benthic habitat in the photic zone, the soft bottom habitat the benthic habitat in the aphotic zone and the pelagic habitat the open water habitat, both photic and aphotic.

The modelled basins in the Forsmark area were assumed to have the same structure in terms of habitat distribution. Thus, the basins differ from each other mainly in terms of total area, surface areas for each habitat and volumes as a result of different light penetration depths and bathymetry.

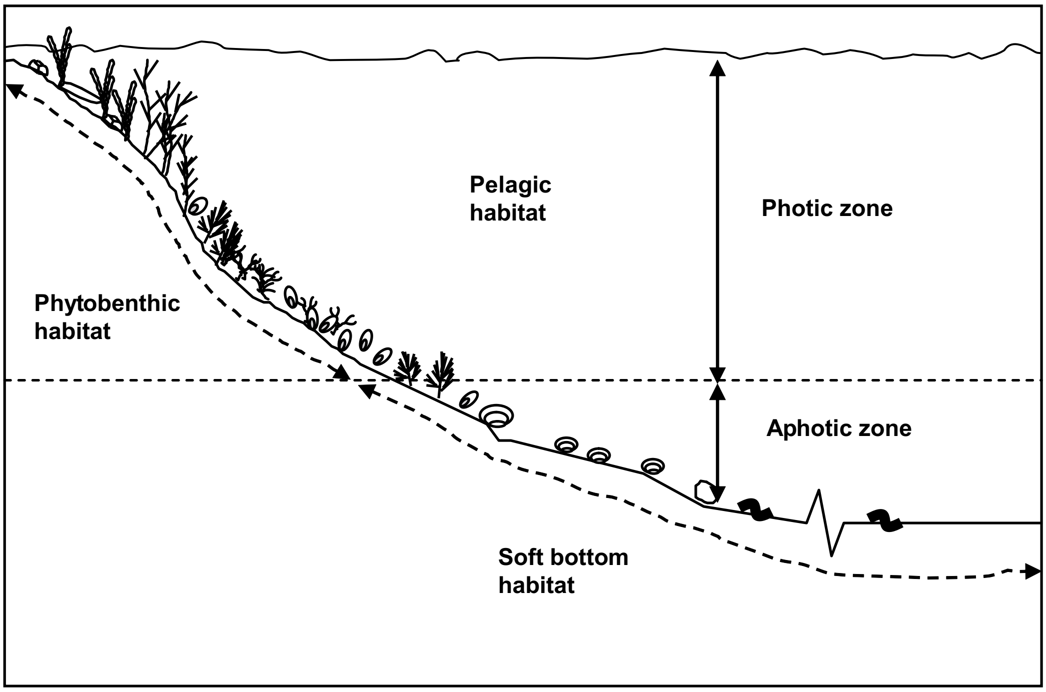


Figure 4-15. Conceptual figure of the marine coastal ecosystem in Forsmark including illustrations of the habitats (phytobenthic, soft bottom and pelagic).

Functional groups – Primary producers

The major groups among primary producers in the Forsmark area are macrophytes (including macroalgae), microphytobenthos and phytoplankton (cf Section 3.9). This grouping of primary producers has also been used in the quantitative model of the marine ecosystem.

In the phytobenthic habitat, both biomass and primary production is dominated by macrophytes. The macrophyte taxa that contribute most to the biomass in the benthic community in Forsmark are the red algae *Polysiphonia nigrescens*, the brown algae *Fucus vesiculosus* and *Sphacelaria arctica* and the vascular plant *Potamogeton filiformis* /Kautsky et al. 1999/. Epiphytic primary producers, i.e. algae that are attached to the surfaces of macrophytes, have been assumed to be already included in the macroalgae data. In the same habitat also microphytobenthos are present. This organism group is in Baltic systems often important both in terms of biomass and primary production. In the Forsmark area the microphytobenthos is mainly composed of various diatom species.

Phytoplankton is the only primary producing organism group in the pelagic habitat and are in Forsmark strongly dominated by diatoms and dinoflagellates during springtime, and blue-green algae and small flagellates during summer and autumn /Lindahl and Wallström, 1980/.

Functional groups – Consumers

The functional group consumers include all heterotrophic organisms, i.e. herbivores, carnivores and detrivores, and these are in the quantitative model divided into the major groups; bacterioplankton, zooplankton, fish (zooplankton feeding, benthic feeding and carnivorous), benthic herbivores, benthic filter feeders, benthic detrivores (including meiofauna), benthic carnivores, benthic bacteria, birds and seals.

Bacteria have an important role in the mineralization process of dead organic material and the recirculation of nutrients. The species composition of the bacteria is not known and is assumed to not be of importance for the budget calculations in this study. Because bacteria on different substrate are assumed to assimilate carbon from different pools and be predated at different rates, bacteria were divided into two groups, pelagic bacteria (bacterioplankton) and benthic bacteria. None of these organism groups have been studied in the Forsmark area and therefore have data from elsewhere been used. For the pelagic bacteria data from /Kuparinnen, 1987/ were used and for the benthic bacteria data from /Mohammadi et al. 1993/.

The group zooplankton is a very heterogeneous group with respect to organism size, life cycle and food choice. However, in this budget the zooplankton has been treated as one homogenous group and a higher level of detail was assumed to not be of importance for the carbon budget calculations.

Fish, on the other hand, was divided into the functional groups zooplanktivorous fish (zooplankton feeding fish), bentivorous fish (benthic fauna feeding fish) and piscivorous fish (carnivorous or predatory fish). It was assumed that 75% of the total fish biomass was zooplankton feeding fish, 20% was benthic feeding fish and 5% was carnivorous fish. This assumption was based both on the species distribution in Öregrundsgrepen reported /by Neuman, 1982/ and on former modelling analyses performed in basin SAFE-area which concluded that this distribution was feasible with regard to the available sources /Kumblad and Kautsky, 2004/.

The macrofauna grazing on the macrophytes (i.e. benthic herbivores) were dominated by herbivorous gastropods, e.g. *Theodoxus fluviatilis*, and herbivore and omnivore crustaceans, such as *Gammarus spp*. and *Idothea spp*. Omnivores living the phytobenthic community were assumed to also belong to the benthic herbivores, although they not solely consume plant material. This is a simplification but probably not influence the budget to any larger extent.

The remaining benthic macrofauna species present in the area were classified into filter feeders, detrivores or carnivores due to their main food preferences. The filter feeders in this area were dominated by the bivalve *Cardium spp*. (by biomass), the detrivores by the facultative filter feeding and detrivorous bivalve *Macoma baltica* and the carnivores by the crustacean *Mesidothea enthomon*. To the detrivores, also benthic meiofauna has been included since this group often are dominated by nematodes and zooplankton species which often are detrivorous and sediment dwelling species. Meiofauna has not been studied quantitatively in the Forsmark area. Instead data from a survey by /Ankar, 1977/ performed in the Askö archipelago was used in the budget calculations.

Although there has been an extensive bird investigation in the terrestrial part of the modelling area describing e.g. the amount of bird species and territories, abundance of terrestrial birds along transects and in certain areas /Green, 2003, 2004/, birds have been excluded in this budget. This was because the abundance of the waterfowl was not included in the bird study and it was therefore difficult to use the presented data. However, quantitative seabird studies are currently being performed and will thus be included in later versions of this report.

Seals are seldom found in the Forsmark area but are occasionally seen in the region. In the calculations in this study estimates on one individual seal have been performed to give an overview of the possible consumption of seals and the potential interactions with the system. The data used for seal originate from the Natural Museum of History in Stockholm (Roos, 2000, pers comm).

Food web relationships

The assumed distribution of consumption pattern from various food sources are shown in Table 4-23. The consumption of different food sources were estimated by identifying the food web relationships between the functional groups in the system and calculating the demand of food (total consumption) by each consumer. For the consumers that consume more than one food source/prey it was assumed that they eat in proportion to what was available of their food source (in biomass).

All primary producers, i.e. macrophytes, microphytobenthos and phytoplankton, were assumed to assimilate 100% of their carbon from the dissolved inorganic carbon pool in the water (DIC).

Bacteria can assimilate both Dissolved Organic Carbon (DOC) and Particular Organic Carbon (POC). However, in the budget the bacteria were assumed to only consume POC since the availability of POC is much larger than DOC in marine waters.

Zooplankton was assumed to consume both bacterioplankton and phytoplankton in proportion to their availability.

Benthic herbivores were assumed to consume macrophytes and microphytobenthos, and the benthic filter feeders POC, phytoplankton, bacterioplankton and zooplankton. The benthic detrivores were assumed to consume POC and benthic bacteria, and the benthic carnivores the other benthic fauna groups, i.e. benthic herbivores, filter feeders and detrivores.

Table 4-23. Food web matrix (food web relationships) used in the ecosystem model of the Forsmark area.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1. Phytoplankton																		x	
2. Microphytes																		x	
3. Macrophytes																		x	
4. Bacterioplankton																			x
5. Zooplankton	x			x															
6. Zooplankton feeding fish					x														
7. Benthic fauna feeding fish									x	x	x	x							
8. Carnivorous fish						x	x	x											
9. Benthic herbivores		x	x																
10. Benthic filter feeders	x			x	x														x
11. Benthic detrivores													x						x
12. Benthic carnivores									x	x	x								
13. Benthic bacteria																			x
14. Fish feeding birds						x	x	x											
15. Benthic feeding birds			x						x	x	x	x							
16. Seals						x	x	x											
17. Humans						x	x	x											
18. DIC																			
19. POC																			

Zooplankton feeding fish were assumed to consume zooplankton whereas POC, phytoplankton and bacterioplankton were assumed to be too small to be ingested. Fish feeding on benthic fauna (benthic fauna feeding fish) are most probably selective. We have no detailed information on this, and therefore the benthic feeding fish were assumed to consume in proportion to what was available of the benthic fauna (benthic herbivores, filter feeders, detrivores and carnivores). Carnivorous fish were assumed to eat only fish. Most likely, the shift from other food sources to fish will not be complete but was assumed so in this budget.

4.3.2 Quantitative site specific model

In this section the quantitative models of Basin Stånggrundsfjärden and Basin SAFE-area in the Forsmark area is described. First the modelling assumptions related to habitat preferences and occurrence of the functional groups, to biomass estimates, calculation of primary production, respiration and consumption, and the used conversion factors are presented. Then a quantitative carbon flow model for each basin is illustrated.

Basin Stånggrundsfjärden and Basin SAFE-area were chosen as examples of site-specific models representative for the area. Furthermore, these two basins are recipients of the Bolundsfjärdens catchment area (Forsmark catchment 2).

Modelling assumptions

General

Surface areas for the basins were calculated with GIS by using the shoreline from the map data from Metria. The two dimensional area was assumed to be approximately the same as the actual bottom area. For the Basins Stångholmsfjärden and SAFE-area presented below both the area above and below the photic zone has been presented.

The water volume of the basins (photic and aphotic) was calculated as the average water depth multiplied by the surface area. The photic volume was calculated as the total volume minus the volume in the aphotic zone.

Carbon transport to and from the basins were based on modelled oceanographic water movement (retention time), see Section 3.5, and fresh water discharge from land, multiplied with the carbon content in the water from measurements in field during 2002–2003 /Nilsson et al. 2003/.

Habitat preferences and occurrence

Phytoplankton was assumed to be evenly present in the photic zone of the pelagic habitat whereas zooplankton and bacterioplankton were assumed to be present in the whole water column. The benthic area in the photic zone was assumed to be occupied by macrophytes, microphytobenthos and benthic herbivores. In the aphotic zone of the benthic habitat the remaining benthic macrofauna were assumed to reside. The benthic bacteria and benthic filter feeders were assumed to be present at all depth of the seabed. Fish was assumed to be present within the whole pelagial.

Biomass

Biomasses of phytoplankton, zooplankton, microphytobenthos, macrophytes, and benthic macrofauna (i.e. benthic herbivores, benthic filter feeders, detrivores and carnivores) have been measured at various locations in the marine area in Forsmark (cf Section 3.9). These biomasses have been used for budget calculations for both Basin Stångholmsfjärden and Basin SAFE-area.

For bacteria in the system biomass data from /Kuparinnen, 1987; Mohammadi et al. 1993/ were used for pelagic and benthic bacteria, respectively. Fish biomass data were not available from the Forsmark area. Instead, biomass data from a diving survey performed in the northern Baltic proper (including 33 species, 0–20 m depth) by /Jansson et al. 1985/ were used. From the species distribution reported from the Forsmark area /Neuman, 1982/ the total biomass was estimated from biomass data per length and species presented in /Jansson et al. 1985/.

Primary production

Values of primary production of phytoplankton measured in Öregrundsgrepen /Lindahl and Wallström, 1980/ were used in both basins in combination with biomass data from /Huononen and Borgiel, 2005/ (cf Section 3.9). Macroalgae primary production was estimated by calculations from the biomass data and species-specific conversion factors /Wallentinus, 1978; Gutenstam, 1979; Kautsky, 1995/ and the insolation during the year (SKB, HMS database). The epiphyte primary production was assumed to be included in the macrophyte production.

Respiration

The respiration was for the major part of the functional fauna groups (zooplankton, fish, benthic herbivores, filter feeders, detrivores carnivores and benthic bacteria) calculated from the biomass with the aid of species-specific conversion factors /Jansson et al. 1982; Ankar and Elmgren, 1976; Schneider, 1990; Kautsky, 1995/ and the temperature during the year (SKB, HMS database). The bacterioplankton respiration was obtained from filed measurement performed by /Kuparinnen, 1987/. The plant respiration was assumed to be zero since both the measured and calculated primary production was the net primary production (i.e. the gross primary production subtracted by the respiration). The respiration was calculated as daily respiration multiplied by normalized degree days over the year (2400) /Kautsky, 1995/.

Consumption

The consumption of bacteria was assumed to be two times the calculated respiration. The consumption of the remaining consumers was assumed to be three times the respiration /Elmgren, 1984/, except for fish where the consumption was assumed to be 1.73 times the respiration.

Predatory fish consume to some extent organisms from their own taxonomic group, and this has been accounted for in the budget calculations. The total biomass of predatory fish was assumed to be available for consumption by themselves. However, since the other fish groups have higher biomass than the carnivorous fish, they just consume about 5% of themselves.

Dissolved inorganic carbon (DIC) and particulate organic carbon (POC)

The abiotic carbon pools were calculated using average concentrations described elsewhere in this report (Section 3.8) and basin volumes. The inflows of abiotic carbon from runoff were calculated by using average concentrations of the dominating water course and modelled runoff (see Section 3.8). The inflow of abiotic carbon from water exchange with other sea basins were calculated using average basin concentrations of carbon and yearly water exchange. Water exchange was calculated using the Average Transit Residence (ATR) time according to (Equation 4-2).

$$waterexchange = \left(V \bullet \frac{365}{ATR} \right) - runoff \qquad \text{(Equation 4-2)}$$

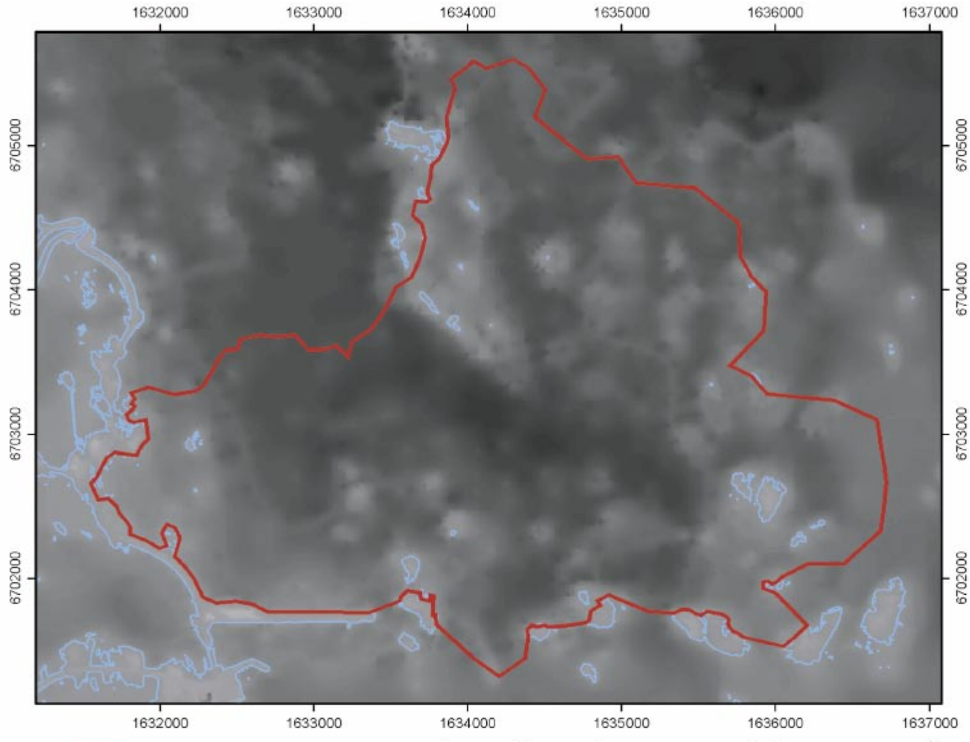
where V is basin volume.

Conversion factors

Except for the conversion factors described for the calculations of primary production and respiration from biomass data, conversion factors compiled by /Kautsky, 1995/ have been used to convert biomass data (dry weight or wet weight) into carbon (gC).

Ecosystem model for Basin SAFE-area

The Basin SAFE-area in Forsmark is located just above the SFR-1 repository (Figure 4-16) and has a total surface area of 11.5 km^2 and water volume of 0.11 km^3 (Table 4-24). The maximum depth in this basin is about 19 m, the average depth 10 m and light penetration depth is about 7.6 m /Nilsson et al. 2003/. Approximately 2.5% of the surface area of the basin is occupied of land and the average annual retention time for the water in this basin is about 0.7 days.



From GSD-Fastighetskartan © Lantmäteriverket Gävle 2001, Consent M2001/5268 2004-12-20, 13:20

Figure 4-16. *Basin SAFE area in the Forsmark modelling area.*

Table 4-24. Total surface area and volume of Basin SAFE-area in Forsmark and divided into photic and aphotic zone.

	Surface area m^2	 %	Volume m^3	 %
Photic zone	3.71×10^6	32	9.10×10^7	82
Aphotic zone	7.78×10^6	68	1.96×10^7	18
Total	1.15×10^7	100	1.11×10^8	100

Food web matrix

When assuming that the functional groups, identified to be present in Basin SAFE-area, consume in proportion to available biomass of their respective food source, the resulting food web matrix for the basin changes, Table 4-25.

Table 4-25. Food web matrix including food proportions (estimated from the food web matrix and the identified available biomass of their respective food source) for Basin SAFE-area in Forsmark.

	1	2	3	4	5	6	7	8	9	10	11	12	13	18	19
1. Phytoplankton														1.00	
2. Microphytes														1.00	
3. Macrophytes														1.00	
4. Bacterioplankton															1.00
5. Zooplankton	0.26			0.74											
6. Zooplankton feeding fish					1.00										
7. Benthic fauna feeding fish									0.05	0.02	0.92	0.01			
8. Carnivorous fish						0.75	0.20	0.05							
9. Benthic herbivores		0.23	0.77												
10. Benthic filter feeders	0.02			0.05	0.02										0.91
11. Benthic detrivores													0.20		0.80
12. Benthic carnivores									0.05	0.02	0.93				
13. Benthic bacteria															1.00
16. Seals						0.75	0.20	0.05							
18. DIC															
19. POC															

Ecosystem model – Carbon budget for Basin SAFE-area

The total biomass (excluding DIC and POC) in Basin SAFE-area amount to about 2.3×10^8 gC, where 94% of the biomass is associated to the benthic habitats (37% flora and 57% fauna) (Table 4-26, Figure 4-18). The biomass is clearly dominated by benthic primary producers and detrivores. The phytoplankton plays a minor role in terms of biomass, but contributes to a substantial part of the primary production (64%) (Figures 4-17 and 4-19). The annual amount of primary production (1.4×10^9 gC/yr) equals the respiration (1.3×10^9 gC/yr), and the supply of carbon available for consumption (grazing or predation) (3.6×10^9 gC/yr) is about five times higher than the carbon demand resulting in an excess of carbon (biota biomass) of 2.8×10^{9} gC/yr (this estimate does not include the inflow of POC to the area) (Table 4-26). As a consequence of a positive net excess value and a total primary production exceeding the total respiration the basin can be considered as net autotrophic. However, for two organism groups, i.e. zooplankton and benthic bacteria, the estimated predation is higher than the estimated supply of carbon from each group, respectively (Figures 4-17 and 4-19). For zooplankton this is possibly due to the poor estimations of fish biomass and fish consumption because of the lack of site-specific data for fish. The reason for the over-predation on the benthic bacteria by the benthic detrivores is related to that the model is a static illustration of the ecosystem.

In the calculations presented in this section, the net inflow of DIC and POC from runoff and exchange with other sea basins has not been accounted for. The basin has a modelled Average Transit Residence (ATR) time of 0.66 days which possibly generates an exchange and possible addition of POC to the system corresponding to 2.7×10^{10} gC. Thus, the noticed carbon shortage of benthic detrivores will be more than well covered by the addition of POC each year. Since the water exchange also affects planktonic organisms, this contributes to sustaining the zooplankton in the system. The exchange with surrounding water also results in a potential inflow of 6.4×10^{11} gC DIC. As the water exchange rate is rapid in Basin SAFE-area, the annual terrestrial runoff was assumed to be of insignificant importance.

Table 4-26. Biomass (gC/basin), annual primary production or consumption of carbon by each functional group (gC/yr/basin), respiration (gC/yr/basin), supply (available for grazing or predation) (gC/yr/basin), grazing or predation on the functional groups (gC/yr/basin) and excess (gC/yr/basin) in the ecosystem in Basin SAFE-area. (Birds and humans have been excluded due to lack of data.)

Basin SAFE-area	Biomass (gC/basin)	Prod or Cons (gC/basin)	Respiration (gC/basin)	Supply[1] (gC/basin)	Graz or pred[2] (gC/basin)	Excess[3] (gC/basin)
Phytoplankton	1.1×10^{6}	8.9×10^{8}	–	8.9×10^{8}	1.6×10^{7}	8.8×10^{8}
Microphytes	2.0×10^{7}	2.1×10^{8}	–	2.1×10^{8}	1.7×10^{7}	1.9×10^{8}
Macrophytes	6.5×10^{7}	3.0×10^{8}	–	3.0×10^{8}	5.7×10^{7}	2.4×10^{8}
Bacterioplankton	2.6×10^{6}	4.2×10^{8}	2.1×10^{8}	2.1×10^{8}	3.7×10^{7}	1.7×10^{8}
Zooplankton	1.3×10^{6}	5.2×10^{7}	1.7×10^{7}	3.4×10^{7}	7.6×10^{7}	-4.2×10^{7}
Zoopl. feeding fish	6.4×10^{6}	7.6×10^{7}	2.5×10^{7}	5.1×10^{7}	3.9×10^{6}	4.7×10^{7}
Benthic feeding fish	1.7×10^{6}	2.0×10^{7}	6.7×10^{6}	1.4×10^{7}	1.1×10^{6}	1.2×10^{7}
Predatory fish	4.3×10^{5}	5.1×10^{6}	1.7×10^{6}	3.4×10^{6}	2.6×10^{5}	3.1×10^{6}
Benthic herbivores	5.9×10^{6}	7.4×10^{7}	2.5×10^{7}	4.9×10^{7}	3.8×10^{6}	4.6×10^{7}
Benthic filter feeders	1.8×10^{6}	1.3×10^{7}	4.3×10^{6}	8.6×10^{6}	1.1×10^{6}	7.5×10^{6}
Benthic detrivores	1.1×10^{8}	2.6×10^{9}	8.7×10^{8}	1.7×10^{9}	6.8×10^{7}	1.7×10^{9}
Benthic carnivores	1.5×10^{6}	5.3×10^{7}	1.8×10^{7}	3.5×10^{7}	2.6×10^{5}	3.5×10^{7}
Benthic bacteria	1.2×10^{7}	2.0×10^{8}	1.0×10^{8}	1.0×10^{8}	5.2×10^{8}	-4.2×10^{8}
Fish feeding birds	–	–	–	–	–	–
Benthic feeding birds	–	–	–	–	–	–
Seals	2.0×10^{4}	1.9×10^{5}	–	1.9×10^{5}	–	1.9×10^{5}
Humans	–	–	–	–	–	–
DIC	1.2×10^{9}	–	–	1.2×10^{9}	1.4×10^{9}	-2.4×10^{8}
POC	4.9×10^{7}	–	–	4.9×10^{7}	2.7×10^{9}	-2.7×10^{9}
Total (only biota)	2.3×10^{8}	(prod) 1.4×10^{9} (cons) 3.5×10^{9}	1.3×10^{9}	3.6×10^{9}	8.0×10^{8}	2.8×10^{9}

[1] Supply = consumption – respiration.

[2] Grazing or predation upon the respective functional group.

[3] Excess = supply – grazing or predation.

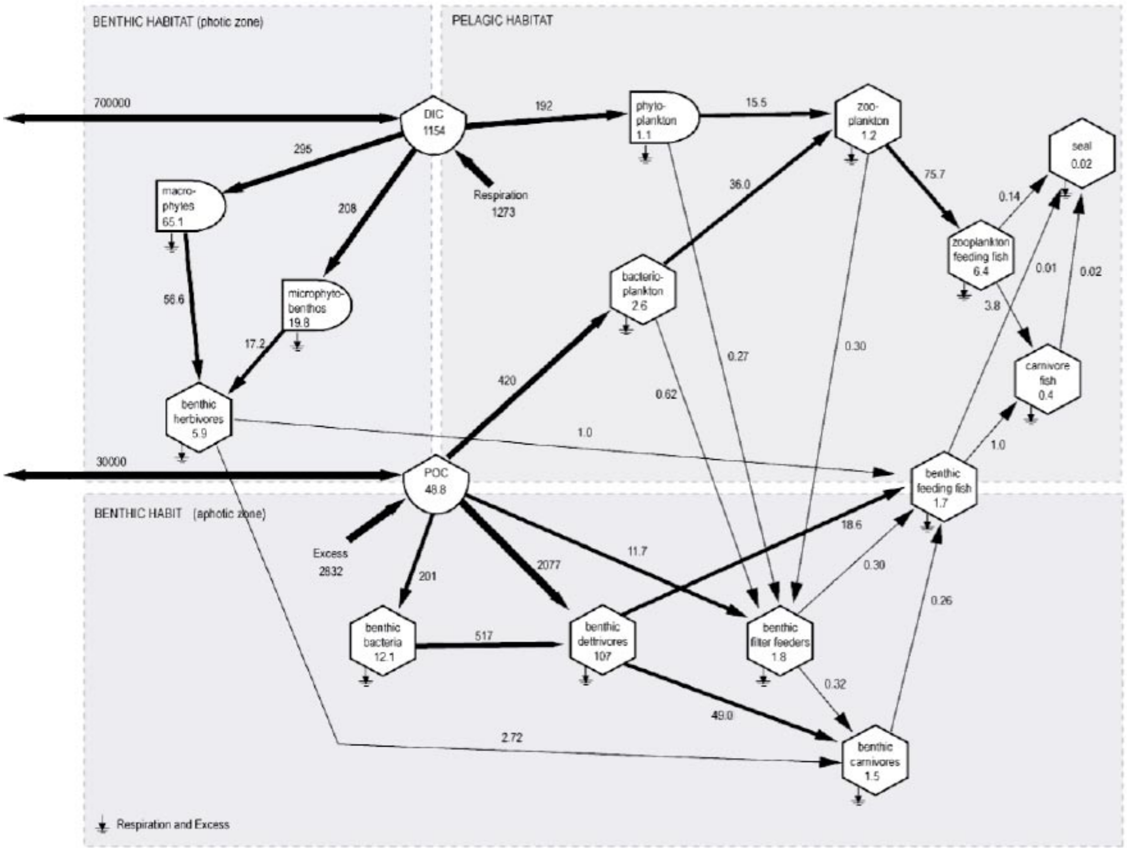


Figure 4-17. Carbon flow model for Basin SAFE-area in Forsmark. Biomasses (10^6 gC) and flow of carbon between the functional groups, i.e. consumption (10^6 gC yr^{-1}).

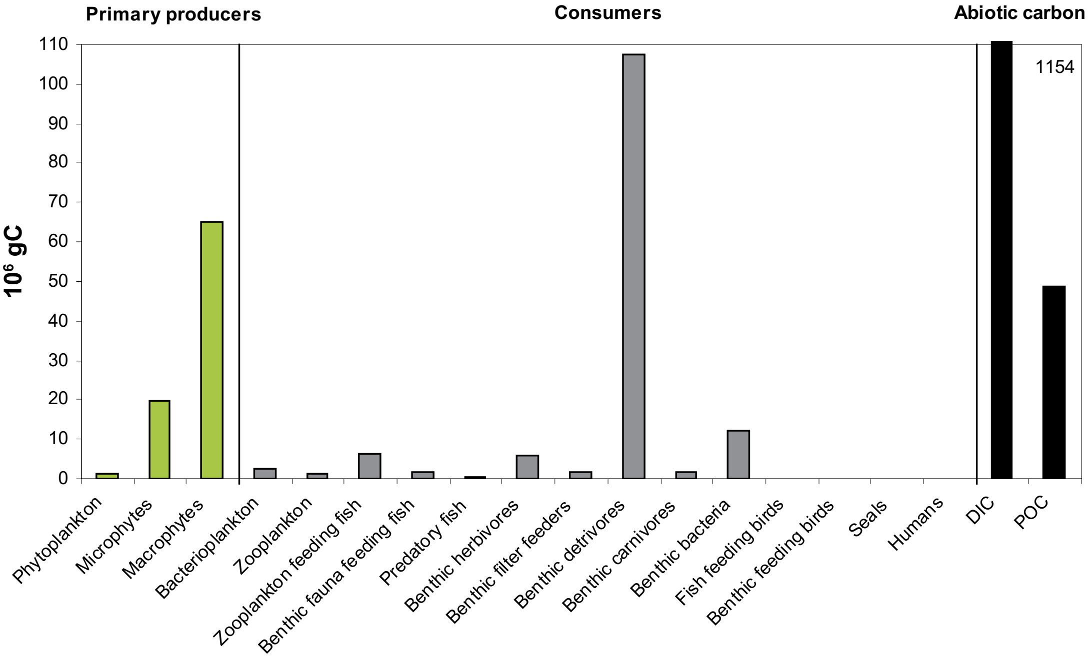


Figure 4-18. Biomass (10^6 gC) in Basin SAFE-area, Forsmark, for all functional groups and abiotic carbon pools. Primary producers in green, consumers in grey, and DIC and POC in black.

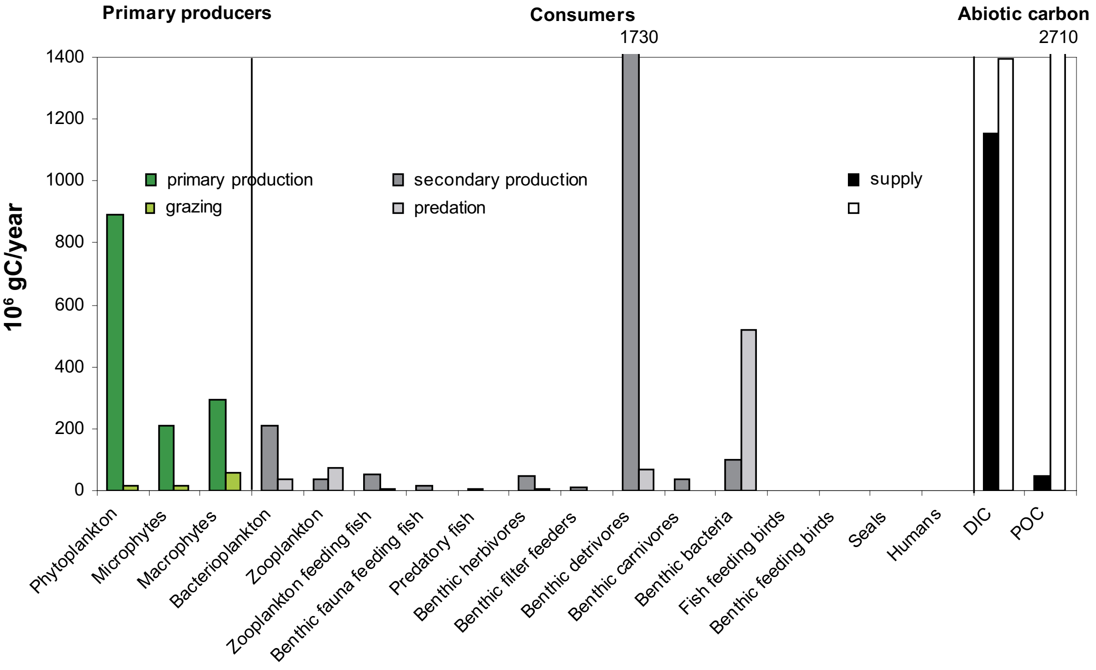


***Figure 4-19.** Supply (dark) and demand (light) of carbon from/by primary producers (green), consumers (grey) and DIC and POC (black) in Basin SAFE-area, Forsmark, (10^6 gC yr^{-1}).*

Ecosystem model for Basin Stånggrundsfjärden

Basin Stånggrundsfjärden in the Forsmark area is located just south of the Basins SAFE-area (Figure 4-20). The basin has a total surface area of 5.5 km^2 and water volume of 0.021 km^3 (Table 4-27). The maximum depth in this basin is about 13 m, the average depth 6 m and light penetration depth is about 6.7 m /Nilsson et al. 2003/. The average annual retention time for the water in this basin is less than half a day.

Table 4-27. Total surface area and volume of Basin Stånggrundsfjärden in Forsmark and divided into photic and aphotic zone.

	Surface area m^2	 %	Volume m^3	 %
Photic zone	2.53×10^6	57	1.46×10^7	70
Aphotic zone	1.94×10^6	43	6.29×10^6	30
Total	4.47×10^6	100	2.08×10^7	100

Food web matrix

When assuming that the functional groups, identified to be present in Basin Stånggrundsfjärden, consume in proportion to available biomass of their respective food source, the resulting food web matrix for the basin changes, Table 4-28.

Table 4-28. Food web matrix including food proportions (estimated from the food web matrix and the identified available biomass of their respective food source) for Basin Stånggrundsfjärden in Forsmark.

	1	2	3	4	5	6	7	8	9	10	11	12	13	18	19
1. Phytoplankton														1.00	
2. Microphytes														1.00	
3. Macrophytes														1.00	
4. Bacterioplankton															1.00
5. Zooplankton	0.27			0.73											
6. Zooplankton feeding fish					1.00										
7. Benthic fauna feeding fish									0.03	0.02	0.94	0.01			
8. Carnivorous fish						0.75	0.20	0.05							
9. Benthic herbivores		0.23	0.77												
10. Benthic filter feeders	0.02			0.05	0.02										0.91
11. Benthic detrivores													0.34		0.66
12. Benthic carnivores									0.03	0.02	0.95				
13. Benthic bacteria															1.00
16. Seals						0.75	0.20	0.05							
18. DIC															
19. POC															

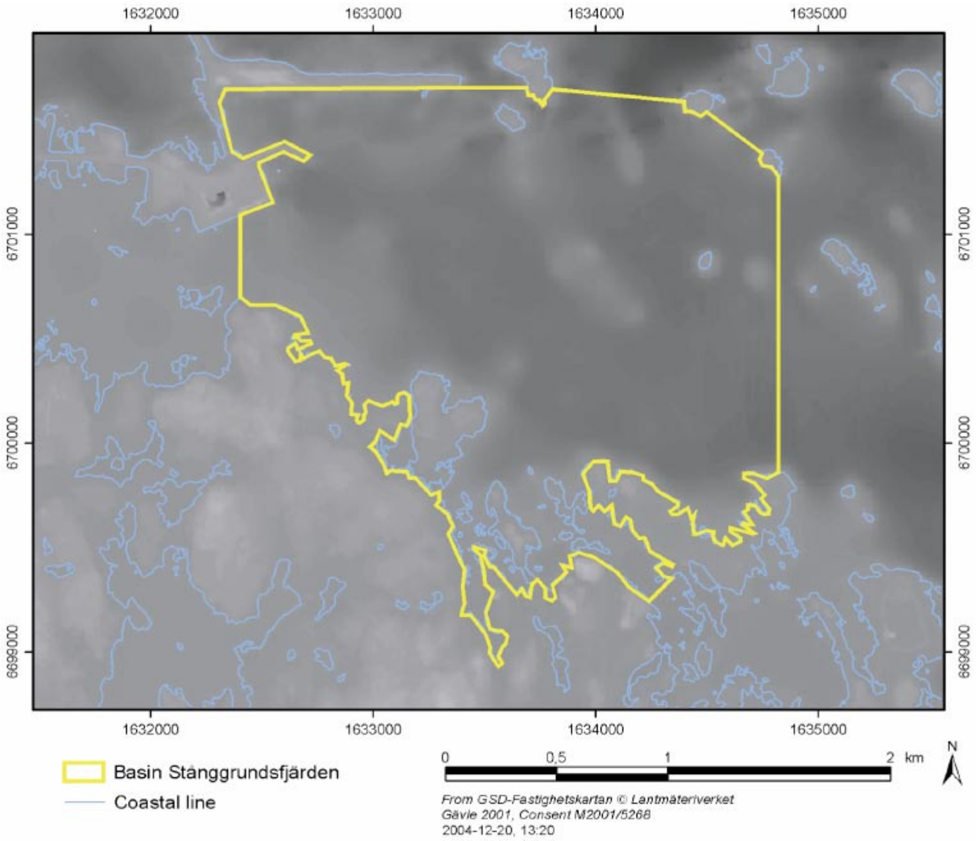


Figure 4-20. Basin Stånggrundsfjärden in the Forsmark modelling area.

Ecosystem model – Carbon budget for Basin Stånggrundsfjärden

The total biomass (excluding DIC and POC) in Basin Stånggrundsfjärden amount to about 1.1×10^8 gC, where 96% of the biomass is associated to the benthic habitats (52% flora and 44% fauna) (Table 4-29, Figure 4-22). The biomass is as in Basin SAFE-area clearly dominated by benthic primary producers and detrivores. The phytoplankton, macrophytes and microphytes contribute with about one third each of the total primary production (Figures 4-21 and 4-23). As for the SAFE-area, the annual amount of primary production (4.9×10^8 gC/yr) equals the respiration (4.7×10^8 gC/yr) (Table 4-29). The supply of carbon available for consumption (grazing or predation) (1.3×10^9 gC/yr) is about three times higher than the carbon demand resulting in an excess of carbon (biota biomass) of 4.3×10^8 gC/yr (this estimate does not include the inflow of POC to the area). As a consequence of a positive net excess value and a total primary production exceeding the total respiration, the basin could be considered as net autotrophic. However, as for the SAFE-area the estimated predation on zooplankton and benthic bacteria is higher than the estimated supply of carbon from these groups. The reasons for this are probably analogous as for the Basin SAFE-area.

Table 4-29. Biomass (gC/basin), annual primary production or consumption of carbon by each functional group (gC/yr/basin), respiration (gC/yr/basin), supply (available for grazing or predation) (gC/yr/basin), grazing or predation on the functional groups (gC/yr/basin) and excess (gC/yr/basin) in the ecosystem in Basin Stånggrundsfjärden. (Birds and humans have been excluded due to lack of data.)

Basin Stånggrundsfjärden	Biomass (gC/basin)	Prod or Cons (gC/basin)	Respiration (gC/basin)	Supply[1] (gC/basin)	Graz. or pred.[2] (gC/basin)	Excess[3] (gC/basin)
Phytoplankton	1.8×10^5	1.4×10^8	–	1.4×10^8	2.7×10^6	1.4×10^8
Microphytes	1.3×10^7	1.4×10^8	–	1.4×10^8	4.3×10^6	1.4×10^8
Macrophytes	4.4×10^7	2.0×10^8	–	2.0×10^8	1.4×10^7	1.9×10^8
Bacterioplankton	4.9×10^5	7.9×10^7	4.0×10^7	4.0×10^7	7.4×10^6	3.2×10^7
Zooplankton	2.4×10^5	9.7×10^6	3.2×10^6	6.5×10^6	3.0×10^7	-2.3×10^7
Zoopl. feeding fish	2.5×10^6	2.9×10^7	9.8×10^6	2.0×10^7	1.6×10^6	1.8×10^7
Benthic feeding fish	6.6×10^5	7.9×10^6	2.6×10^6	5.2×10^6	4.3×10^5	4.8×10^6
Predatory fish	1.7×10^5	2.0×10^6	6.5×10^5	1.3×10^6	1.1×10^5	1.2×10^6
Benthic herbivores	1.5×10^6	1.8×10^7	6.1×10^6	1.2×10^7	9.5×10^5	1.1×10^7
Benthic filter feeders	6.8×10^5	5.0×10^6	1.7×10^6	3.3×10^6	4.4×10^5	2.9×10^6
Benthic detrivores	4.2×10^7	1.0×10^9	3.4×10^8	6.7×10^8	2.7×10^7	6.5×10^8
Benthic carnivores	5.8×10^5	2.1×10^7	6.8×10^6	1.4×10^7	1.0×10^5	1.4×10^7
Benthic bacteria	4.7×10^6	7.8×10^7	3.9×10^7	3.9×10^7	3.4×10^8	-3.0×10^8
Fish feeding birds	–	–	–	–	–	–
Benthic feeding birds	–	–	–	–	–	–
Seals	2.0×10^4	1.9×10^5	–	1.9×10^5	–	1.9×10^5
Humans	–	–	–	–	–	–
DIC	2.2×10^8	–	–	2.2×10^8	4.9×10^8	-2.7×10^8
POC	9.2×10^6	–	–	9.2×10^6	8.3×10^8	-8.2×10^8
Total (only biota)	1.1×10^8	(prod.) 4.9×10^8	4.5×10^8	1.3×10^9	4.3×10^8	8.7×10^8
		(cons.) 1.3×10^9			net excess	4.8×10^7

[1] Supply = consumption – respiration.

[2] Grazing or predation upon the respective functional group.

[3] Excess = supply – grazing or predation.

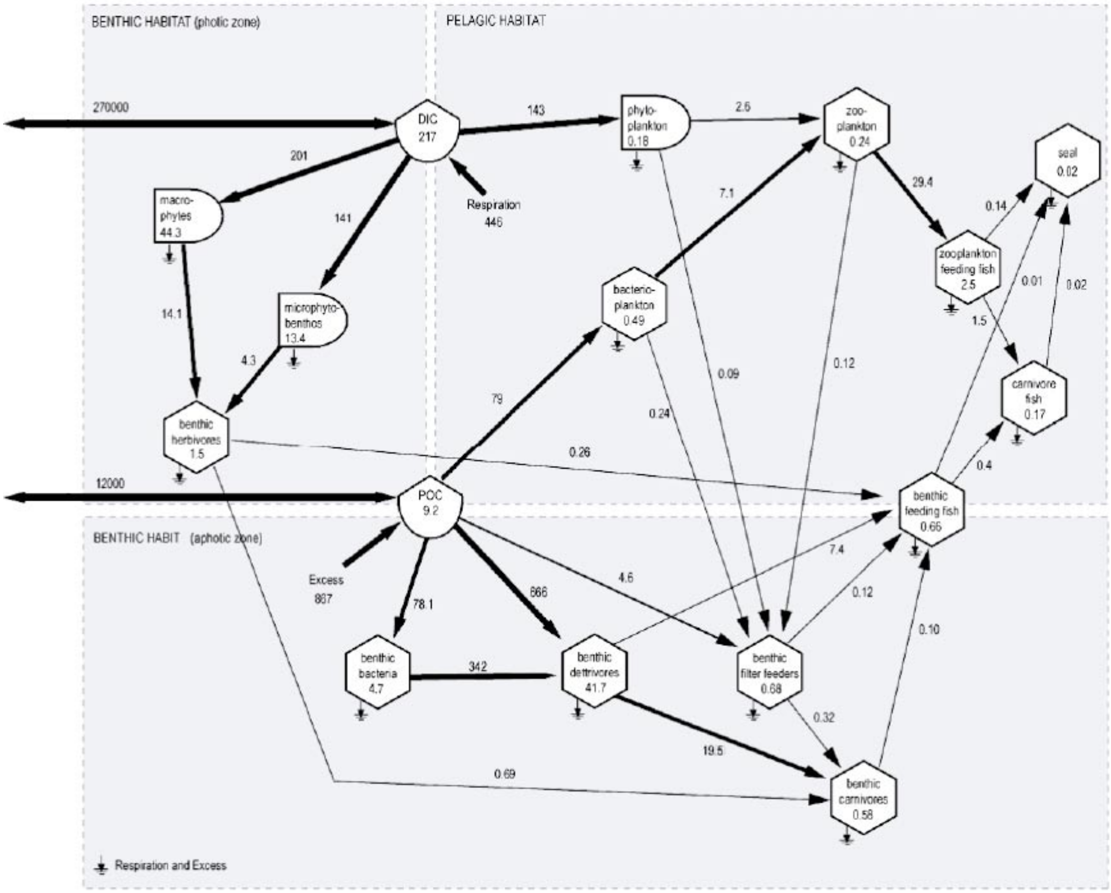


Figure 4-21. *Carbon flow model for Basin Stånggrundsfjärden in Forsmark. Biomass (10^6 gC) and flow of carbon between the functional groups, i.e. consumption (10^6 gC yr^{-1}).*

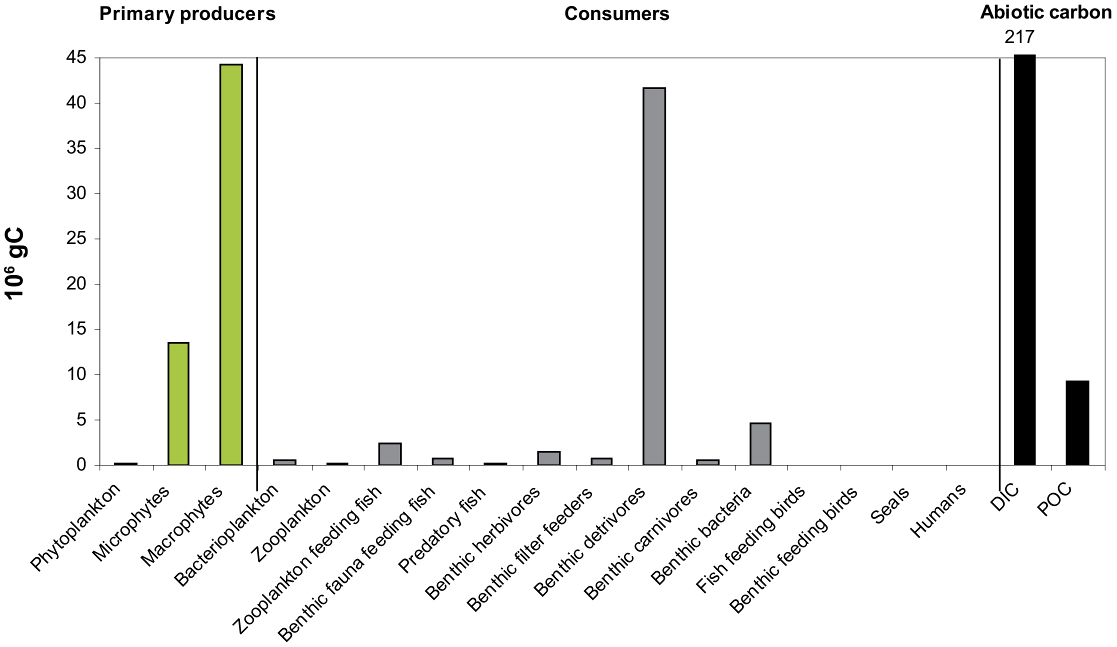


Figure 4-22. *Biomass (10^6 gC) in Basin Stånggrundsfjärden, Forsmark, for all functional groups and abiotic carbon pools. Primary producers in green, consumers in grey, and DIC and POC in black.*

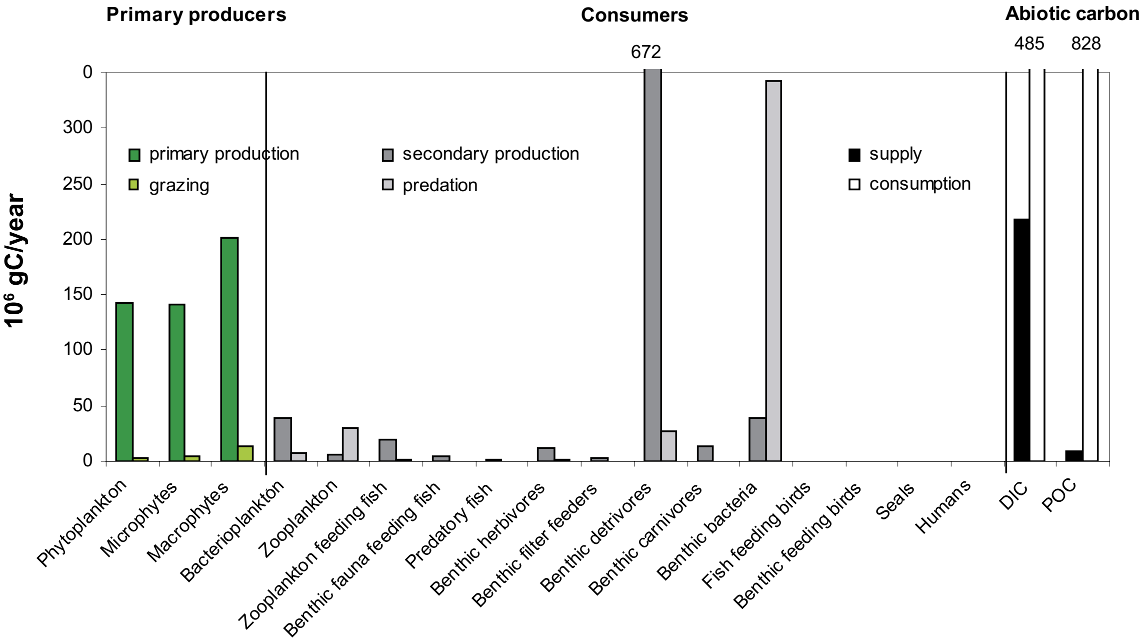


Figure 4-23. *Supply (dark) and demand (light) of carbon from/by primary producers (green), consumers (grey) and DIC and POC (black) in Basin Stånggrundsfjärden, Forsmark, (10^6 gC yr^{-1}).*

In these calculations, the net inflow of DIC and POC from runoff and exchange with other sea basins has not been included. For Basin Stånggrundsfjärden the annual terrestrial runoff was assumed to be of insignificant importance compared to the water exchange rate in the sea. The basin has a modelled Average Transit Residence (ATR) time of 0.30 days which possibly generates an exchange of POC corresponding to 1.2×10^{10} gC. The total excess of biota, i.e. supply – grazing or predation, also contributes to the POC pool but is two orders of magnitudes lower than the POC flow caused by the water fluxes. The exchange with surrounding water also results in a potential inflow of 2.7×10^{11} gC DIC.

Confidence and uncertainties

General

The bathymetric data that were used to estimate the areas and volumes of the basins originate from a combination of recent site-specific measurements and existing digital sea charts has considered to be of a very high quality and representativity (cf geometry, Section 3.2).

The estimations of the extensions of the photic and aphotic zone were based on a rough assumption that the photic zone is twice the light penetration depth (which has been measured in the vicinity). An assumption that is probably fairly correct. However, it would have been good to correlate the estimates of the photic zone to the actual depth where plants actually are present in some of the basins to validate the assumption. The extension of the photic zone can also differ within a basin, which not has been taken into account in the budget calculations. The estimates of the extension of the photic zone have a large influence of the final results of the carbon budgets and are thus very important. The influence of ice-cover on the extension zone has not been taken into account.

The primary production was generally estimated from the biomass, conversion factors, and the solar insolation during the year. Optimal would have been to measure the primary production at the sites during the year. However, the calculated primary production probably has a sufficient good quality since the used conversion factors were species-specific in most cases and mostly obtained from the Baltic Sea, and the insolation measurements used in the calculations were site-specific with a high resolution. The assumption that the epiphyte biomass and primary production was included in the macrophyte estimates probably contributes to a small underestimation in total biomass and primary production. The primary production for phytoplankton was measured in Öregrundsgrepen during a two year period and is considered to have a good quality.

The reasoning applicable for the estimates of the primary production also applies to the estimates of the respiration, i.e. that real measurements probably would have given a better estimate than the calculations used in this study. But as for the primary production, species-specific conversion factors contributed to that the calculations probably are fairly correct. The assumption that the respiration to consumption ratio is approximately 1:3 is a fairly accepted relationship, as is also that it is less for bacteria (1:2), since their metabolism has a higher rate.

Carbon transport to and from the basins were based on modelled oceanographic water movement (turnover time), which is described in detail in Section 3.5. Evaluations of the modelled runoff from land is described in Section 3.4. Concentrations of DIC and POC were based on a 2.5 year monitoring sampling programme with samples every second to third week. The estimation of total carbon flow is probably of low quality since the variation of concentration of carbon and runoff is great and these two parameters normally covariates and only averages for each parameter was used here.

Phytoplankton

Estimations of biomass were made from five samples at one station (*Sw: Forslingens grund*). Compared to phytoplankton biomasses in Öregrundsgrepen reported by /Lindahl and Wallström, 1980/ these biomass estimates are about twice as high. The quality of the calculated specific net primary production is good but not species specific. However, this have probably little affect on the quality of the estimates used in this budget.

Microphytes

The microphytes biomass or primary production has been measured at the site. The used microphyte data originate from studies performed in and around the biotest basin off Forsmark nuclear power plant during 1985 and 1986 /Snoeijs 1985, 1986/. The quality of the data is high but as only a few data points have been used in this study (because the majority of the data points were located within the biotest basin and therefore were considered to be unrepresentative) the confidence is reduced. There was no information on the annual variation.

Macrophytes

Field measurements of biomass and distribution are of high quality, but the quality of the extrapolations made (from point and line data to area data) has not been quantified. Samples have only been taken in Basin SAFE-area but these are considered to be representative for Basin Stånggrundfjärden as well. There was no information on the annual variation.

Bacterioplankton

The bacterioplankton biomass or respiration has not been measured at the site. The used data was instead obtained from a study performed in Tvärminne, Finland /Kuparinnen, 1987/. Data from this study was also used to estimate the respiration and consumption. The Tvärminne data has a high quality, but is probably not very representative for this area.

Zooplankton

Estimations of biomass were made from five samples from one station (*Sw: Forslingens grund*). The used zooplankton biomass estimated was almost four times higher than estimates performed by /Eriksson et al. 1977/. The respiration and consumption has been calculated with an aid of conversion factors, which is considered to give estimates of fairly good quality.

Fish

Data on fish biomass, species distribution of fish, consumption and respiration are not available from the area. Instead, biomass data from a SCUBA diving survey performed in the Trosa archipelago were used /Jansson et al. 1985/. The proportions between fish having different feeding habits originate both from a survey by /Neumann, 1982/ presenting species distribution in the open sea in Öregrundsgrepen and from model simulations where the available resources in the area were taken into account /Kumblad et al. 2003; Kumblad and Kautsky, 2004/.

Benthic fauna

The benthic macrofauna was sampled in the Basin SAFE-area in a fairly thorough investigation and thus the biomass data may for these functional groups be considered to have high quality and be very representative. Although the samples only were taken in Basin SAFE-area, the data is considered to be representative also for Basin Stånggrundfjärden. There was no information on the annual variation.

The meiofauna have not been studied in this area and data used originate from Askö /Ankar, 1977/. How representative this study is for the Forsmark area is not known, but it may be considered as low.

Benthic bacteria

Neither the benthic bacteria biomass nor the respiration has been measured at the site. The used data was obtained from a study performed in the Bothnian Sea /Mohammadi et al. 1993/. Data from this study was also used to estimate the respiration and consumption. The data has a high quality, but is probably not very representative for this area.

Birds

Birds were excluded due to lack of quantitative data in this version of the carbon budget.

Seals

The quality of the data used for seals is considered to be of moderate to high quality and low-medium representativity. However, the data is for grey seals, which probably is the most common seal in the area. The biomass estimate was obtained from the Museum of Natural History in Stockholm, which probably has the highest experience of this in Sweden.

4.4 Integrated ecosystem model

4.4.1 Introduction

In this section, the stocks and flows of water and carbon in the three ecosystems are connected, using information from the discharge area Forsmark 2, the lakes and the connected marine basins, described in previous sections. The Forsmark 2 discharge area has here a higher resolution than in the section "The terrestrial ecosystem model" using data for the different sub-catchments within Forsmark 2. The main aims of integrating the separate ecosystem models are to: 1) quantitatively follow the path of carbon from the binding into primary producers on land to the last hold, in this scenario, the Baltic Sea, 2) quantitatively illustrate the turnover of different pools in the landscape, and 3) provide the safety assessment with input to landscape modelling and identify important properties of biosphere objects.

Because water is the principal media for transport and accumulation of elements and matter in the landscape, the work is in the first step focused on establishing an integrated model describing the hydrology. The next step is to combine the knowledge from the ecosystem specific carbon budgets with landscape hydrology. Below follows a description of the conceptual model, followed by a description of the major pools and fluxes within the three ecosystems that are used to build the integrated model. The last section concludes on the carbon budget for the integrated ecosystem model.

4.4.2 Conceptual description of an integrated ecosystem model

The integrated model combines the previously described ecosystem models covering the terrestrial, limnic and marine environments. The processes in focus are:

- Transport.
- Accumulation.
- Carbon turnover.

Transport

The transport processes are mediated by water flow and at the landscape scale is the focus on the horizontal flow between the ecosystems. These flows are driven by hydrological processes that are described using the following parameters:

- Precipitation.
- Evapotranspiration.
- Water residence time.
- Flow into the system.
- Flow out of the system.

The water fluxes are presented in Figure 4-24 and the carbon fluxes is presented in Figure 4-25 for the different ecosystems and subsystems constituting the landscape.

Accumulation

Carbon may be accumulated both in living biomass, in necromass and as organic carbon in soil or sediment.

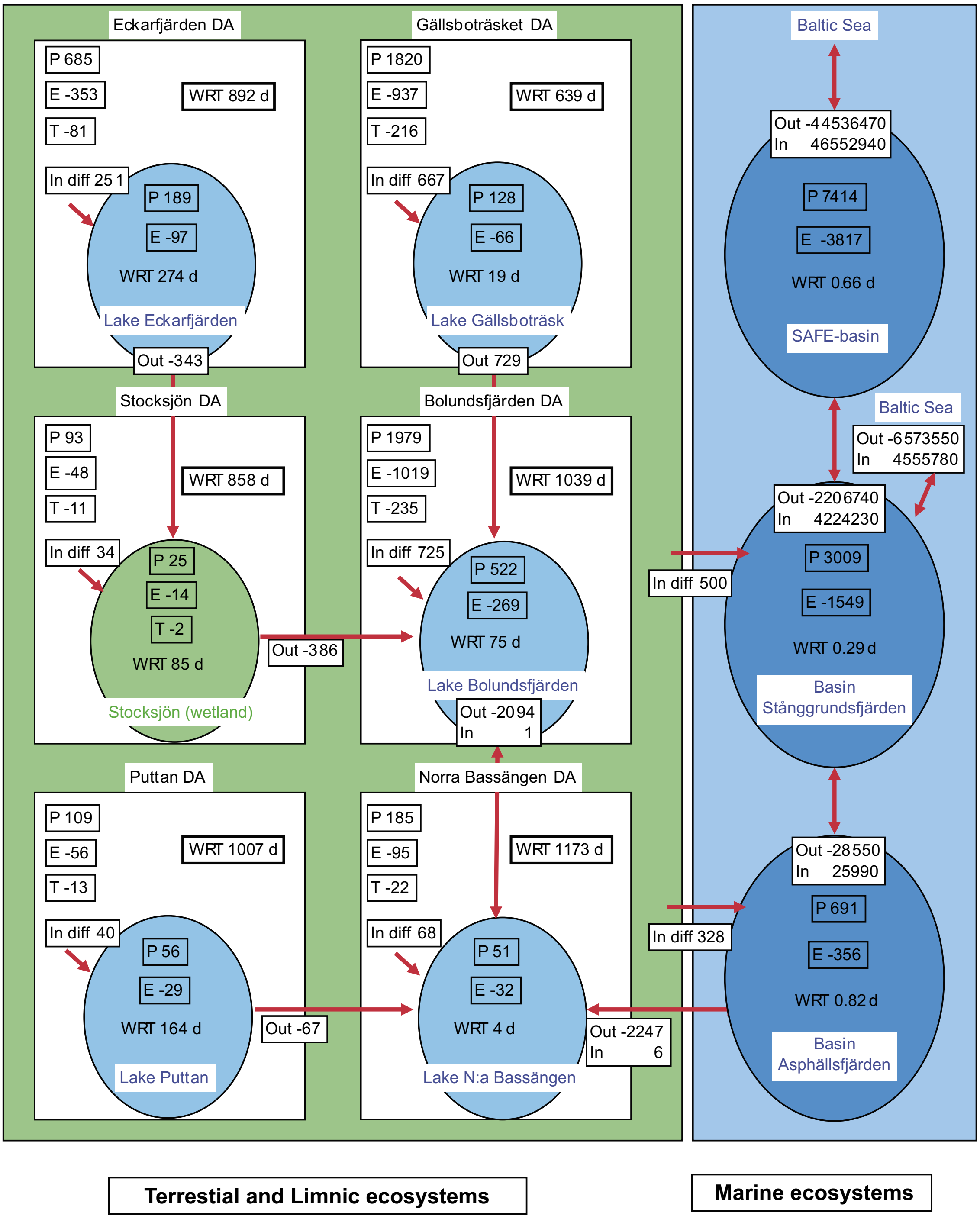


Figure 4-24. *An annual water budget for the discharge area Forsmark 2 and adjacent coastal basins, where land, lakes and the coastal basins have been interconnected. Negative sign indicates a flux that is leaving the specific subsystem, e.g. evapotranspiration or water transport from the lake or a specific basin. P = Precipitation, ET = Evapotranspiration, In diff = diffuse inflow from terrestrial parts of the catchment area, WRT = Water Residence Time in days for the specific subsystem, DA = Drainage area. All numbers are on the base* 1×10^3 *and have the unit* m^3*, except for the WRT.*

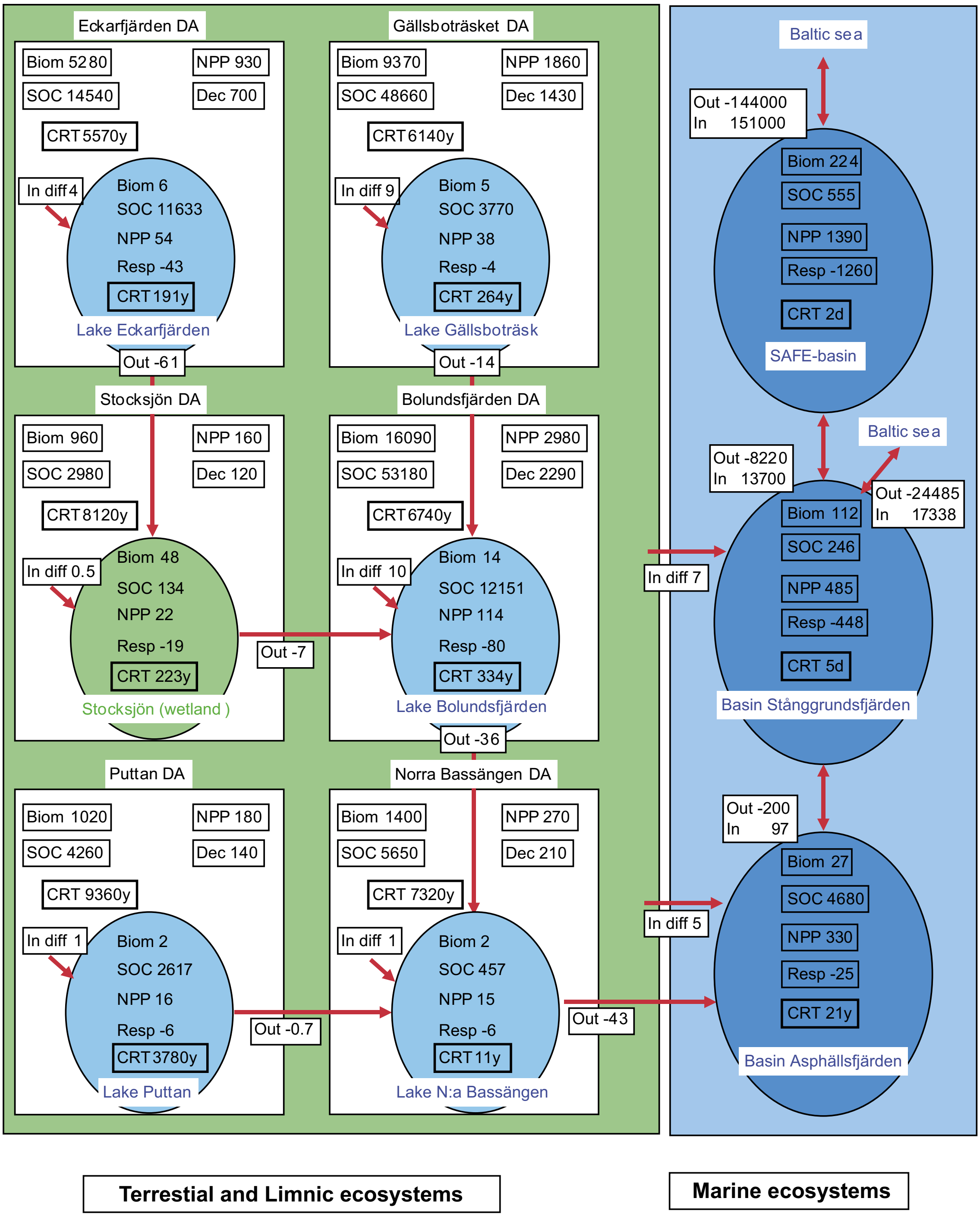


Figure 4-25. *An annual carbon budget for the discharge area Forsmark 2 and adjacent coastal basins, where land, lakes and the coastal basins have been interconnected. (MgC in units denotes* 10^6 *gC). Negative sign indicates a flux that is leaving the specific subsystem, e.g. respiration. NPP = Net Primary Production, Biom = Biomass, SOC = Soil/Sediment Organic Carbon, Resp = Respiration, Dec = Decomposition, In diff = diffuse inflow of carbon from terrestrial parts of the catchment area, CRT = Carbon Residence Time (theoretical) for all organic carbon in the specific subsystem, DA = Drainage area.*

Carbon turnover

The turnover of carbon in different pools is an estimate of how long time the carbon remains in a certain pool before it is released again (residence time). This estimation is of course based on a number of premises that in this version of the model are more or less realistic e.g. some parts of the pool may be more easily retained, while others have a higher turnover rate. The carbon pool mass is set in relation to processes that either add or remove carbon from the pool, e.g. litter input to the ground carbon pool/sediment pool in relation to respiration (mineralization).

4.4.3 Quantitative descriptive model

The ecosystem is described using a number of hydrological parameters (which in turn describe transport processes) and a number of carbon pools that are described below, separately for each subsystem. The carbon pools are described along with those fluxes that are considered to be the most important in adding and/or removing carbon, i.e. influencing the turnover of the pool.

Hydrology

Below are a number of basic hydrological parameters presented that have been used for the calculations of water exchange:

- Precipitation is set to 674 mm×y^{-1} /Johansson et al. 2005/.
- Runoff is estimated to 7.1 s^{-1}×km^{-2} using regional data (Section 3.4).
- Evapotranspiration is estimated to 427 mm y^{-1} (Section 3.4).
- Transpiration from the terrestrial system in the discharge area Forsmark 2 is set to 80 mm×m^{-3}×y^{-1} (see Figure 4-2).

A number of derived properties were calculated as follows:

- Evaporation was calculated as the difference between evapotranspiration and transpiration.
- The total runoff from the land surface was calculated using the land area and the specific runoff.

Water residence time of the mobile groundwater store in the discharge area was calculated using the following assumptions. The soil contains a saturated and an unsaturated zone. The lower 2/3 of the soil is belonging to the water-saturated zone and the upper 1/3 is unsaturated. The mobile groundwater storage was calculated as a function of the land area and an assumed proportion of mobile groundwater in soil (30% of the volume in the saturated zone and 10% in the unsaturated zone). Mean soil depth within each sub-catchment was calculated from the descriptive soil depth model presented in Section 3-3 (Table 4-30). The storage was then divided with the runoff to get an estimate of the water residence time.

Table 4-30. Mean soil depth in the different sub-catchment areas in the larger catchment area Forsmark 2, calculated from the soil depth model. A weighted mean was used for the joined sub-catchments 2:3–2:7.

Discharge area	Mean soil depth (m)	Standard dev	Min (m)	Max (m)
2:1	2.66	1.43	0.00	9.85
2:2	2.61	1.32	0.02	6.30
2:3–2:7	2.20	–	0.00	13.84
2:8	1.73	1.01	0.00	8.48
2:9	1.97	1.49	0.00	11.39
2:10	2.02	1.70	0.00	10.25
2:11	1.92	0.85	0.00	7.25

Table 4-31. Carbon concentrations in surface water at different locations in Forsmark 2 and the adjacent coastal area. These concentrations were used to calculate carbon content and fluxes in and between ecosystems. One star (*) denotes mean value derived from measurements from the actual site /Sonesten, 2005/, and two stars (**) denotes mean value from another sampling site within the Forsmark area, as similar as possible to the actual site.

Catchment area	Name	Total Organic Carbon (gC m^{-3})
2:10	Eckarfjärden discharge area	12**
	Eckarfjärden outlet	18*
2:9	Stocksjön discharge area	16**
	Stocksjön	18**
2:8	Gällsboträsket discharge area	20*
	Gällsboträsket	20**
2:3, 2:2, 2:7, 2:6, 2:5, 2:4	Bolundsfjärden discharge area	16**
	Bolundsfjärden	17*
2:11	Puttan discharge area	16**
	Puttan	17**
2:1	N:a Bassängen discharge area	16**
	N:a Bassängen	19*
	Remaining discharge areas, adjacent to marine basins	16**
	Basin Asphällsfjärden	7**
	Basin Stånggrundsfjärden	4**
	SAFE-basin	3**

The terrestrial ecosystem

The carbon budget of Forsmark 2 (Figure 4-3) is subdivided into a number of sub-catchment areas, Table 4-31. The parameterisation of the seven discharge areas and the wetland (Stocksjön) is based on information from the detailed descriptions in previous chapters in this report (mainly Sections 3.7 and 4.1.3).

Primary producers

The primary producers are the main biomass pool in the terrestrial environment including the overall biomass of trees, shrubs, field and ground layer above and below ground. Similarly, is the flux of carbon into the primary producers an aggregated value.

Consumers

The total biomass of herbivores and carnivores in the discharge area is 3.1×10^5 gC (Figure 4-3). In relation to the other carbon pools, this pool is small, but may, however, be important due the relative high carbon flow (in relation to weight) via herbivores. This pool does also contain several species that are regularly hunted by humans. Carbon residence time of this pool has not been estimated in this version and neither is the pool included in Figure 4-25.

Necromass and soil organic carbon

The soil carbon pool is the largest carbon pool in the terrestrial environment (see Section 4.1). To this pool is the much smaller pool of necromass (logs and litter) added (from Figure 4-2). The residence time of this combined pool is calculated assuming that the decomposition equals the annual input of litter in Figure 4-3. This is most certainly an overestimation (see discussion in Section 4.1.3), but may in this version serve as a base for further discussions.

Transport from the ecosystem

The transport of dissolved organic carbon (DOC) from the terrestrial discharge areas was calculated using a value from /Canhem et al. 2004/ who estimated leaching of DOC from conifer forests in Canada to 3.5 $gC \times m^{-2} \times y^{-1}$. This figure was multiplied with the terrestrial area (including wetlands) to get an estimate of the carbon transport from the terrestrial discharge area.

Carbon turnover

The hypothetical overall carbon residence time in the terrestrial system is a function of the total carbon pool (dead + living) and the yearly leakage of carbon by runoff to the lake and the closest basin.

The wetland Stocksjön

This wetland has a large inflow of water from Lake Eckarfjärden flowing directly through the central part of the wetland. This assumption is partly supported by the fact that the wetland has a small area of open water in the central part. This open water area was treated as a lake when calculating estimates of biomasses and production (see the limnic ecosystem). The terrestrial inflow of water was added to the inflow from Lake Eckarfjärden, and the precipitation over the wetland, to calculate the total outflow. The transport of organic carbon out from the wetland was calculated as a function of the discharge from the terrestrial area and the input from Lake Eckarfjärden, which was estimated from the concentration of total organic carbon (TOC) in the outlet of Lake Eckarfjärden (see Table 4-31). The water flux originating from diffuse inflow and precipitation (over the wetland) was assumed to have a TOC content using a mean for three different small discharge areas Table 4-31. No sorption processes was assumed to bind organic carbon.

These calculations resulted in an amount of carbon entering the wetland that was only slightly smaller than what was leaving the wetland. However, this is not seen in Figure 4-25 because of rounding. Accumulation in peat was set to 60.4 gC×m^{-2}, in accordance to Figure 3-84. The budget for the wetland resulted in a minus that is attributed to decomposition. This minus in the carbon budget (635 gC×m^{-2} y^{-1}) is however 50% larger than expected from literature (see discussion under wetlands in the terrestrial ecosystem, Section 4.2).

The limnic ecosystem

The parameterisation for limnic ecosystem model is based on information from the detailed descriptions in previous chapters in this report (mainly Sections 3.8 and 4.2.2).

Primary producers

According to the carbon budgets presented in Section 4.2.2, primary producers (i.e. macrophytes, macroalgae, phytoplankton and epiphytic algae), constitute together more than 80% of the total biomass in the Forsmark lakes. Macrophytes comprise 50–90% of both the biomass and the primary production, the higher share in the smaller lakes where major parts are covered by reed. However, in the larger lakes, primary producers in the benthic habitat (Chara and microphytobenthos in the microbial mat) are almost equally important as the emergent macrophytes concerning both production and biomass. The theoretical residence time for the carbon in primary producers, calculated as the mean biomass divided by the annual net input from the photosynthesis (respiration excluded), is c 0.1 year.

Consumers

The estimated total biomass of consumers (i.e. both predators and decomposers) is dominated by benthic bacteria, but also benthic invertbrates and benthivore fish contribute appreciably to total biomass (Section 4.2). The theoretical residence time for the carbon in limnic consumers, calculated as total consumer biomass divided by annual respiration, is c 0.03 year.

Necromass and soil organic carbon

The carbon pool in lake sediments (gC) was calculated from data given in /Hedenström, 2004b/ by multiplying the density of carbon in the sediment (gC×m^{-3}) with the estimated sediment volume in each lake. Sediment depth for each lake was estimated as the mean depth of post-glacial sediments in the sediment core samples. Percentage carbon per sediment dry weight for each stratum (gyttja, clay-gyttja/gyttje-clay, clay) was calculated from the overall mean carbon content per strata from all investigated lakes (14%, 5% and 1%, respectively). Sediment water content was assumed to be on average 86%. The resulting carbon pool in the sediment is by far the largest carbon pool in the limnic system (see Figure 4-25).

The accumulation rate of carbon into lake sediments was calculated using an estimated total sedimentation rate of 1.0 mm per year /Hedenström and Risberg, 2003/. The ratio of the sediment carbon pool and the annual accumulation rate of carbon into the sediments, gives a theoretical residence time of carbon in the sediment ranging from 150 years in Lake N:a Bassängen to almost 1,000 years in Lake Eckarfjärden.

Transport to the ecosystem

The transport of carbon to the limnic system is assumed to correspond to the transport of DOC from the terrestrial discharge area (as described above).

Transport from the ecosystem

The transport of carbon from the limnic system was calculated from monthly mean values of total organic carbon (TOC) concentrations in lake surface water, and modelled monthly discharge from the lake.

Carbon turnover

A hypothetical total carbon residence time was calculated as the ratio between the total carbon pool in the lake (dead+living) and the annual transport of carbon from the lake, as calculated above.

The marine ecosystem

The large-scale flows of carbon within the marine ecosystem, and the flows from adjacent ecosystems, are described in terms of runoff from the surrounding terrestrial environments to the three different sub-basins, water exchange to/from/between the basins, and the primary production, respiration and sedimentation of carbon within the basins.

The carbon pools are described along with those fluxes that are considered to be the most important for adding and/or removing carbon, i.e. influencing the turnover of the total carbon pool in the system. The parameterisation is done using information from the detailed descriptions in Section 3.9 in this report. One of the basins, basin Asphällsfjärden, is not described in Section 3.9, however, the same assumptions are made as for the other to basins, with the following exception: the intake of cooling water to the nuclear power station is assumed not to be present in our calculations, neither in the oceanographic model nor the biological and chemical characterization of the system, as the integrated ecosystem model is supposed to be applicable to conditions when the power station is turned off.

Primary producers

The total biomass and production of primary producers (i.e. macrophytes including macroalgae, microphytes and phytoplankton) in the three different sub-basins are presented in Section 4.3. The theoretical carbon residence time (year) for marine primary producers, which was calculated as the ratio of the biomass (gC) and the primary production rate (gC×year^{-1}), varied between 0.06 and 0.14 year for the three basins.

Consumers

The biomass and respiration of the autotrophic organisms (including bacterioplankton, zooplankton, fish, benthic herbivores, benthic filter feeders, benthic detrivores, benthic carnivores, benthic bacteria, and birds) in the three sub-basins are presented in Section 4.3. The values are merged values that describe the overall biomass and respiration. The theoretical residence time for carbon in marine consumers (year), calculated as the ratio of the biomass (gC) and the respiration rate (gC×year^{-1}), varied between 0.11 and 0.14 year in the three basins.

Sediment and sedimentation

The total carbon content in the sediment (gC) was calculated as the density of carbon in the sediment (gC×m^{-3}) multiplied with the estimated sediment volume in each basin. The sediment volume was calculated as seafloor surface of the substrate multiplied with average thickness of the substrate.

The density of carbon in the sediment was estimated as the product of the density of dry substance (gds×m^{-3}) in the sediment and the relative amount dry substance in the sediment (%). The density of dry substance was estimated to be 480 gds×m^{-3} (calculated from water content of 76%) in Asphällsfjärden /Hedenström and Risberg, 2003/ and 2650 gds×m^{-3} for sand in the other basins (Hedenström pers comm). The carbon content of the dry substance in Basin Asphällsfjärden was assumed to be 19%, which is a median value from sediment in Lake Eckarfjärden, deposited when the lake was a bay in the Baltic Sea, 975 to 1,175 yearBP /Hedenström and Risberg, 2003/. It was also assumed that the particulate fraction of the sediment had twice the weight compared to the dissolved fraction. In Basin SAFE and Stånggrundsfjärden, sand was assumed to have a small amount of carbon (0.3% of dry substance).

The sedimentation rate for the whole basin (gC×year^{-1}), was calculated from the sedimentation rate per square metre (gC×m^{-2} year^{-1}) and the accumulation area (m^{2}). The sedimentation rate per square metre was calculated from the sediment density (gC×m^{-3}) and the accumulation rate (1×10^{-3} m year^{-1}) from a sediment core in Lake Eckarfjärden during the period 975 to 1,175 yearBP reported by /Hedenström and Risberg, 2003/. The accumulation area in basin Asphällsfjärden was estimated to be 25% of the total area. Basin SAFE and basin Stånggrundsfjärden was assumed to have no net accumulation, as the soil map /Elhammer and Sandqvist, in press/ suggest that no recent deposited sediment is present. The theoretical residence time for carbon in the sediment (year), estimated by the ratio of carbon content in the sediment (gC) and the sedimentation rate (gC×year^{-1}), was c 200 years in Asphällsfjärden.

Transport to the marine basins from terrestrial runoff

The total transport of water and carbon to the three sub-basins from terrestrial runoff was estimated by using the hydrological model described in Section 3.4 and a mean annual organic carbon (TOC) concentration of 19.03 gC×m^{-3} in water from Lake N:a Bassängen /Sonesten, 2005/ (i.e. the drainage area Forsmark 2), and 3.5 gC×m^{-3}×yr^{-1} /Canhem et al. 2004/ for diffuse runoff from the remaining terrestrial areas.

Transport to and from the marine basins from other basins and the Baltic Sea

Water exchange between other basins and the open Baltic Sea plays an important role in water and carbon transport to and from the basins. This is pronounced in basin Stånggrundsfjärden and Basin SAFE (see Figure 4-24 and 4-20 where a simplified illustration of the net water and carbon flow to and from the three basins is presented). The water flows were estimated in the oceanographic model, described in Section 3.5. The resulting carbon transport was calculated using median values of organic carbon (TOC) /Sonesten, 2005/ from sampling sites in similar basins, or for basin Asphällsfjärden from Kallrigafjärden, assumed to resemble conditions in Asphällsfjärden without the intake of cooling water to the nuclear power plant.

Overall carbon transport to and from the basins

The processes contributing with carbon to the basins are primary production, runoff from the terrestrial environment, while respiration and sedimentation remove carbon from the system. Water exchange is both a contributing and a removing process, depending on net flow direction of water. In Figure 4-25, the major inflows and outflows of carbon in Asphällsfjärden, Stångrundsfjärden and SAFE-area are illustrated. In basins Stånggrundsfjärden and SAFE, the transport of carbon is dominated of the transport generated by water exchange between the basins and the Baltic Sea. The water exchange is large and the overall carbon retention time is calculated to be only 2–5 days in these basins. In the secluded basin Asphällsfjärden on the other hand the inflow of carbon is dominated (c 75%) by macrophyte primary production. Carbon is transported from the basin mainly via water exchange and only to a small extent by sedimentation or respiration. Carbon retention time in basin Asphällsfjärden is estimated to be c 23 years.

The net flow of the contributing and removing processes was expected to be zero. However, on an annual basis there is a calculated net contribution of carbon of 2.0×10^8; 7.6×10^8 and 3.7×10^9 gC in basin Asphällsfjärden, Stånggrundsfjärden and SAFE, respectively. This net contribution corresponds to approximately 43%, 3% and 2%, respectively, of the inflow of carbon. One plausible explanation for the large surplus of carbon in Asphällsfjärden can be an underestimation of sedimentation. The primary production of macrophytes may be overestimated as figures on biomass and production are gathered from offshore, shallow areas (e.g. basin SAFE) where the relatively clear water probably enables a higher production, compared to the more enclosed conditions of basin Asphällsfjärden.

4.4.4 Conclusions on the landscape carbon budget

When the separate ecosystem models are connected it is apparent that the magnitude of estimated fluxes of water and carbon over system borders are roughly consistent, even though they have been estimated independently with different models and with measured fluxes or concentrations.

The largest fluxes of both water and carbon in the Forsmark area are driven by the exchange of water between the marine basins and between the basins and the open Baltic Sea. The estimated carbon fluxes from terrestrial areas to the marine basins, based on the measured concentration of TOC in the streams, are proportional to the water fluxes. However, the major pathways for water and carbon flux differ. High carbon fluxes are generated from the net primary production (NPP). The fixation of atmospheric carbon (and thus also uptake of essential nutrients) is partly balanced by high relative fluxes due to respiration (release to the atmosphere and mineralization), especially on land and in lakes. Another large fraction is the storage of organic carbon in soil and sediment.

For water it is assumed that there is no annual storage. The highest fluxes are found in the coastal area. The runoff from the watersheds contribute with about 10% of the total water flow into the most affected basin, Asphällsfjärden, and less than 2‰ into the basin Stånggrundsfjärden. Thus, any inflow of matter from the terrestrial and limnic systems to the marine basins will be highly diluted due to the large flows and fast water turnover in the coastal area.

The theoretical residence time for water (water volume divided by flow) was estimated to parts of days in the coastal area, whereas it ranged between some days and almost a year for the lakes and the wetland. The longest water residence times were found in the terrestrial parts of the watersheds, ranging between 2 and 3 years.

The theoretical residence time for carbon (biomass or organic carbon pool dived by the outflow) is considerably longer, ranging from days in the outer coastal basins to 5,000–10,000 years for terrestrial ecosystems. This is mainly due to the large amount of carbon stored in the sediments and soils. There are, however, large differences between the different marine basins and between the different lakes. The theoretical carbon residence time is a function of the amount of carbon in sediments and the water turnover. As an example, Lake Puttan has a long carbon residence time due to deep sediments and slow water turnover (i.e. a small catchment area), whereas Lake N:a Bassängen has relatively thin sediments and fast water turnover. This can also be seen in the coastal basins, where the innermost basin with deeper sediments and long water residence time has a much longer carbon retention time than the outer basins.

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

The ecosystem budget calculated in this study is a unique attempt to obtain a holistic view of the landscape, providing both the safety assessment with values for parameters used in the dose models, e.g. landscape information on fluxes, and also with possible limits for residence times and fluxes.

The water and carbon budgets describing the different ecosystems are more or less well balanced, partly due to estimation of net flows from the differences between large numbers. Small errors in the originate estimates will therefore contribute to large errors in the net flow estimates. This is probably mainly the case for the marine basins. These errors can be estimated and in some cases minimised by further use of collected data of other elements than carbon. Unbalanced budgets may also be a consequence of low spatial resolution in the measurements of e.g. TOC contents in marine basins, or that the metabolic rate constants for organisms are generic or estimated. This can be improved and refined by *in situ* process measurements in the area as planned for the next stage of the site investigations (KPLU).

The amount of resources in the area that humans can utilise is described in Section 3.10. In the next version of the site description, this information will be distributed over the different ecosystems in order to estimate how much food that can be obtained from each ecosystem for a sustainable population of humans. This will also enable estimations of the maximum sustainable population at the site.

In summary, this first attempt to obtain an overall carbon budget for the different connected ecosystems in the Forsmark area has given a platform to build dose models, to obtain data for biosphere objects and to build a landscape model (see Appendix 2). There are still issues which need to be resolved by reinterpretation of available data, by collection of new data (especially process measurements), as well as a thorough review of the many assumptions and calculations. The major benefit is that already at this stage of the site-investigation, a large set of quantitative data from the site can be utilised.

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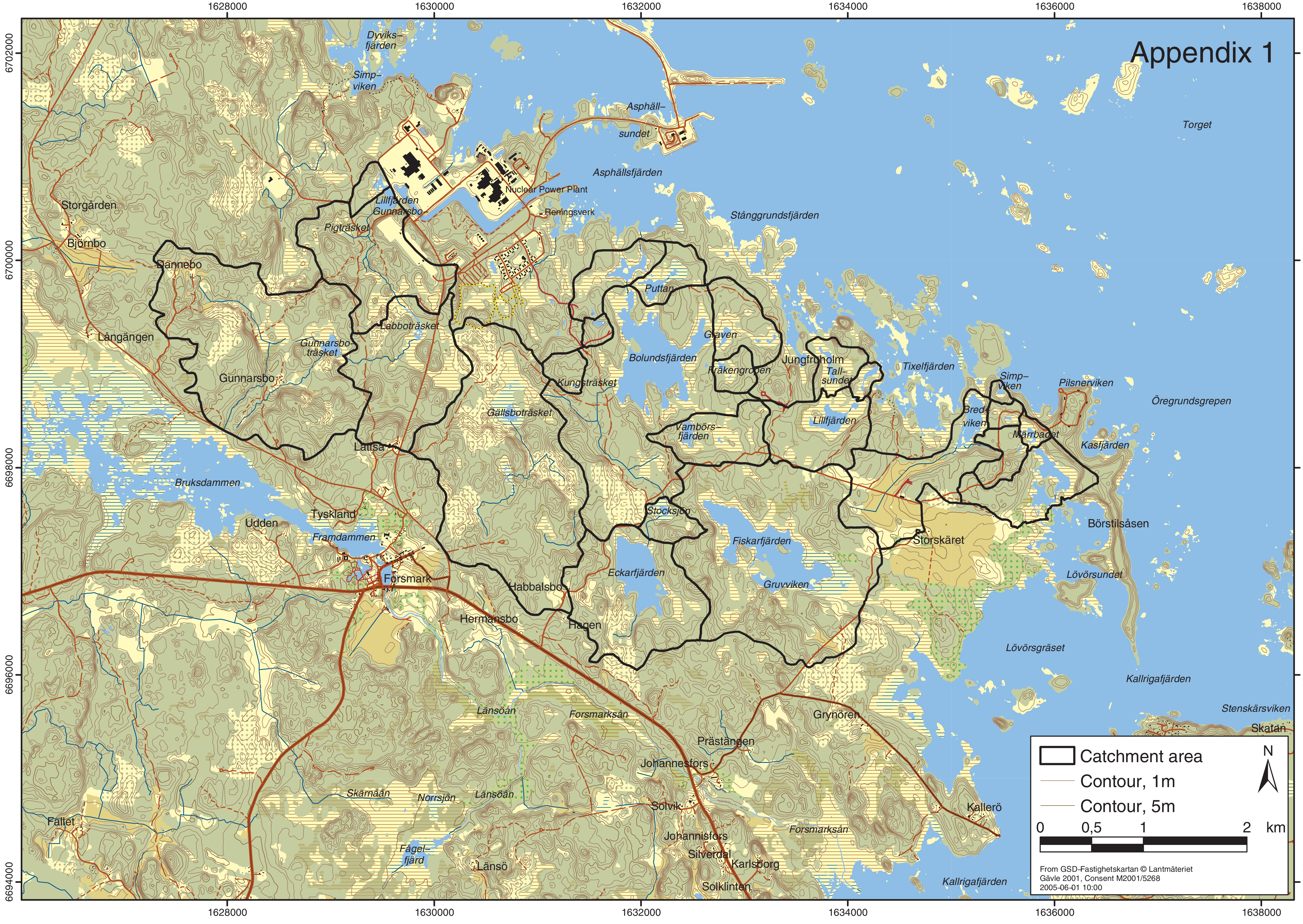
Appendix 1



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Appendix 2

Application for safety assessment

The biosphere is an essential part of the system that has to be understood and analysed in a safety assessment of a nuclear waste repository, since the consequences of a potential release occur in the biosphere. For the time scales of relevance to the safety assessment, the biosphere will undergo considerable development, in particular due to expected future climate changes involving periods of permafrost and glacial conditions. A realistic, site specific handling of the biosphere is likely to yield very low doses during most of the assessment period /cf SKB, 2004c/.

Releases from the repository are expected to be negligible for thousands of years into the future when today's biosphere has undergone considerable development. Nevertheless, it is essential to obtain a thorough understanding of the current biosphere, e.g. from site data, since this is the best available basis for a description of future biospheres during temperate conditions. Also, an important factor affecting the biosphere structure in an interglacial period is the position of the shoreline which is fairly predictable, partly since it is strongly related to the local topography, i.e. the DEM (Section 3.2). Furthermore, much of the knowledge required to describe the functioning of the biosphere is generic in nature meaning that results regarding the current biosphere from the site investigation are applicable also for altered future biosphere conditions. Studying and analysing the biosphere is therefore an essential part of the ongoing site investigations and the results of these studies are of direct relevance for the safety assessment.

In this section an overview is given how site data will be used in the safety assessment together with some examples. The data used in the following examples are from earlier versions of site data. Thus data presented elsewhere have not been incorporated yet, but that will be in the work for SR-Can. Further information regarding the safety analysis is provided in the SR-Can interim report, and later in dedicated reports regarding the safety analysis and the biosphere.

Integrated landscape model

The novel approach for the biosphere is to assign different biosphere objects which can be interconnected in an integrated landscape model (cf Figure A2-2). The landscape models are created for different representations of critical time periods as described in section (Time periods).

The biosphere will be defined as a combination of specific biosphere objects. The objects have different spatial extension and properties. Each such object can be regarded as an ecosystem with an intrinsic turnover of matter.

The two main categories of ecosystems, aquatic and terrestrial, are further subdivided into a number of ecosystem types. Aquatic ecosystems include marine systems, lakes and running water, and terrestrial systems include agricultural land, mire and forest. For each of these, there are in general several possible model types that can be applied. Some of the exposure models are similar to the marine or lake models shown in Chapter 4.2 and 4.3. They use site data in a large extent. Others, like the mire model, exemplified in section use a smaller part of the site data collected.

In order to assess doses to humans, given the calculated distribution of radionuclides in the landscape, a number of assumptions have to be made concerning living habits, exploitation of the landscape etc. Many of these must be generic, but the characteristics of the site and its potential future states do also provide a number of constraints on such assumptions. It is e.g. possible to estimate the number of individuals that can live off the natural resources at a site.

The interconnection of the biosphere objects is facilitated from the understanding of the surface hydrology and the locations of the discharge points.

After identification of the positions of the discharges and the associated ecosystem type, the accumulation of the discharged radionuclides downstream in the catchment will be modelled. The discharge points of radionuclides from the geosphere to biosphere, obtained from the geosphere modelling, in SR-Can interim report /SKB, 2004c/, were selected as an illustration of how the biosphere objects will be connected and positioned in relation to the discharge points. From the discharge points, the major biosphere types were identified (Figure A2-1). If there are several stream-tubes entering the same catchment basin, but in different biosphere objects, these will be combined by connecting the different biosphere objects together based on site-specific maps. The maps not only describe how the biosphere objects are interconnected with each other, but also provide estimates of important parameters such as water turnover, accumulated runoff and information on how the biosphere can be utilised by humans.

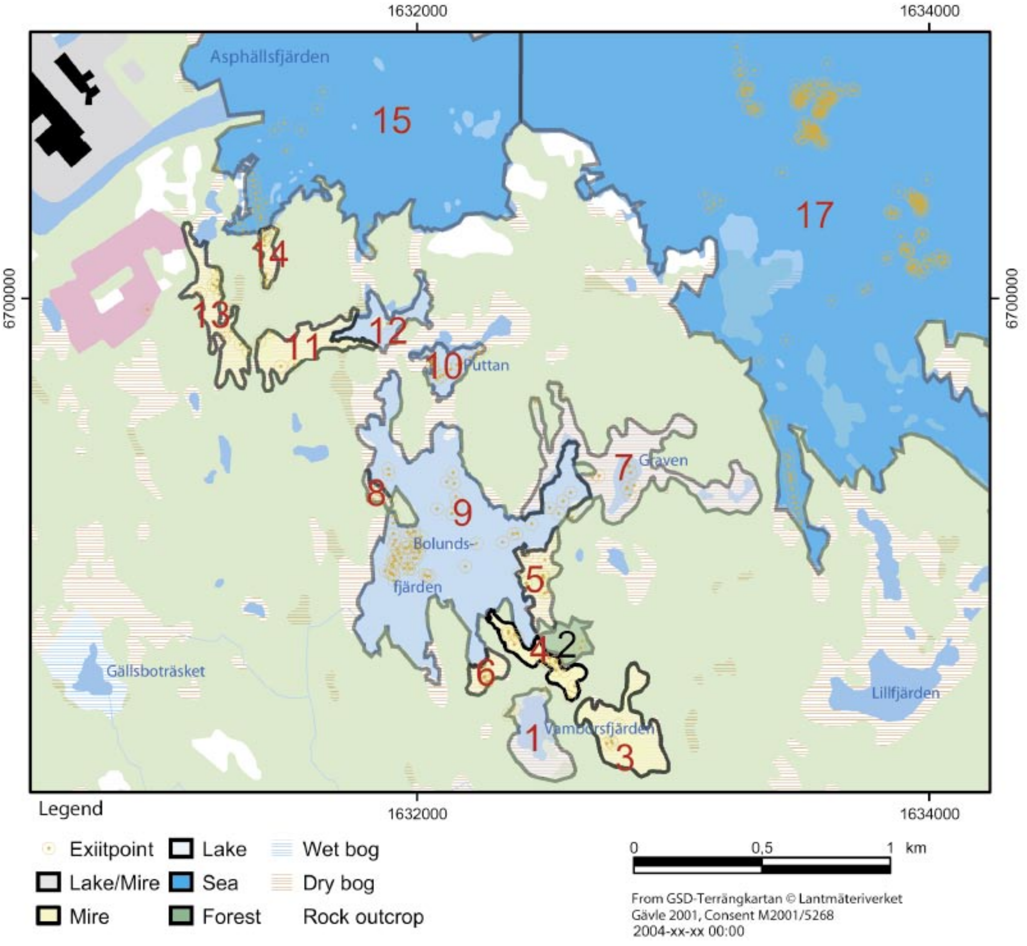

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Figure A2-1. Map with biosphere objects classified according to the exit points of radionuclides to the biosphere, cf legend. The objects are numbered. Sea object 16, 18 and 19 are outside the of the map area.

The result from this preliminary analysis shows that more than half of the exit points are located at the coastal sea floor (Sea 17). Approximately 200 (5% of the total) have also advective travel times less than 1,000 years, i.e. still a coastal situation. Another large fraction (27%) of exit points are in Lake Bolundsfjärden (area 9) and fringing mires (areas 4 and 8). For the majority of these points the advective travel time is less than 1,000 years. That is within the projected persistence of Bolundsfjärden. Notable from this exercise is that very few points (0.5%) are in terrestrial environments other than mire.

These findings from the preliminary data indicate that it is likely that the coast, lakes and fringing mires are the primary receivers of discharge from the geosphere. This confirms earlier analysis. The identified biosphere objects were represented with corresponding dose models, which are interconnected, see Figure A2-2. The dose models are listed in Table A2-1 and described in relevant sections later. As far as possible site-specific data have been used in the different models (listed in Table A2-1). Some data are from the SAFE study /Karlsson et al. 2001/ and data used are listed in a data report /cf SKB, 2004b/.

A constant unit release of 1 Bq/year was applied to the most upstream object Varmbörsfjärden (Mire1). Four hypothetical radionuclides with near infinite half life and with K_d values in the range 1–1,000 (m^3/kg) were simulated in the model over 10,000 years.

The results show that radionuclides with lower K_d (1 m^3/kg) flowed through the network of connected ecosystems out into the sea. On the other hand nuclides with higher K_d (1,000 m^3/kg), remained almost exclusively in the first three ecosystems nearest the simulated discharge from the geosphere. The radionuclides with intermediate K_d values (10 and 100 m^3/kg) were found in the middle of the chain, in Lake Bolundsfjärden. A considerable fraction of these radionuclides also left the system.

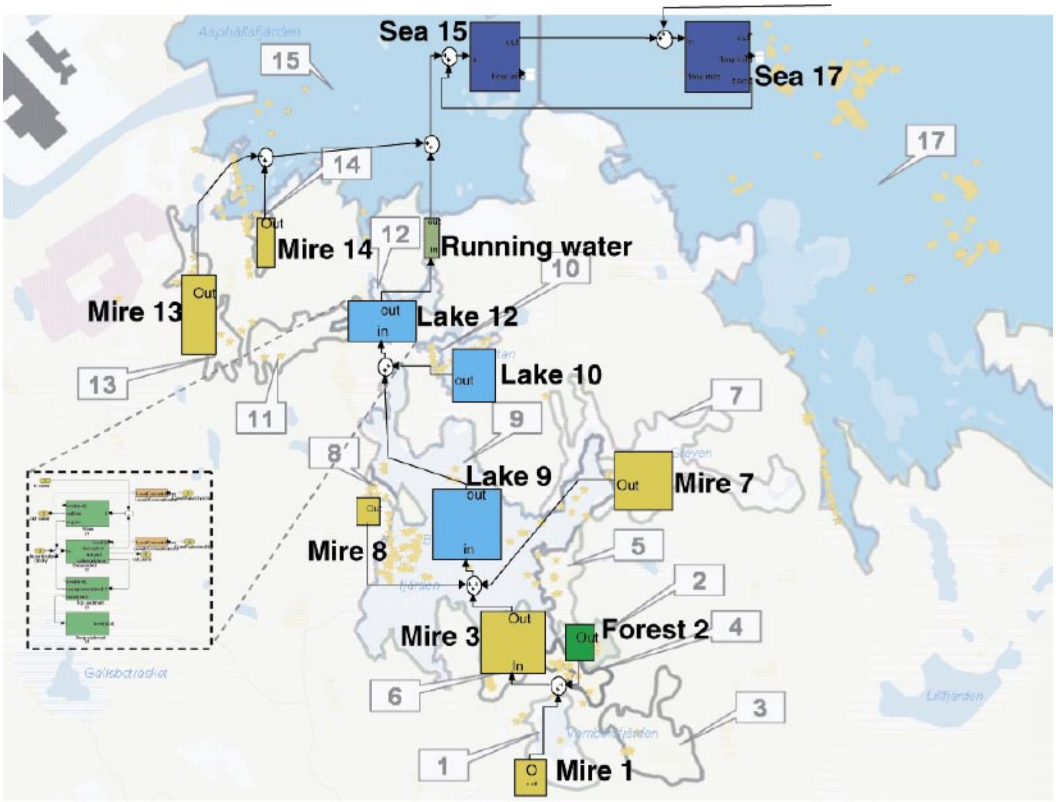

Figure A2-2. Integrated landscape model consisting of a number of connected biosphere objects. Each biosphere object is a representation of underlying biosphere model, cf Lake 12 and the hatched panel at the left.

Table A2-1. Classification and properties of ecosystem objects including statistics of discharge points to the biosphere and associated advective transport times. Data for the object are an example from an earlier version used in the SR-Can interim report /SKB, 2004b/.

Name	Id	Eco-system	Number of points		Adv. transp. time		Model	Object area	Drainage			
			(n)	(%)	median (years)	max (years)		(10^3 m^2)	area (10^3 m^2)	mean depth (m)	volume (10^3 m^2)	turn over time (years)
Vambörsfjärden	1	Mire/Lake	76	1.7	35	178	Mire1	56	484	0.4	21	0.19
	2	Forest	22	0.5	37	510	Forest2	22	702			
Djupsundsdel.	3	Mire	32	0.7	35	281	Mire3	70	695			
	4	Mire	367	8.2	35	12,670	Mire3	32	1,280			
	5	Mire	77	1.7	24	922	Mire3	36	1,267			
	6	Mire	59	1.3	14	80	Mire3	16	63			
						tot	Mire3	154	2,610			
Graven	7	Mire/Lake	53	1.2	32	184	Mire7	50	615	0.1	6	0.07
	8	Mire/Lake	419	9.3	26	3,605	Mire8	7	26			
Bolundsfjärden	9	Lake	406	9.0	60	2,440	Lake9	610	8,003	0.6	374	0.21
Puttan	10	Lake	120	2.7	29	4,361	Lake10	80	236	0.4	30	0.02
	11	Mire	7	0.2	4	18	Lake12	52	271			
N. Bassängen	12	Lake	2	0.0	3,217	4,321	Lake12	80	13,440	0.3	24	0.01
	13	Mire	61	1.4	7	1,187	Mire13	54	709			
	14	Mire	92	2.0	28	97,830	Mire14	13	61			
Asphällsfjärden	15	Sea	207	4.6	26	2,072	Sea15	1,026		1.8	1,856	0.002
	16	Sea	36	0.8	4,327	10,670	Sea16	1,557		2.3	3,550	0.002
	17	Sea	2,343	52.1	3,613	84,410	Sea17	4,465		3.8	17,012	
	18	Sea	12	0.3	7,932	30,370	Sea17	4,398		4.2	18,340	
						tot	Sea17	8,863		4.0	35,351	0.002
	19	Sea	103	2.3	10,250	57,320	Sea19	11,490		10.7	122,943	0.002
Öregrunds-grepen		Sea	0	0	0	0	Sea	456,000		11.2	5,107,000	0.033

The preliminary results from this exercise indicate that the coastal ecosystems, lakes and some type of mires are all major receivers of discharges and that the highest concentrations and the highest doses will arrive closest to the discharge points.

In SR-Can this method will be used and applied for the biosphere at the different periods dependent on availability of spatial data.

Biosphere objects

The biosphere objects available are the mire, lake, sea, forest, running water, agricultural land and well. Each of them has site specific properties as geometry (position, length, area, volume etc) and local hydrology (effective precipitation, discharge etc). Other site data are important for some of the objects, depending on the model type.

The biosphere objects can be used in the landscape model described above or alternatively as site-generic average representative objects, not positioned in the landscape.

The biosphere objects are described elsewhere /Bergström et al. 1999; Karlsson et al. 2001; SKB, 2004c/, here only the well and the mire are shortly mentioned.

Wells constitute an important pathway for human exposure of potential releases from the repository. The approach to modelling of wells in SR-Can is based partly on site specific information (e.g. well capacity, density, depth, position) and considers constraints on the size of a population (cf Section 3.10) that can utilise a local well /SKB, 2004c/. Other data are universal, e.g. water consumption by humans or cattle, irrigation practises etc.

The mire model

In many areas around the sites, mires are the common pre-stage before they are drained by ditching and used as agricultural land. The model of the mire object is, in principle, the same as was used in the safety assessments SR97 and SAFE /Bergström et al. 1999; Karlsson et al. 2001/ except that the water turnover in this version is estimated from the total amount of water coming from the drainage area according to the equation:

$TC = \frac{R}{\varepsilon \cdot D} \frac{A_d}{A_m}$ where R = Effective precipitation, ε = Porosity, D = Depth,

A_d = Drainage area, A_m =Mire area

In the previous model, only the surface area of the mire was receiving the effective precipitation, not the drainage area. The geometry of the mires and their position is based on the statistics from site-specific data, collected from about 200 mires in the area (Figure A2-3). In Table A2-1 the mires used in the landscape model are listed.

Effective precipitation from /Larsson-McCann et al. 2002; Karlsson et al. 2001/. Wetlands statistic from SICADA database and areas from GIS. Data from SICADA based on smallest cultivation depth, best estimate depth is from database while max depth is taken from /Karlsson et al. 2001/.

The ecosystem specific dose conversion factors (EDF) were calculated using probabilistic simulations with the Tensit tool /cf Jones et al. 2004/ integrated over a 10,000 years period. An example of the EDF distributions for some radionuclides is shown in SR-Can interim report.

Table A2-2. Data used in the mire model. Min and max are truncations of normal (N) and log-normal (LN) distributions and minimum and maximum values for triangular (T) or log-triangular (LT) distributions.

Parameter	Units	Dist	Best est.	Std	Min – max	Type
Runoff[1]	m/year	N	0.23	0.078	0.071–0.451	Site-specific
Density[2]	kg/m^3	T	100		80–120	Site-specific
Porosity[2]	–	T	0.9		0.8–0.95	Site-specific
Area[3]	m^2	LN	10,931	3.82	$900–1.1 \times 10^6$	Site-specific
Depth[4]	m	T	0.33		0.2–2.1	Site-specific
Drainagearea[3]	m^2	LN	550,935	2.61	$9\ 10^3–1.7 \times 10^7$	Site-specific
Tk[2]	year	LT	10^{-3}		$10^{-5}–10^{-1}$	Universal

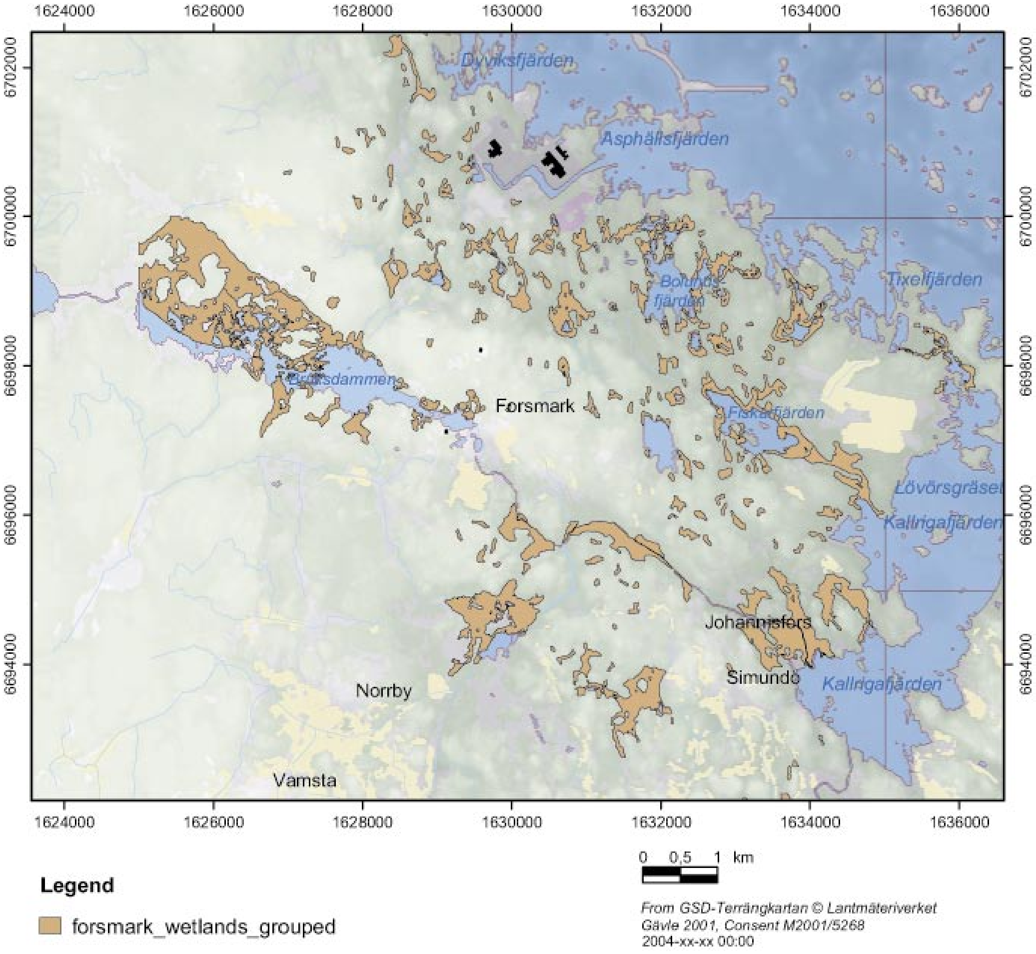

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Figure A2-3. *Mires identified from an early version of site data from Forsmark.*

For most radionuclides the EDFs in SR-Can are one to two orders of magnitude lower than in SR97 for the mire model. This decrease is mainly because the drainage area is larger than the mire. However, there are also other site-specific parameters contributing to the differences, i.e. the depth and surface area of the mire.

This relatively simple mire model shows that the use of site-specific information improves understanding for the actual site and thus the model formulation, which results in considerable changes in estimated doses. Still this type of EDF model is a very coarse estimate which is probably pessimistic. For example the accumulation time in mire affects the dose considerable and thus the assumptions of how long time mire can be used for agriculture before the transition from mire to agricultural land is important. Many mires can be utilised before 10,000 years of accumulation, which gives lower doses. The growth of the mire is omitted which gives higher concentrations in the peat etc. Most of these parameters can be obtained from the site data and a careful analysis of historical development of the site /Bergström, 2001; Brydsten, 2004b/ and this will be developed.

Understanding of future conditions / Ecosystem and landscape succession

Apart from providing descriptions of the geosphere and the biosphere, the site descriptive model gives an understanding of past and ongoing processes at the site. This information will be useful for the description and modelling of the future development in the safety assessment. The results should be compatible with the understanding of the site history.

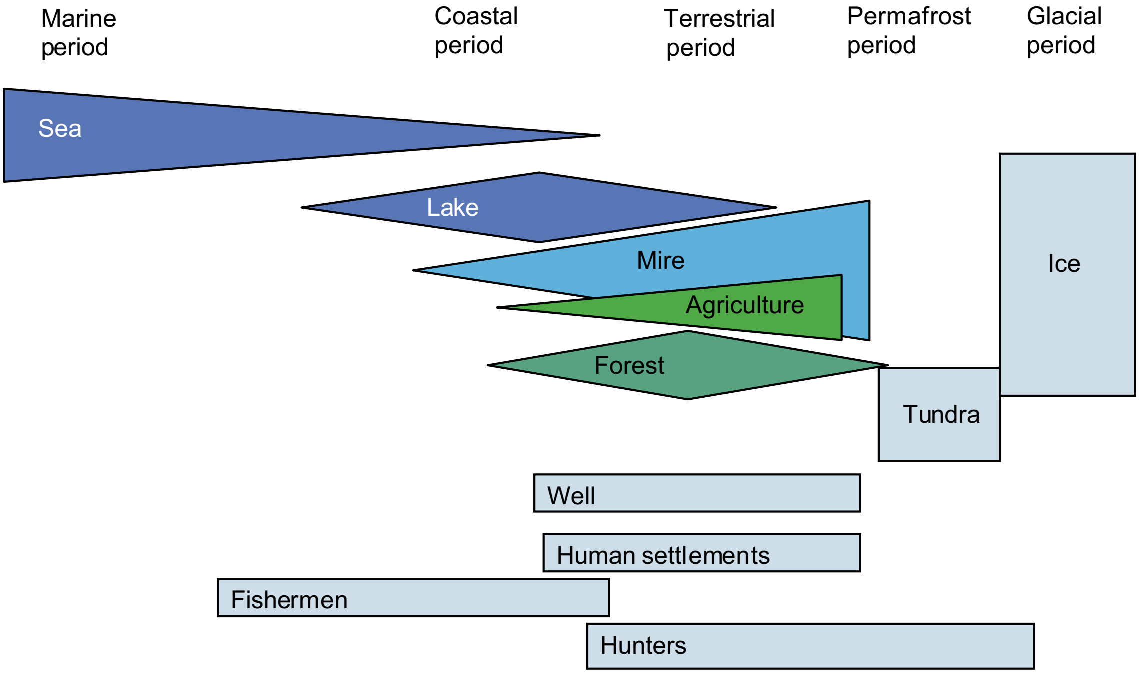

***Figure A2-4.** Hypothetical extension of different ecosystems and human settlement during an interglacial period at a site.*

The characteristics of the ecosystems will vary over time which is outlined in the following section. The most important long-term external factors are shoreline displacement and the glacial cycle. These factors affect the selection of models, e.g. terrestrial, marine or when a well can be drilled. For most contexts this is handled by selecting an appropriate configuration of ecosystem objects to provide a snapshot representation of the overall environment for each time period. A critical parameter is how long time the ecosystem persists. This affects the total amount of radionuclides accumulated in the system. For the marine ecosystem, which persists throughout the major part of the interglacial period, shoreline displacement has a significant effect on model parameters which affects calculated radionuclide concentration. The shoreline displacement is inferred from site data.

Long-term internal development can also affect the persistence of the ecosystems. This is obvious for lakes, which transforms to mires, but this can also be applied to wells, agricultural land and mires which also have constraints in life length and thus also a maximum time for radionuclide accumulation. This information is obtained partly from the site. Finally, locations of discharge points from the geosphere is likely to vary with time.

Handling of the temporal development of the biosphere

For the present temperate period, the overall development of the biosphere at the site will be outlined in a 1,000 year perspective and beyond, essentially based on the ongoing land-uplift and the understanding of the impact this has on the biosphere. The information will be summarised as a succession of simulated biosphere maps of the site, each representing a certain part of the temperate period, Figure A2-5. The maps will be the basis for the further modelling of the biosphere.

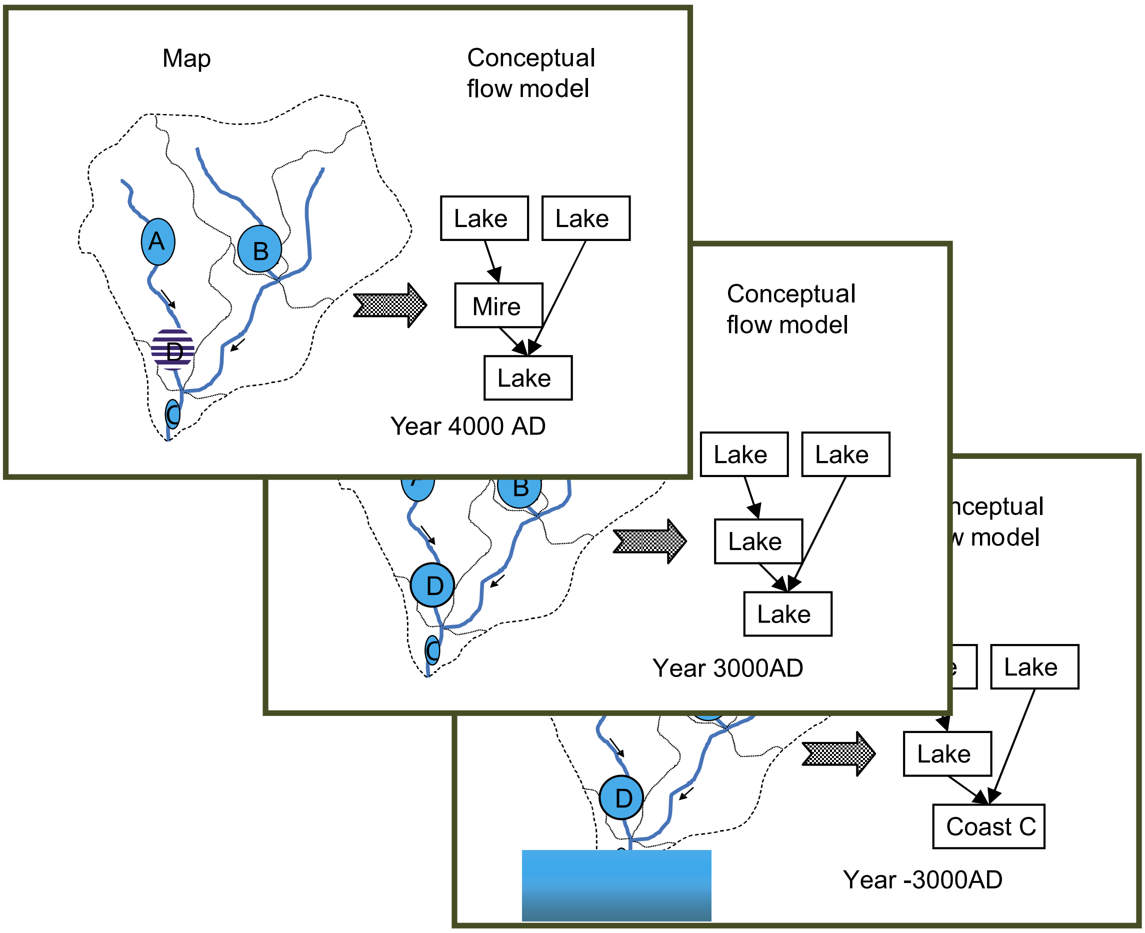

Figure A2-5. Example of a succession of biosphere maps for temperate conditions. The maps represent different time periods with different biosphere objects and data. A new map is compiled for a new state when a relevant change from the previous state has occurred.

Next 1,000 years

The development of the shoreline will induce changes of the internal biosphere conditions such as biosphere succession (mire and forest development) and sediment redistribution (sedimentation and resuspension/erosion). The future shoreline displacement and sedimentation processes are in the assessment inferred from the historical development e.g. information about the sediment stratigraphy and shoreline displacement (Section 3.1 and Section 3.3).

For the future ecosystem, vegetation and associated fauna are gradually following the shoreline displacement. Some processes will interact, e.g. peat development and forest succession, which can also be inferred from site data (see Section 3.7).

The expected effects of the shoreline displacement on the landscape the next 1,000 years are exemplified in Figure A2-6, based on an early version of the bathymetry. In the area above the repository the shoreline is displaced some 100 meters from the present. That means that some of the bays, e.g. Äsphällsfjärden, are transformed to land and some larger islands appear. However, the main part of the regional modelling area is still a marine environment, with shallower bays.

Figure A2-6. The Formark region in 1,000 years. Today's shoreline is marked as a grey dotted line based on the version 1.1 of DEM.

The infilling of lakes and transformation to mires will be further analysed based on the rates estimated in the site description (Section 3.8). The properties of future lakes are inferred from information of lakes today at the site.

Other expected changes of importance during the coming 1,000 years are human exploitation of the sites and climate change. Predicting human behaviour is always uncertain but the detailed description of the current conditions of the biosphere at the site, the historic land use and the catchments development during the coming 1,000 years indicates constraints for human settlement, food and water supply etc. Future human exploitation of the environment at the sites in terms of e.g. farming, fishing, hunting, collecting berries and mushrooms, is thus estimated by the prediction of availability of suitable soils and water and their productivity, which is based on the DEM (Section 3.2) and the marine geological maps (Section 3.3). Moreover, old cadastral maps give input information of previous land use of the site (Section 3.1), which can be extrapolated for the future. The maps developed for the coming 1,000 years will contribute to estimating the constraints of possibilities to use the area for different purposes, e.g. agriculture. The use of the wetlands will be constrained based on the further analysis of the site data on Quaternary deposits (Section 3.3) which indicates that areas with e.g. large boulders are unsuitable for farming.

Climate change or variability due to the greenhouse effect the coming 1,000 years is also expected to influence important parameters in the biosphere such as the hydrological cycle, sea level, and salinity of the Baltic Sea e.g. /Gustafsson, 2004a/. However, climatic alterations are more difficult to put into the context of a continuously changing environment, because the rate of change and variability cannot be defined. The expected magnitude and trends are mainly based on large scale simulations, where site data have little contribution. However, the variability of site data can be used to study extreme situations which are maybe future averages.

In summary, the biosphere at the site during the next 1,000 years is assumed to be quite similar to the present situation. The most important changes are the natural infilling of lakes and slight withdrawal of the sea with its effects on the coastal basins.

Until next glaciation

The continued shoreline displacement will influence the local biosphere and eventually result in a situation where the site is located in the inland rather than at the coast (Figure A2-7). This will in turn influence the positions of the potential discharge points of radionuclides. The shoreline displacement and subsequent ecosystem development will also change the possible exploitation of the ecosystems. Previous lakes will e.g. have become agricultural areas. Moreover, erosion processes of the regolith can change the topography and consequently the potential discharge points for radionuclides.

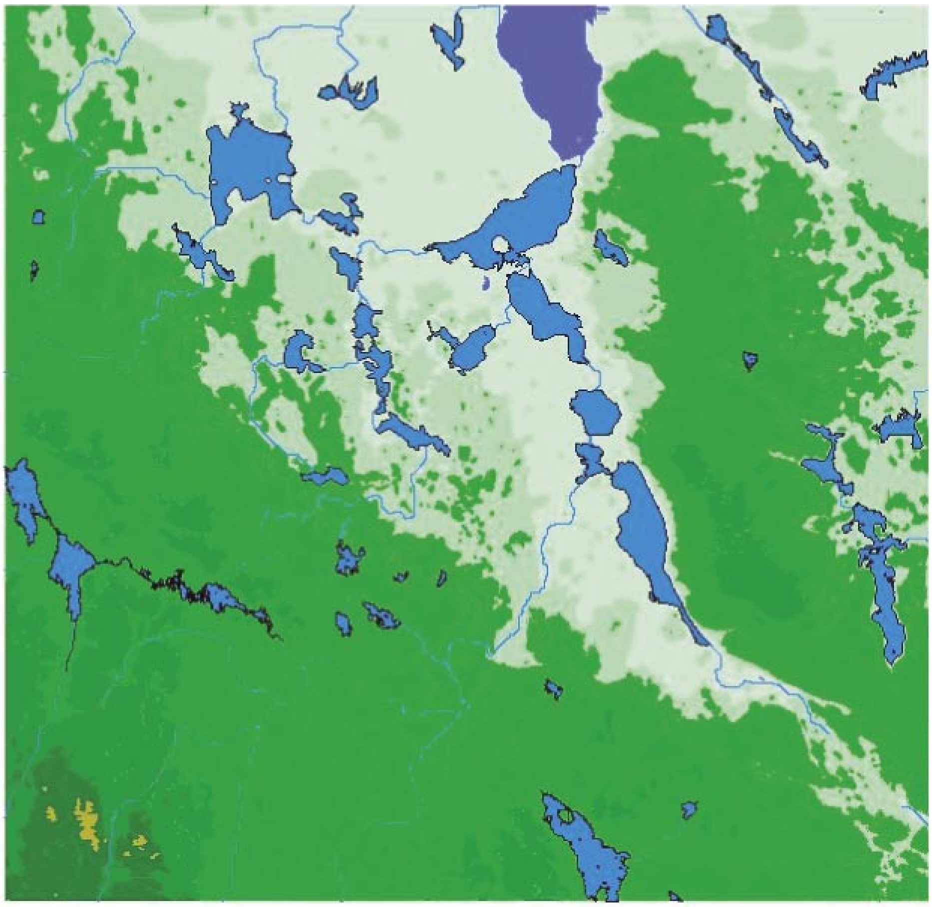

Figure A2-7. *The expected Forsmark region at 7,000AD. The entire area is terrestrial and some large deep lakes are situated along the former island Gräsö.*

During the series of transitions dependent on shoreline displacement and succession, several important stages can be identified. The aim is to systematically look at the transitions of the coast to lakes, rivers and possibly other critical development phases.

The major data input is from the DEM of the site and rates of ecosystem processes as infilling and mire growth. Moreover, the present ecosystems will be scaled to the future map. The properties of e.g. lakes are inferred from lakes today in the region.

Complete glacial cycle

Permafrost conditions

The permafrost and tundra situation will be described and discussed in SR-Can. The sources of data on parameters and processes of importance for potential transport of radionuclides are based on knowledge from other places than the site. However, the DEM of the site and the knowledge about the soils will determine how the general data should be applied.

Glacial conditions

During glacial conditions the surface ecosystems are expected to contain few species and food chains and human population is likely absent or sparse. Therefore, the doses from potentially discharged radionuclides are expected to become very low. A description of the glaciated and ice-margin surface ecosystems and its human exploitation will be compiled for SR-Can. Data for this will be derived from generic data and not from the site.

Next interglacial period

The Forsmark area has earlier been submerged by the sea or very large freshwater lakes. The sea has likely experienced periods with higher salinity than today /Westman et al. 1999/, and, immediately after deglaciation, also freshwater periods. After a future glaciation the shoreline displacement is expected to gradually make the Forsmark area less submerged and eventually the first land in the area will appear, maybe 10,000 years after the ice retreat. The sediments are expected to be eroded by strong, wave driven resuspension forces /Brydsten, 1999/ during this period, before transformation to a terrestrial environment will occur. Only some limited areas along Gräsö are expected to have continuous accumulation bottoms during the next 10,000 years (Figure A2-8). Thereafter, similar to the present situation, a period dominated by a coastal environment is expected to take over, followed by a terrestrial period when lakes, rivers and mires will be formed.

In general the ecosystem processes during the next interglacial period are expected to be similar to those occurring during the present interglacial. There will be a Baltic Sea basin, with a lower salinity than ocean water. Rock outcrops and depressions with till, bays, lakes and bogs will probably be located at approximately at the same places as today, since their locations are essentially controlled by the underlying geological structures which have persisted the last millions of years. However, eskers cannot be generalised in this way. Humans will probably be able to exploit the sea, the lakes and the land in similar ways as today, and their needs are assumed to be the same. Thus, the description of the coming 10,000 years and the historic description of the biosphere can serve as a general “model” for all coming interglacial periods. That means that the knowledge about the site today and its history as well as the DEM from the site will be important site information.

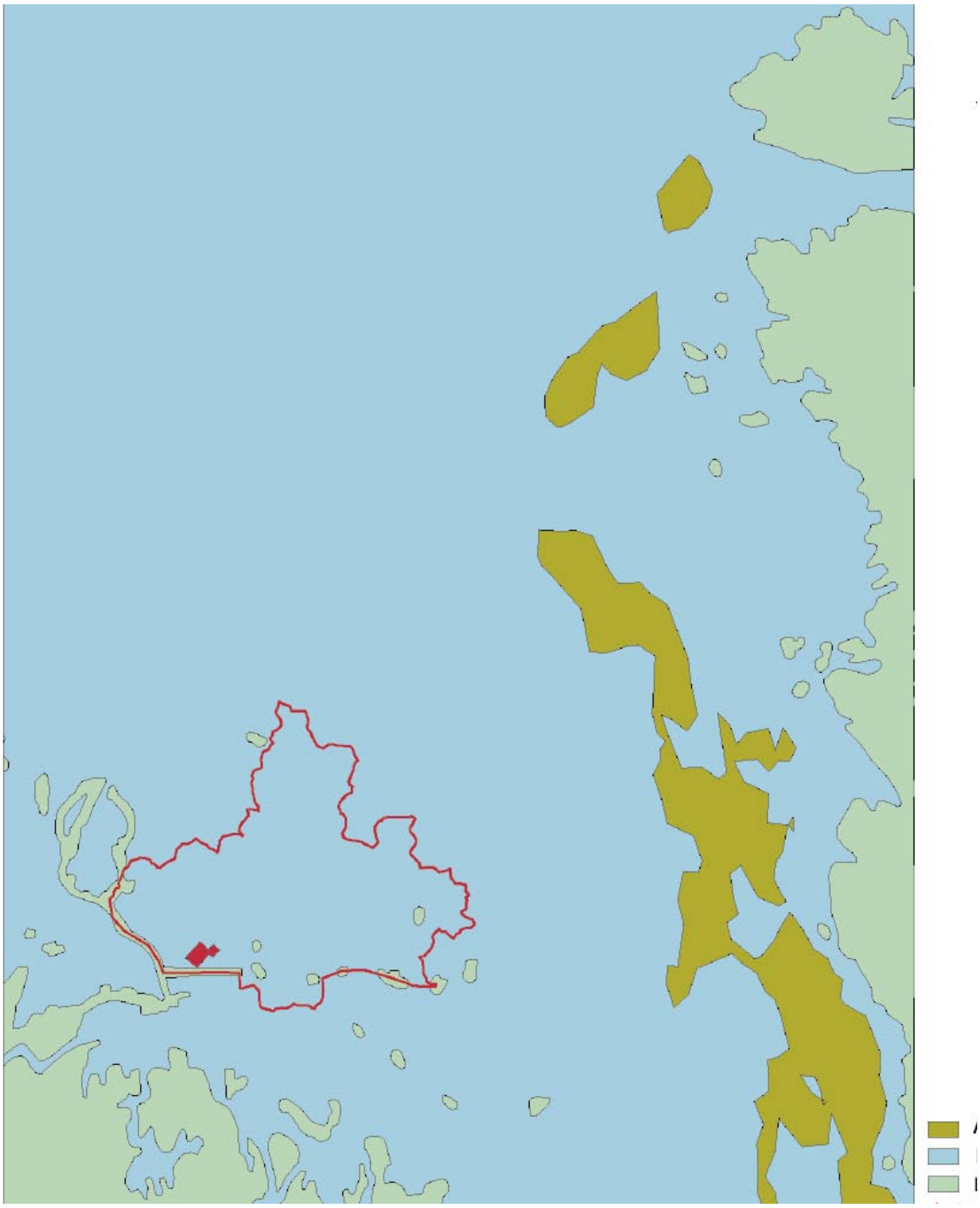

Figure A2-8. *Areas along the Gräsö island that are expected to have continuous accumulation bottoms during the next 10,000 year /Brydsten, 1999/.*